Reliability Modelling for Asset Management in South East Water

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ABSTRACT

Over the years, the reliability modelling of water assets has generated increasing interest among both researchers and practitioners. Statistical methods and software packages for assessing asset reliability have been developed in order to improve asset availability, indirectly reduce water losses, and hence improve the efficiency of water assets. OFWAT, which is the economic regulator of the water sector in England and Wales, aims to ensure that water companies operate under their statutory functions and have sufficient financial means to perform these functions adequately. Water companies need to prepare a five-year business plan for OFWAT, in order to certify they have enough capital and are transparent when carrying out their statutory functions. Hence, this thesis aims to analyse the reliability of two selected types of assets at South East Water to help plan their future investments on vehicles and future maintenance costs on borehole assets.

This thesis will provide an extensive literature review on reliability modelling in water distribution networks. An MS Excel-based decision support system will be developed for both vehicles and borehole assets, using data collected from South East Water. For the transport model, a block replacement policy will be developed by using Visual Basic, to obtain the optimum time of replacing a vehicle. Performance analysis will be conducted on the borehole data to pinpoint the worst performers among the 16 boreholes under analysis.

Disclaimer

Please note that because of the Data Protection Act, all the original data collected from South East Water have been masked in this thesis.

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CHAPTER 1. INTRODUCTION

1.1 The UK Water Industry

Water is considered as one of the most important substances for all living forms on earth. Water covers about 71% of the earth's surface. Apart from being crucial for survival, there are several uses of water. For example, water can be used for domestic, agricultural, industrial, commercial and recreation purposes and even hydropower generation. The domestic use of water includes water being used for ordinary household purposes, such as drinking, cleaning, food preparations and so on. Moreover, no harvesting can be done without water, thus making it essential for agricultural purposes. If the crops are not adequately irrigated or rainfed with the required amount of water, they will not develop and bear fruit. Hence, a large amount of fresh water is required to cultivate the crops, which are being consumed domestically and throughout the world.

As mentioned above, water is also essential in commerce and industry. Commercial operations are those who provide a service, such as hospitals, restaurants and schools. On the other hand, industry involves product manufacturing. Water helps in the smooth and efficient functioning of the machines used to make the products. It can also be a crucial part of the product, such as in soft drinks or energy drinks. Furthermore, water is also being used in the generation of electrical power, for example, to push the turbines or cooling equipment that are the crucial process of producing electricity. The pulp and paper industry is another big water users as they use millions of gallons of water in various processes that will produce a piece of paper from a log.

Water can be collected via different sources such as surface water, river or lakes, springs, rock catchment areas, excavated dams, rainwater tanks, boreholes and artesian bores. Surface water means water that fell to the ground as rain or hails and has then been stored into a natural or humanmade barrier called a dam or reservoir. Rock catchment areas collect water from rain in large rocky outcrops with low areas to trap the water. Excavated dams are made by digging the soil to make a sizeable shallow hole to collect water. Rainwater tanks collect rainwater, which falls on the roofs of houses usually by making use of roof guttering passing through a pipe to a storage tank. Boreholes, one of the primary sources of water collection in the UK, are holes drilled into the ground deep enough to find a long-lasting body of water. A pipe is used to run down the hole into the water, while a pump is utilised to get the water up to ground level.

The UK water industry is different when compared to the water industries of most other countries. Usually, water utilities are owned and controlled by the government. However, in the UK, water utilities are privately owned since 1989. They cover a large geographic area and serve tens of millions of people. There are 32 privately owned companies in the UK, which provide good quality water, to over 50 million household and non-household customers in England and Wales. For example, South East Water is one of the companies that supply drinking water, and more details about this company will be given in Section 1.3. There are three organisations in charge of the regulations of the operations of the water companies in England and Wales. These are the Water Services Regulation Authority, the Drinking Water Inspectorate and the Environment Agency.

The Water Services Regulation Authority (OFWAT) is the economic regulator of the water and sewerage sectors that ultimately decides the bills that the consumers will pay. It ensures that water companies keep the bills at a reasonable level, in order to protect the interests of the consumers. However, it also takes into account the significant operational costs and investments required to maintain the infrastructure for future generations incurred by the water companies when assessing the bills. This is to make sure that the water companies can adequately carry out their functions. It has recently introduced the Service Incentive Mechanism (SIM), who aims at adding a dimension of customer satisfaction into the monitoring of services. OFWAT also monitors the quality of the services provided by the companies, by comparing it to their competitors, in order to promote competition. However, opportunities for competition in UK water are limited at the moment as the water industry is a monopoly type industry. Moreover, it promotes economy and efficiency, while contributing to the achievement of sustainable development. More details about OFWAT will be presented in Chapter 4.

The Drinking Water Inspectorate (DWI) is a part of the Department for Environment, Food and Rural Affairs that regulates drinking water quality, in order to ensure that the supply water is fit and safe to drink. This body provides an independent analysis of the activities of the water companies in England and Wales. It also publishes statistics on the water quality provided, while enforcing the legislation on UK water quality. They do this by checking the test that the water companies perform on their drinking water and also, by inspecting the individual companies. The Environment Agency, on the other hand, in an agency that will regulate how the water is sourced and how it is finally discharged. The main aim of this agency is to protect the environment. It comprises a range of areas, such as water abstraction licensing, water resource management and drought planning, pollution control and discharge permitting, monitoring of bathing beaches and bathing water quality and finally, the disposal of sludge from the wastewater treatment processes.

1.2 Asset Management in the Water Sector

Keeping the guaranteed availability of water assets is essential. The availability is defined as the capacity of an item to be in a position to carry out a specific task under given conditions at a given moment or over a given time interim, assuming that the demanded external resources are given (Standard 1993). As can be seen, the availability of an item is related to its reliability and maintainability.

If we assume a system is composed of more than one component. Then, the high reliability of a system can be achieved through two methods

1. To increase the reliability of the components in the system; or
2. To add redundant components into the system.

Of course, to require high reliability of a system, one needs to make good plans at different stages of the lifecycle of the system. Usually, an engineering system may have different stages in its lifecycle. Those stages are design, manufacturing, operation, and disposal. Along with other requirements such as product quality, reliability may be considered at the design stage. The decisions and activities made at the design stage of a product until the production stage. However, proper maintenance can reduce the probability of failure of a system.

Asset management is a process to maintain assets properly to ensure they are operated at a level of availability and under a given cost (US EPA 2018). Hence, effective and efficient management of asset is vitally crucial for water companies due to the needs to meet predetermined levels of service to customers and to comply with statutory obligations. Another benefit of asset management is that the life of the assets can be prolonged, in addition to an improvement in the decisions made about the assets' rehabilitation, repair, and replacement. Moreover, water companies will be able to meet service expectations and regulatory requirements through asset management.

Vast amounts of operation data on infrastructure and non-infrastructure systems of water services organisations have been collected during the last decades. These data are collected from multiple sources, including subjective (e.g., expert elicited data) and objective data, dynamic and static data, and data with various levels of quality (i.e., missing data, uncertain data). Complex operating conditions of these systems and their high investment and operating costs require strict guidelines for accurate data collection into risk and reliability databases. These databases have been developed not only to collect the relevant data but also to provide information concerning central reliability and maintenance indicators, weak components in the systems, common cause failures, trends, and so on. To meet these demands, a decision support tool for data pre-processing and further analysis are always needed.

Progressive water utilities have in place formal risk management structures and tools support a preventative approach to business risk management. Decisions that rely on this data include the planning of capital investment and maintenance programmes, environmental improvement plans including flood risk management, and regulatory performance reviews. Effective decisions on managing risk need to be active rather than reactive and well structured. Utilities that have effectively integrated their risk management activity across their business have amassed substantive data and information. However, the challenge for many of them is now to convert this into sound organisational learning.

Reliability data are gold assets for companies, as they embody critical information and knowledge on business exposure. The reality of much of this knowledge is that the data are not always appropriately analysed, efficiently or effectively because:

1. The data might present various problems. They may be present in different types of formats, subjective, static, dynamic, or be stored in various data storage systems. Some of them represent knowledge elicited from domain experts, and it is not easy to either collect or cleanse the data by using conventional data pre-processing techniques.
2. Only offline data analysis techniques are utilised. In the water utility sector,

real-time data analysis is critical for decision-making.

3. Data analysis is frequently not presented in a user-friendly way, which hampers onward application of the data.

Consequently, reliability modelling has always been a vitally important step for any water services companies, before asset behaviours are analysed through various techniques such as expert elicitation and statistical lifetime analysis techniques. Where the expert elicitation method is used for the scenario when there is no failure data, and statistical lifetime analysis is used for the scenario when there are a sufficient amount of data available.

1.3 South East Water

South East Water is a private limited UK water company that supplies safe and high-quality drinking water to over 2.2 million consumers in the regions of Kent, Sussex, Hampshire and Berkshire. The company came into existence in December 2017 after a merger with Mid Kent Water. South East Water has a daily supply average of 517 million litres of drinking water from its 83 water treatment works and through a network of 9000 miles of pipe. They supply over more than a 5000 square kilometres area while managing more than 9000 miles of its water mains. They currently employ around 983 employees. For the financial year ending on 31 March 2018, South East Water has obtained revenue of £224.8 million; an operating profit of £75 million and it has experienced a capital expenditure of £96 million.

Each year, South East Water ensures around 500,000 water quality tests in order to keep their water quality to the highest standards. It had maintained a high overall water quality of 99.95 per cent of samples passing standards set by the DWI. Their primary sources of water are surface water such as rivers, reservoirs but also, underground sources under abstraction licences provided by the Environment Agency. The company own over 2000 hectares of land for their groundwater sources, whereby it ensures high-quality drinking water being extracted after going through the natural filtering of underground aquifers. They have 33 sites within areas of Special Scientific Interest, which include the national nature reserve, Lillington Health in East Sussex, two nature reserves, Arlington Reservoir and Ardingly Reservoir in Sussex.

1.4 Aim and Objectives

South East Water is keen to explore ways to integrate multiple source data, which will result in predicting the behaviours of an asset more precisely. This project aims to develop an approach to data analysis for the company, which can analyse data and present the data analysis results in an easily understandable way to inform risk-based decision-making.

Moreover, the main objectives of this project are to

1. Conduct a targeted and sharply focused literature review on reliability modelling for asset management.
2. Analyse the costs and failures of the vehicles in their distribution and production department.
3. Highlight the worst performing boreholes from a sample of 16 boreholes.
4. Provide some recommendations on how to improve the problems found in both the transport and borehole model.

It is considered that the infrastructures in this water company will be subject to three types of failures, which are repairable, non-repairable and deterioration. In this research, the two main assets that will require data analysis are namely, transport and boreholes (as mentioned above). Hence, this project also aims to provide a cost-effective maintenance model, with the specific objective of dramatically improving the power and presentation of business risk knowledge.

1.5 Thesis Structure

Chapter 1 presents an overview of the UK Water Industry followed by a brief on the roles of asset management in the water sector. An introduction of South East Water is also provided. Finally, this chapter provides the aims and objectives for both the transport and borehole models. For the transport model, the primary objective is to analyse the costs and failures of the vans based on their department and model types. On the other hand, South East Water is interested in knowing their worst performing boreholes from a sample of 16 boreholes.

Chapter 2 concentrates on the literature review on reliability modelling, maintenance and maintainability while providing an extensive range of earlier and latest papers focusing on reliability modelling in water distribution networks. An explanation of the different types of water assets, namely aboveground and underground water assets will also be presented. Studies that will be relevant for this project and the research gaps will be reviewed.

In Chapter 3, a brief explanation of OFWAT will be presented. The research questions and analyses for both transport and borehole model is provided. For the transport model, VB codes will be used to find the optimum point to replace a vehicle. Calculations for the total whole life cost and the cost per mile of each vehicle model will also be required. For the borehole model, the performance condition of each borehole will be analysed. A brief explanation of the types of borehole maintenance perform at South East Water will also be given. Finally, the data collected to solve the business problems of the company will also be listed.

Chapter 4 presents the reliability modelling of transport assets. The block replacement policy has been used to design the VB codes to solve for the optimum point of replacement of the vehicles. This chapter also reviews some papers on the renewal process, non-homogeneous Poisson process and block replacement process. Moreover, a detailed explanation of the VB codes used to implement the block replacement policy will also be presented.

In Chapter 5, a thorough description of the decision support system designed for the transport and borehole model will be given. Each worksheet in the MS Excel file will be explained while providing an analysis of the findings generated.

Chapter 6 will summarise the conclusion of the outcomes that have been found in this research, followed by highlights of several recommendations that could be worthwhile addressing in future research.

CHAPTER 2. LITERATURE REVIEW

2.1 Water Assets

There are about 110 million cubic meters of water falling as rain on Earth every year. However, thousands of people die every day due to inadequate supplies of clean water. Aboveground water is water being collected above the surface, for example, a lake or pond storing rainwater. Underground water, also known as groundwater, is a term to define all the water stored beneath the surface of the ground, which is often exploited by digging wells. Hydrogeology is the science devoted to studying the underground water, its movement, behaviour and quality.

To supply water to its customers, water companies need to invest in assets. Water assets can be classified into above ground water assets (AGWS) and underground water assets (UGWS). Examples of the AGWS are pumps, mixers, vehicles and reservoirs. Examples of the UGWS are water mains and some parts of boreholes. Water main is the main underground pipe in the pipes system supplying water to a region. Hence, the networks of pipes in a city and all the components related to this network, such as valves, pumps or reservoirs, constitute a water supply asset.

Huge investments are required for water and wastewater infrastructures of distribution and collection pipes, treatment facilities, storage tanks and reservoirs. In most cities, the underground piping for water distribution was installed centuries ago, and their replacement value will amount to millions of pounds for every city. This is where water management comes in order to preserve these assets' functionalities. Water management takes into account the climate change, industrial development and ageing water assets that continuously affect the water and wastewater technologies and infrastructures.

2.2 Reliability, Maintenance and Maintainability

Reliability can be defined by the degree to which an assessment tool produces constant and reliable results. For example, companies need to choose the proper materials and other inputs needed to manufacture their product as well as proper maintenance, and quality control should be made after production. These decisions and activities will have a significant impact on the costs of production, purchase and product ownership. For these reasons, Blischke and Murthy (2003) stated that for both the manufacturer and the purchaser, reliability is one of the most consistent qualities and is a standout amongst the essential attributes characterising the nature of an item or framework. Some of the main objectives of a reliability study can be the understanding of the failure phenomena and the estimation and prediction of reliability, optimisation and many others.

Factors affecting the reliability of an item are from different stages of the item's lifecycle, which includes system design, material selection, assembly in the manufacturing process, operations as well as maintenance. Apparently, in order to address these issues, data collected from those different stages are needed to build models, and testing on the items is required. Additional testing, additional analysis or even, reengineering may frequently be necessary to perform reliability study and to ensure a level of reliability further. Generally, maintenance and maintainability are considered to be two critical issues to ensure a level of item reliability.

There are two principal types of maintenance actions. The first one is preventive maintenance, which usually requires a complete shutdown of an operational system in order to increase the length of its lifetime and its reliability. Preventive actions extend from generally minor servicing requiring a short downtime, for example, grease, testing, arranged substitution of parts or segments to real upgrades requiring a lot of downtimes (Blischke and Murthy 2003). Preventive maintenance may be categorised into time-based preventive maintenance and condition-based preventive maintenance. The second type of maintenance actions is corrective maintenance, which comprises of actions taken to return a failed product or system to its operational state. These activities include fix or substitution (by either new or utilised things) of all fizzled parts and segments fundamental for the successful operation of the item.

There are different kinds of corrective maintenance and preventive maintenance. For example, for corrective maintenance, the behaviour of an item after a repair depends on the type of repair being carried out for a repairable product. In Blischke and Murthy (2003), various types of repair actions have been described. For example, one repair action is the good-as-new repair, where the failure time distribution of the repaired product is the same as that of a new product. An ordinary renewal process is usually used to model failures after this repair action. However, in reality, this type of repair rarely occurs. Another repair action is the minimal repair, where a failed product is returned to the stage with the same active age as it was before the failure occurred. Failures after this repair often occur as per a nonhomogeneous Poisson process, whose intensity function is nonlinear concerning time.

Similarly, preventive maintenance actions can be classified into various categories. For example, one category is clock-based maintenance (i.e., time-based preventive maintenance), where preventive maintenance actions are carried out at set times. An example of this is the block replacement policy, which will be discussed in more length later in this thesis. Another category is the age-based maintenance, where the preventive actions are based on the age of the component. The Age replacement policy is an example of this category, which will be discussed in more details later in this thesis. Usage-based maintenance is another category, whereby preventive actions are based on the usage of the product. Another category is the condition-based maintenance, where the preventive maintenance actions are based on the condition of the component being maintained, usually involving the observation of one or more variables depicting the wear process. Preventive maintenance is generally carried out at discrete time instants. However, in cases where the preventive maintenance actions are carried out fairly regularly, they can be treated as occurring continuously over time.

On the other hand, maintainability is the probability that a failed system can be restored to the operating state in a specified period. Maintainability, as mentioned earlier, involves design issues involving maintenance problems. Design issues can trade off the accessibility of part for repair, standardisation of parts, modular construction and advancement of diagnostic methodology and equipment (Blischke and Murthy 2003). However, reliability and maintainability are only two of several dimensions of the broader concept of quality. For example, some quality characteristics are conformance, performance, features, aesthetics, durability, serviceability, reparability and availability. Serviceability, in other words, means the rapidity and competency of the repair work, while availability means the probability that a product or system is operational.

Reliability modelling and analysis deal with estimation and prediction of the probability of failure and its related issues such as maintenance policy optimisation, cost analysis, to name a few (Blischke and Murthy 2003). Factors such as design, materials, manufacture, quality control, shipping and handling, storage, use, environment, age or quality of repair after a previous failure can cause the failure of an item or contribute towards the likelihood of failure. As failures cannot be eliminated, companies invest in minimising the probability of occurrence and the impact of failures when they do occur. Increasing both reliability and maintenance efforts will almost certainly lead to a decrease in failure rates as well as the costs incurred due to the occurrences of the failures.

Therefore, reliability, maintenance and maintainability are important factors when dealing with engineered or manufactured products. These factors are applied in a large number of areas. For example, reliability has been applied in consumer goods, commercial goods, and software, and infrastructure, aerospace and even, construction. Cases of reliability in the infrastructure area are, for example, an underground gas pipeline or a system of dykes. For the consumer goods, on the other hand, reliability modelling has been applied to motorcycle, automobile or even DVD player. Maintenance applications include plant maintenance, aircraft engines or even mining equipment.

2.3 History of Reliability Modelling

Blischke and Murthy (2003) reported that first scientific approaches to reliability theory and methods had been initiated and applied to many operational and strategic problems after World War 2. However, since then the development and literature of reliability modelling has increased rapidly. The quantitative approach, based on mathematical modelling and analysis of reliability has been driven by the increasing needs of modern technology, especially the complex systems used in the military and space programs. For example, in space applications, there is a need for high reliability because of the high level of system complexity and the inability for repairs once the system is deployed in an outer space mission.

Hundreds of books on general reliability, numerous journals and conferences have since then been published. High reliability has been integrated into several disciplines such as engineering, mathematics, materials science, operations analysis, statistics, computer science and so on (Blischke and Murthy 2003). For instance, Rust and Cooil (1994) presented a comparative analysis of reliability approaches for both quantitative and qualitative data as the latter's are considered to be the measures of reliability.

However, the main focus of this research is the study of reliability modelling within the water industry. Goulter (1987) is one of the initial studies of the reliability of water distribution networks, is one of the most perplex unsolved problems within the water industry. Goulter (1987) analysed the current and future use of optimisation techniques in the water distribution network design. In the early optimisation techniques, the cost was the primary objective. However, over the years, maximising reliability has become of the most important objective for a water distribution network design. The main concern of reliability assessment of a water distribution network is to measure the capacity of the framework to meet the consumer prerequisites in terms of quantity and quality under both normal and abnormal working conditions (Xu and Goulter 1998).

Over the years, failure modelling of water infrastructures has attracted attention from various researchers. For example, Andreou, Marks and Clark (1987) introduced a new methodology for modelling breaks in deteriorating water distribution systems by identifying two separate stages of deterioration. The first stage, which is the early stage with fewer breaks, is modelled with a proportional hazards model. However, the second stage, which is a stage with random failures, is modelled with a Poisson type model (Andreou, Marks and Clark 1987). These techniques are used to analyse individual pipe levels while letting the hazard rate depend on covariates reflecting various pipe and environmental characteristics.

Ormsbee and Kessler (1990) developed a least-cost methodology in order to support any single component failure by upgrading the existing single-source water distribution networks. They designed a methodology by casting the network-reliability problem in terms of an exact level of system redundancy. However, this has resulted in avoiding the minimum cut set computations as well as the must to select an arbitrary level of system reliability. Two different levels of system redundancy have been generated from the proposed methodology. The first level is topologic redundancy, where satisfaction will be through the applications of methods from graph theory. The other level is hydraulic redundancy, where satisfaction will be through the application of linear programming.

Park and Liebman (1993) have developed a gradient-modified linear-programming model for minimum-cost design subject to reliability constraints, based on a surrogate measure of reliability that enables incorporation of some considerations of frequency, duration and severity of damage. In order to compare different designs and make use of an optimisation approach in the design stage of a system, they quantify the amount of redundancy in a looped water distribution network using the expected shortage due to the failure of individual pipes as a surrogate measure described above. The model limits the shortage at each node in the network to be less than or equal to some specified fraction of demand. They also proposed a solution to overcome computational complexity, which has therefore obtained good results by bringing practical-sized network solutions within reach.

Besides, there are a significant amount of studies focusing on the reliability aspects arising from the mechanical failure of components. Mechanical failure identifies to the circumstances related to the failure of system components, for instance, burst of mains, blockage of valves, loss of pumping stations, and so on (Xu and Goulter 1998). For example, Goulter and Coals (1986) focused on the quantitative approaches when assessing reliability in pipe networks. They used the Poisson probability distribution to model the probability of failure of individual links in water distribution networks. Similar studies include Lansey et al. (1989), Jowitt and Xu (1993), Bao and Mays (1990) and Gupta and Bhave (1994).

2.4 Recent Studies for Reliability Modelling in Water Distribution Networks

Over the years, several tools and methodologies have been developed in order to reduce water losses and improve the efficiency of water distribution systems. For example, Babovic et al. (2002) propose the use of advanced data mining methods in order to determine the risk of pipe bursts. In order to establish a risk model as a function of associated characteristics of bursting pipe (its age, diameter or material of which it is built), soil type in which a pipe is constructed, climatological factors (such as temperature) and traffic loading, an analysis of a database of already occurred burst events has been used. They analyse when pipes are to be replaced as well as providing an optimal rehabilitation strategy before a burst occurs, and find that leakages typically causes water losses between 35% and 65% of the total supplied volume of water. High pipe burst rates are often a result of the poor condition of water supply assets, hence resulting in high water leakages rates.

In Sadiq, Kleiner and Rajani (2004), a framework for the analysis of aggregative risk associated with water quality failure in the distribution system is outlined. There are five pathways through which water quality in the distribution network can be compromised. These are interruption of contaminants into the distribution system (for instance, through cross connection), regrowth of bacteria in pipes and distribution storage tanks, water treatment breakthrough, filtering of synthetic compounds or consumption items from framework parts (for models, pipes, tanks or even, liners), lastly, pervasion of natural mixes through plastic pipe and pipe segments in the framework (Sadiq, Kleiner and Rajani 2004). It has been proven to be a tough task to quantify and characterise the various risk factors in the water distribution systems.

Frequently, the lack of data availability and the need to fulfil different types of restrictions turn design processes into real optimisation problems, where the classical methods often fail. Hence, there is the need to use the current modelling techniques such as neural networks, genetic algorithm, fuzzy theory and chaos theory (Izquierdo, Pérez and Iglesias 2004). Because it is unrealistic for a model to work correctly, the modelling techniques used need to take into consideration uncertainties such as poor quality of data, an incorrect structure of the model or lack of available information for the calibration of all the parameters. As a result, an analysis of the error of a model is encouraged in order to pinpoint the constraints of the model, which encourages the quantitative evaluation of error bounds, fundamental for correct decision-making. Hence, making it necessary to be able to estimate the uncertainty in the results.

Setiadi, Tanyimboh and Templeman (2005) suggest that reliability analysis is a vital element in the design, operation and maintenance stages of water distribution systems. Many researchers have tried to integrate reliability in the design of water distribution systems. The calculation of reliability for a water distribution system are however very difficult to solve. To solve this problem, several researchers make use of entropy, which is a surrogate measure for the reliability of water distribution systems. The computational advantages of entropy are that it is easier to calculate and include in the optimisation procedures. Most papers make use of demand-driven simulation models to analyse the hydraulic behaviour of water distribution systems. Hence, assuming that demands in the networks are fully satisfied regardless of the pressure in the system.

However, water distribution systems involve component failures or tremendous demands, which may result in a decrease in system pressure. As a result, demand-driven analysis frequently gives outcomes that suggest that the system is still supplying the full demand at lower, and occasionally, negative pressures. Therefore, head-dependent analysis approach was used in this study as it has been suggested that this approach provide more realistic results when the water distribution systems operate under subnormal pressure conditions. Hence, Setiadi, Tanyimboh and Templeman (2005) report the possible influence of modelling errors on the relationship between entropy and hydraulic reliability of water distribution systems. This paper also analysed a sample water distribution network. The findings suggest that there is a strong relationship between entropy and reliability. Small, unavoidable modelling errors do not have a significant influence on the entropy-reliability relationship.

Tanyimboh, Tietavainen and Saleh (2011) assessed the reliability of water distribution systems with statistical entropy and other surrogate measures. In order to be satisfactory, water distribution networks need to operate above the minimum required level, even if there is the presence of component failures. As a result, genetic algorithms have been developed to ensure the water distribution networks are within the demand level as well as minimising the cost of the networks. Therefore, they aim to evaluate the correlation of surrogate reliability measures about more accurate measures. The authors used surrogate measures such as resilience index and statistical entropy because of the considerable computational effort required to calculate absolute reliability or failure tolerance.

Boxall et al. (2007) derived the predictive expressions for annual burst rate in cast-iron and asbestos-cement pipes for two sample datasets from the UK. Many cities in the UK have large proportions of their networks constructed of cast-iron pipes dating from Victorian times, 100+ years old. These ageing pipelines have consequences such as a rise in water loss and an increase in the frequency of bursts. However, these increases are not only caused because of age, and therefore, a single number for ‘service life' of a pipe is not indeed definite of the need for rehabilitation or replacement. Previous studies showed that burst behaviours of the pipelines are a complex function of a considerable amount of variables, whereby most of them are unknown or not quantifiable. Hence, the prediction of future burst behaviour of a pipe has proven difficult because of the shortage or lack of burst data currently available.

Another paper is Mutikanga, Sharma and Vairavamoorthy (2012), where the efficiency of various water loss management tools and methods have been analysed. There are about 48 billion m^3 of water that are being lost annually from the water distribution systems. Several researchers have used mathematical programming techniques in order to minimise water leakages using the optimal location or optimal setting of flow control valves. Evolutionary algorithms such as genetic algorithms have also been adopted as stochastic optimisation techniques. Besides, multi-objective optimisation based on genetic algorithms has also been used to solve leakage problems.

Multi-criteria decision analysis is a tool that has been developed in order to resolve operational research problems with a limited number of decision options based on a set of evaluation criteria. On the other hand, online monitoring, also known as real-time control, has enabled continuous collection of flow and pressure data from the water distribution system in (near) real time. This method has led to numerous developments of systems that can detect and diagnose abnormalities in water distribution systems and prompt near real-time intervention measures. Mutikanga, Sharma and Vairavamoorthy (2012) analysed the various tools and methodologies that can help water utilities in evaluating and prioritising water loss reduction strategies.

Reliable infrastructure assets have a significant impact on quality of life while providing a secure foundation for economic growth and competitiveness. Hence, decisions about asset management have become very important. Pudney (2010) had four primary objectives. The first objective was to develop a new Asset Management Decision Framework (AMDF) in order to identify and classify asset management decisions. Application of multi-criteria decision theory, classical management theory and life cycle management developed the AMDF.

Tabesh et al. (2009) developed two models based on Data-Driven Modelling techniques in order to improve the prediction of pipe failure rates and to provide a better assessment of the reliability of the pipes. This paper aims to investigate whether the two models, namely artificial neural network and neuro-fuzzy systems, can accurately predict pipes failure rate using various system parameters such as pipe age, diameter, depth, length and pressure. According to Hornik, Stinchcombe and White (1989), an artificial neural network is parametric regression estimators that can estimate any measurable function up to any arbitrary degree of accuracy. On the other hand, as a neuro-fuzzy system is a combination of both fuzzy systems, it will have the benefits of both these fields. With the help of these two models, the findings of this research, which are the predicted failure rates, are highly accurate.

St. Clair and Sinha (2012) provide comprehensive literature and current practice review on water pipe condition as well as an exhaustive overview on a large number of works being done for a structural deterioration of water mains. It also explores deterioration and failure rate prediction models to point out the gaps between various models found in the literature and the models being used by water utilities globally. When the relationships between components are evident, deterministic models are usually used. The two different approaches in which the deterministic model can be developed are an empirical and mechanistic approach. The empirical approach is only applied to cohorts of pipes as in deterministic modelling; it relates to the failure rates to the attributes of the asset. On the other hand, the mechanistic approach predicts the service lifetimes of distinctive assets.

Nishiyama and Filion (2013) provide a critical review of statistical water main break forecasting prediction model published in a ten years period, which is from 2002 to 2012. The models being reviewed all have similar statistical characterisation for their historical failure data of the break rate of the water mains. Over the last 30 years, several physically based and statistically based water main prediction models. In order to identify failure patterns, statistical models extrapolate the patterns to predict future pipe breaks by making use of historical data. On the other hand, physical models forecast pipe breaks by reproducing the mechanics of pipe failure and a pipe's ability to resist failure. Their findings illustrate that different pipe materials respond differently to conditions, based on the temperature covariates. Moreover, it was suggested that air temperature data is sufficient to predict breaks in water mains, but these predictions can be enhanced with the use of further water temperature data.

2.5 Reliability Modelling for Repairable and Deterioration System

Rajpal, Shishodia and Sekhon (2006) present the use of artificial neural networks to model the behaviour of a complex, repairable system. Complex repairable systems present circumstances where operating and maintenance activities occur, and multiple entities (i.e., persons, machines and environments) correlate irregularerly. Dynamic changes frequently occur in the entities themselves. To study the behaviour of such systems, reliability, availability and maintainability (RAM) need to be taken into account. This paper proposed a combined measure of reliability, availability and maintainability parameters to measure the system performance.

Over a specific time frame, a system can be available or unavailable as it depends on the reliability of the system. It also depends on how efficient the support organisation affecting the rate of repair and duration of such repairs are. The systems also often go through preventive maintenance on a scheduled basis, while the analysis considers the modes of failure, the subsystem failure rates, maintenance regimes and different methods of logistical support. Maintenance (renewal time) and reliability (failure time) are considered as stochastic variables that make sense to model these using proper statistical inference methods (Neil and Marquez 2012). As a result, it could predict future behaviour and make decisions about the acceptability of the availability that might be expected to get in a given system. This study assesses the reliability of subsystems by using a Bayesian model combined with component ageing assumption and integrating data with expert elicitation.

Kim and Singh (2010) provide an analysis of the impact of ageing characteristics of components on the calculation of commonly used reliability indices such as loss of load expectation (LOLE). Sequential Monte Carlo simulation method using stochastic point process modelling is used to construct the system failure and repair history of components. The findings are then analysed and compared. To model the failure and repair cycle of a component in a power system reliability evaluation, an alternative renewal process has been used. In other words, from the reliability perspective, the component is assumed to be restored to as good as new condition after going through repairs. However, in practice, as they grow old, some components may experience a declining trend.

Gorjian et al. (2010) paper provides an extensive review of the existing literature on frequently used degradation models in reliability analysis. Due to the increase in complex engineering assets and tight economic requirements, asset reliability has become more essential in Engineering Asset Management (EAM). One primary aim of EAM is to improving the reliability of systems. A significant approach to evaluate the reliability and safety of critical systems is reliability assessment that makes use of degradation data. Degradation data frequently provide more information than failure time data when assessing the reliability and predicting the remaining life of systems. Generally, degradation is the decrease in performance, reliability, and life span of assets (Gorjian et al. 2010).

Degradation models characterise the underlying prognostics into different groups for prognostic approaches in the literature. These approaches are generally classified into four main groups, namely experienced-based approaches, model-based approaches, knowledge-based approaches, and data-driven approaches. Experienced-based approaches are the most accessible form of fault prognostics, as they need less comprehensive information than other prognostic approaches. These approaches are founded on the distribution of event reports of a population of similar items. Many traditional reliability approaches such as Exponential, Weibull, and Lognormal distributions have been used to model asset reliability (Gorjian et al. 2010).

An efficient way for reliability modelling of highly reliable systems is to make use of degradation signals that take into account the health conditions of a product. Its rationale is that a deteriorating item may fail following an underlying degradation process, for example, wear, fatigue, corrosion, and erosion processes. This paper also reviews existing probability models for modelling the degradation over time. Two broad categories of degradation models are stochastic process models, such as the Wiener process, Gamma process and IG process, and general path models.

2.6 Related Work

In order to analyse the trends in the service repair data or fuel cost data for South East Water, the paper Louit, Pascual and Jardine (2009) has been very relevant. Please see Chapter 3 Transport Model for more information. This paper presents a framework for model selection to characterise the failure process for a component or system. The model selection framework compares the use of stochastic point processes (also known as repairable systems approach) to the use of statistical distributions to represent the time to failure (also known as the renewal approach) when the system ages over time. When there is a vast number of data sets collected for maintenance management instead of reliability modelling, the information content can be inadequate or misleading. According to this research, one may use a combination or pooling of data from similar pieces of equipment when the failure data sample is small (Louit, Pascual and Jardine 2009). The availability of data for the boreholes in South East Water will be limited. Therefore, the pooling of data procedure can be used in the reliability analysis of the boreholes.

Hall and Daneshmend (2003) focus on the reliability modelling of surface mining equipment. In order to reduce the failure impacts, there is a need to improve the reliability of the asset. Therefore, this paper points out the relevant techniques that can be used for reliability analysis as well as identifies data requirements and information sources. The first step in improving reliability is the collection and analysis of the relevant data while taking into account various factors affecting the reliability of the asset. The paper also uses the concept of failure mode effects and criticality analysis (FMECA), which aims to identify possible failure modes and related impact. FMECA can be applied in either the transport model or the borehole model when analysing the data for South East Water.

Another relevant paper is Samanta, Sarkar and Mukherjee (2004), where different parameters of a load haul dumper's performance, such as reliability, availability, and maintainability have been evaluated. According to this paper, failures of a repairable asset, such as transport in the Southeast Water research, can be modelled from a renewal process, a homogenous or a non-homogenous Poisson Process or proportional hazard process. In a renewal process, one assumption for the time between failures is that they are independent and are identically distributed. The non-homogenous Poisson process is a stochastic process with a time-dependent intensity A step-by-step study procedure for the reliability, and performance analysis has been developed in Samanta, Sarkar and Mukherjee (2004). Part of this step-by-step procedure may also be applied for the transport model for South East Water.

Dandy and Engelhardt (2001) demonstrate the use of the genetic algorithm techniques to find a near-optimal programme for the replacement of water supply pipes while minimising the present value of capital, repair and damage costs. All water supply systems are exposed to problems, both environmental and human-related, that cause pipes to deteriorate and fail. A rehabilitation strategy needs to accurately represent the system's physical properties and be able to predict the future deterioration process. Before developing a rehabilitation strategy, three main criteria, namely economic, reliability and water quality, need to be investigated. The genetic algorithm can be readily applied to multiple criteria problems. This paper can be useful when developing the techniques to find the replacement age of the boreholes for the South East Water project.

In Black, Brint and Brailsford (2005), a description of how to fit a semi-Markov model to observed condition data and provides the results achieved on two data sets. As infrastructure systems mature and the pressure to enhance the asset performance to operating cost ratio rises, there is a constant move towards using condition information to decide when and how much refurbishment should take place. The Markov decision process method has proven to be an efficient approach to determine good asset management policies. For example, there was a $14 million saving in 1980 when used to manage Arizona's pavements. The optimal asset management policy can be determined by assessing each of the restricted numbers of possible policies, following the model being developed for an item's condition.

The Markov approach models an item's condition as being in one of a small number of states. After each period, the item can deteriorate to another state with a probability that is only dependent on the two states involved. The Markov process assumes that the distribution of an item sojourning at a state follows the exponential distribution. However, a semi-Markov model relaxes this assumption and allows the time is sojourning at a state to follow an arbitrary probability distribution (see Black, Brint and Brailsford 2005, for example). When considering deterioration, this is often closer to the physical reality as the Markov (and semi- Markov) condition states may correspond to intervals of a continuous underlying variable. Therefore, in the future, when developing deterioration models for borehole for South East Water, a Semi-Markov model can be used.

In Ansell and Archibald (2008), a data-driven risk management approach has been developed to analyse the assets in the water industry. Several different maintenance management approaches holistically look after assets, for example, Reliability Centred Maintenance (RCM) and Operational Research Optimal (ORO) strategies. The approach used in Ansell and Archibald (2008) provides an insight into the performance of the asset when it is either repaired or refurbished. The failure rate for an asset can be defined by three parameters, namely the covariates of the asset, the operating age of the asset and the virtual age of the asset. The authors found that with the use of stochastic dynamic programming; the optimal point of repair or refurbishment can be obtained for each asset. This model can also be used to identify the features of the optimal combined maintenance, repair and replacement policy for an asset. Hence, the findings can be useful when forecasting the optimal point of replacement of a borehole for the South East Water project.

According to Ward et al. (2017), low value and high volume buried infrastructure assets in the water distribution networks, such as boreholes or pipes, are not entirely understood and optimally managed when compared to more critical higher value assets. Ward et al. (2017) developed a novel deterioration-modelling framework based on the latest geospatial technologies and statistical analysis. It presents a practical methodology to predict pipe deterioration and failure of small diameter assets when there is a limited amount of data. Lack of data availability and quality for communication pipes are two critical factors preventing the effectiveness of asset management techniques for high volume-low value infrastructures, such as pipes. The paper suggests a logical data hierarchical procedure in order to use the most appropriate and accurate data sources when data available are not precise. In future South East Water projects, boreholes can be analysed under a similar deterioration model, and as there is a lack of data available for this asset, the work of Ward et al. (2017) can be used as a reference to overcoming this obstacle.

2.7 Expert Elicitation

In order to implement effective policies and make optimal management choices, decision makers cannot rely only on the existing data and modelling tools, as they may not have all the information required. Hence, decision makers, such as managers, may make use of the judgment of experts as an alternative form of information. As Morgan, Henrion and Small (1992) claimed that decision makers might consult with domain experts in case traditional science and statistics cannot provide all of the inputs for a model or policy analysis. An approach to quantifying the uncertainty about otherwise unknown factors are to incorporate expert judgment. Methods such as asking a single expert for his best guess, informally reviewing colleagues or following a structured, standard process to obtain and combine probabilistic judgments are called expert elicitation (Colson and Cooke 2018).

According to Colson and Cooke (2018), expert elicitation aims to obtain probabilistic belief statements from experts about unknown quantities or parameters. Elicited probabilities can also be used as inputs to economic, decision analytic and other modelling techniques. An eliciting approach that mathematically aggregates expert judgments and incorporates validation is known as the classical model. There are two types of questions that experts use to quantify their uncertainty, namely target questions and calibration questions. Target questions include the variables of interest, that is, those that cannot be solved by other methods and hence, require expert judgment. Experts also measure a set of calibration questions, which are knowledge either uncertain to the experts or known to the analysts.

Experts quantify their uncertainty for each calibration question and variable of interest in the classical model. There are many forms of this uncertainty quantification. Hence, the classical model enforces a conventional structure that will ensure comparability over a series of applications. Experts usually estimate an uncertain item by stating their fiftieth, and ninety-fifth percentiles. The fiftieth percentile is the median estimate, that is, the expert believes there is an equal likelihood that the real value for that item will fall above or below the specified value. The fifth and ninety-fifth percentiles generate a ninety per cent credible range, whereby the expert assumes there is a ninety per cent chance that the correct value for that item will fall between those bounds (Colson and Cooke 2018).

2.8 Research Gaps

According to Ye and Xie (2015), there is a lack of existing degradation models. The existing models are too simple for the complexity of real problems. Hence, there is a need for more research to make the models more accurate to solve real problems. There are various ways to do so. The first one is to complete the current degradation model. Despite being meaningful and flexible, the inverse Gaussian process is still new in degradation modelling. Therefore, there is growing participation in the development of this model for reliability modelling and decision-making. The second way is degradation physics.

Most of the current degradation models are data-driven, although some of them have a clear physical interpretation. Similarly, degradation models with finite supports require more attention. Hence, more studies in this area, namely degradation models for boreholes, will enable researchers to test their model on existing companies. For example, studies in this topic will be able to help South East Water to develop a degradation model specific to their boreholes, where they can test their degradation rate.

Moreover, there is an absence of research concerning the failure analysis of boreholes. Many researchers have not explored the impact of relevant factors on the failure rates of boreholes. There is a need to develop more appropriate tools and methodologies to deal with water losses within the water distribution systems. This research gap prevents researchers in the current water industry to analyse the water losses within their water distribution systems. For example, testing the failure rate of the boreholes for South East Water has proven to be difficult due to the lack of research.

Moreover, there is a research gap in the development of general methodologies for identifying the relevant parameters that will affect the failure rate of a borehole. Besides, real-time control to optimise dynamic water loss reduction has not been thoroughly studied (Mutikanga, Sharma and Vairavamoorthy 2012). This reseach gap has been preventing current researchers within the water industry to optimize the real-time control of water losses. Similarly, developing a model to optimize dynamic water loss for South East Water has proven to be challenging because there are not enough studies on this matter.

These research gaps allow future researchers to contribute further to the literature of asset management or reliability modelling within the water industry.

CHAPTER 3. CASE STUDIES

As mentioned in Chapter 1, OFWAT is the economic regulator of the water sector in England and Wales. They are a non-ministerial government department that has been established in 1989 when the privatisation of the water and sewerage industry in both England and Wales has arisen. Their role is to mainly make the customers and broader society more trustworthy and confident about the water sector. They need to be precise about what the customers and society expect from the water sector. By overseeing how the sector is performing, OFWAT can ensure the efficiency of the companies and be set to step in, in case the service providers fail. As a result, they need to work together with the water and wastewater companies.

The duties of OFWAT are described in the Water Industry Act 1991. One of their duties is to work towards achieving the consumer objective that will protect their interests while promoting appropriately effective competition. Another duty is to ensure that the water companies are not showing undue preference or discrimination concerning their services, for example by fixing the charges. They need to guarantee that the interests of the consumers are protected towards the unregulated activities of the water companies. They also need to ensure that the water companies, that is both water and sewerage undertakers are operating under their statutory functions, and they have the financial means to carry out these functions properly.

In order to certify that they are transparent and accountable in their regulatory activities and they have enough capital to carry out their statutory functions, water companies need to prepare a five-year business plan to present to OFWAT. As a result, South East Water has recently prepared and published its business plan for the year 2020 to 2025. One of the aims of their business plan is to ensure the public that they are meeting customers' changing needs and expectations of their water usage. However, they also need to show that their future investments on assets and maintenance. Therefore, this project will help South East Water in terms of their future investment on vehicles and future maintenance costs on boreholes.

As mentioned in Chapter 2, water assets can be classified into aboveground and underground water assets. In this research, transport will be categorised as an aboveground asset, while borehole will be an underground asset. Consequently, this chapter will explain the business understanding for both the transport and borehole models. The data collection and analysis for both models will also be presented in this chapter.

3.1 Business Understanding of Transport Model

A repairable asset is one that when it fails, it can be restored to its normal operating condition and performance through repair, including parts replacements or changes to adjustable settings. The reliability of an item under maintenance often depends on the system chronological age. Repairable systems receive maintenance actions that change the overall makeup of the system when they fail. For repairable systems, interest is more around the probability of system failure as a function of system age, rather than in the time of the first failure.

For this research, transport assets for South East Water Company will be considered as a repairable model. For example, if the water pump in a vehicle fails, the water pump will be replaced, but the vehicle will overall be repaired.

One of the central aims of this project is to build an excel tool for the transports assets that will provide an analysis of the transport data collected in order to answer the following research questions:

1) After how many years, will it be the optimum point to replace the vehicles?
2) After how many mileages, will it be the optimum point to replace the vehicles?
3) What is the predicted total whole life cost of the vehicles?

In addition to the above research questions, South East Water is also interested in a few more analysis regarding the transport model. For example:

i. Compare the cost per mile of the vehicles from different departments, which are production and distribution department.
ii. Compare the mileage and the fuel cost of the vehicles.
iii. Create histograms of fuel-cost-per-mile of the drivers in the production and distribution departments, respectively and then, extend the departments to

the entire company, and also based on the different make of vehicles.

iv. Create trend analysis graphs on the use of yearly cost-per-mile of a make and a department, respectively.

South East Water usually replaces its vehicles every five years. The transport department in the company makes this decision to replace a vehicle based on opinions and not facts. Usually, when deciding to replace a vehicle, there is a need to determine its market value. If the vehicle is old and requires services or unexpected repairs, it is essential to consider the costs of the repairs. If the repairs are less than half of the vehicle's market value, repairing the vehicle instead of replacing it might be more profitable.

Similarly, when deciding to replace a vehicle, there is a need to figure out the costs of running it and comparing it to the costs of a new vehicle. Insurance costs are also higher on new vehicles. Depreciation is also a factor to be considered in this decision. For example, new cars usually depreciate about 22% in the first year. Therefore, over the years, the vehicle will require more and more maintenance. If a vehicle requires regular repairs for small failures, which will increase the maintenance costs, buying a new vehicle might be more beneficial for the company instead of paying for regular repairs.

Other factors to examine when deciding on replacing a vehicle are the miles driven per year, fuel price per gallon or age of the vehicles in years. Gas mileages differ significantly between a new and old vehicle. Vehicles with more mileages tend to use more fuel and therefore, increasing the fuel costs for the company. If the company wants to reduce its fuel costs, it might be more profitable for them to trade its old vehicles to a more fuel-efficient vehicle. For example, investing in hybrid cars might be more favourable for the company in terms of fuel costs and being more environmentally friendly.

Moreover, South East Water wants a comparison between the cost-per-mile of the vehicles in its distribution and production department. This comparison will enable the company to compare the vehicles in which department are costing more while considering their mileages. It will also enable it to get an overall idea of the drivers' performance. The worst drivers that are those who are causing more accident and hence, increasing the unexpected repairs will be known. It will help the transport department to increase its overall efficiency while reducing its service and accidental repair costs.

One of the aims of the analysis described above is to save money, in terms of fuel costs, service repair costs and accidental repair costs. Additionally, if there is the need to replace a vehicle, the costs of purchasing a new vehicle as well as its associated implications need to be considered. This is why a comparison between the different vehicle models being used in South East Water will be made. There are seven vehicles model that will be analysed, namely Fiesta Base, Transit 240, Transit Connect 90, Transit Custom 290 Eco-Tech, Ranger XL 4x4, Transit 115 and Transit Connect 75 vans. The decision about purchasing a new vehicle will be more comfortable and quicker when details about which vehicle model has the lowest fuel costs or replacement cost are known.

3.2 Business Understanding of Borehole Models

Boreholes are an essential part of South East Water's infrastructures as the majority (around 75%) of their water comes from underground. Boreholes are often described as a deep vertical hole of small diameter dug into the earth in order to get access to the water table below the ground. However, it can also be drilled into the ground horizontally. Drilling a borehole requires specialised skills as if not done correctly; there might be an underground collapse causing the shaft to seal and contaminate the underground water. Once the shaft is drilled correctly, a pump is lowered into the ground, and usually, a machine is built above ground to assist water extraction as well as controlling the water flow.

The primary purpose of a borehole is for drilling water and water abstraction. Water borehole is considered an excellent way to get pure and natural underground water. This is frequently done in third-world countries, where the availability of clean water is limited. However, it also has other purposes such as, mineral exploration, oil and gas exploration and extraction or monitoring a site construction. Boreholes are also used for research and exploratory purposes. Research and exploratory boreholes can be used to assess the underlying geology of a particular site as well as the aquifer properties and groundwater rebound characteristics. They can also be used as an educational tool to test new drilling techniques or monitor water quality at a site for an extended period.

The performance condition of the boreholes is very critical to the company, and therefore, there is a need to do data analysis in order to answer the following research questions:

4) Whether the output of one borehole in the current year is less or greater than last year?
5) Whether there is a gradual or step change in the flow?
6) When was the latest surveys performed at this borehole?

The main sites of the boreholes being considered in this case study are Crowhurst Bridge, Goudhurst, Groombridge, Powdermill and Sweet Willow. Crowhurst Bridge site has four boreholes, namely BH1, BH5, BH7 and Witherenden. Similarly, Goudhurst site has four boreholes, namely BH8, BH11. BH13 and Lamberhurst. Groombridge site also has four boreholes, that is, BHP1, BHP2, BHP3 and Eridge. Powdermill site has two boreholes, namely BHP1 and BHP3. Finally, Sweet Willow has two boreholes, which are BH3 and BH4.

Comparing the output of different boreholes will enable South East Water to know which boreholes are performing at a lower standard than the others. This project will highlight the worst performers among the 16 boreholes mentioned above. This will allow the company to find out why they are performing poorly and schedule future maintenance surveys in order to pinpoint the exact causes. An analysis of whether there is a gradual or step change in the water flow will enable the company to know whether the borehole is functioning at a satisfactory level or not. The flow rate is described as the maximum rate at which water can be drawn or pumped from a borehole without running it dry.

The water level in a borehole will fluctuate over the years because of several reasons. Water filled in a borehole will vary at different times of the year, especially during prolonged wet or dry season. Moreover, knowing whether there is a steady or decreasing output for a borehole will further help the company knowing their performance and whether there is a need for an intervention. South East Water has four types of borehole maintenance, namely surveys, pumping test, remediation and drilling. The surveys are usually periodic inspections to verify the condition of the borehole. If there is any problem in the assets or quality of water, a borehole survey will help determine that. Nowadays, a camera is used to inspect and help in borehole repairs. The images captured by the camera will enable the inspectors to identify precisely where the problem is.

A pumping test is performed to determine the productivity of the borehole and to ensure that the water flowing out meets the consumers' expectations. These tests also present the company with information about the borehole itself and the characteristics of the aquifer. Additionally, in order to get the optimal depth of a pump for water extraction, water companies make use of pumping tests. They are two types of tests, namely the step-drawdown test and constant-rate test. The step-drawdown test will pump the borehole at increasing discharge rate to evaluate its performance. On the other hand, a constant-rate test will pump at a constant rate for an extended timeframe in order to provide details on the hydraulic characteristics of an aquifer.

Borehole remediation will ensure that the boreholes are operating reliably and efficiently throughout their operational life. It aims to reclaim existing wells by making them operational again instead of abandoning them to drill a new one. Several factors will cause a borehole to need remediation, such as rusty pipe, iron builds up on pumps, cloudy or rusty water, reduction in borehole yield and clogging of fissures. Chemicals, such as chlorine, caustic soda, acids or hydrogen peroxide, are often used to dissolve and remove the encrusting materials from the borehole. Physical techniques, such as explosive, surge pumping, jetting or compressed air surging can also be used in remediation.

If the other borehole maintenance techniques do not work, drilling a new borehole will be the last solution. The boreholes will be drilled depending on the level of the water table, hence affecting their depth and design. The first step in the water borehole drilling process is to let hydro-geologists site the borehole, that is, there is the need first to determine where the water is and how can it be pumped above ground. The second step will be to construct the borehole following the recommendations of the hydro-geologists. An aquifer test will then be performed in order to test and accurately measure the yield of the water borehole. Finally, the pumping and piping systems will be installed in the borehole.

3.3 Data Collection and Preparation

This section will describe the list of data that will be required to model both the transport and borehole model in order to successfully answer the research questions presented in section 3.1 and 3.2 respectively.

3.3.1 Transport Model

In order to build a transport model that will solve the research questions and the other analysis as mentioned in Chapter 3.1, a list of data has been collected over a period of 6 months, that is, from September 2017 to March 2018. The following data have been given by the company or have been collected personally:

Research Question 1 and 2

In order to answer the first and second research questions, which are

- After how many years, will it be the optimum point to replace the vehicles? Also,
- After how many mileages, will it be the optimum point to replace the vehicles?

Respectively, the following list of data is required:

1. Fleet List

   Data for a sample of 33 Fiesta Base vans have been collected to test research question 1 and 2. In the Fleet List, the registration numbers of the vans as well as their registration date have been collected.

2. Service Repair Cost

   The service repair cost data is the cost generated for repairing a van after each failure. The service repair cost for each van in the Fleet List mentioned above was collected from 2012 to 2018.

3. Failure Month

   The failure month data is the month that a van went through servicing and maintenance due to failure. Similarly, the service repair month data was collected from 2012 to 2018.

4. Miles to last failure

   Miles to last failure is the accumulated miles that a van had when it failed. Likewise, the miles to last failure data was collected from 2012 to 2018.

Research Question 3

This research focused on the vans in two departments, namely the production department and the distribution department. A sample of 70 vans in the distribution department and a sample of 53 vans in the production department are considered in the calculation of the total whole life cost of the vehicles.

Total whole life cost will include the value of OPEX and CAPEX while excluding the resale value of the vans. OPEX will include fuel cost and service repair cost. CAPEX, on the other hand, includes the cost of purchasing the van.

Therefore, in order to answer the third question, *what is the predicted total whole life cost of the vehicles?* The following list of data is required:

5. Fuel Cost

   The total fuel cost for each van in both the production and distribution department has been collected for the year 2017.

6. Service Cost

   Similarly, the total service cost for each van in both the production and distribution department has been collected for the year 2017.

7. Cost of Vehicle

   The cost of purchasing a new vehicle, based on the vehicle model, will be necessary for Research Question 3.

8. Resale Value

   Moreover, the resale value, that is the value of a vehicle that the company will get when they sell it will be required and has therefore been collected.

Other Analyses

The following is one of the data required to do the analysis described in Chapter 3.2:

9. Mileage

   In order to find the cost per mile for the vans in the production or distribution department, the total mileage of each van is required. The data listed above will also be used in other analyses.

3.3.2 Borehole Model

The following list data for the 16 boreholes mentioned in Chapter 3.2 for the year 2010 to May 2018 have been extracted from PRISM:

Research Question 4 and 5

In order to answer the fourth and fifth research questions, which are

- Whether the output of one borehole in the current year is less or greater than last year?
- Whether there is a gradual or step change in the flow?

Respectively, the following list of data is required:

1) Water Flow

   Water flow data is the amount of water being pumped out of a borehole. Fifteen minutes of water flow data of the 16 boreholes that have been extracted from PRISM for the year 2010 to 2018.

2) Water Level

   The water level data was only available for the Goudhurst BH13 site. However, in order to compare the flow and water level, the data for the latter needs to be available for each borehole.

Research Question 6

In order to know the latest surveys performed at each borehole, the following data has been extracted:

3) Maintenance Report

   The date of each borehole's last survey has also been recorded.

CHAPTER 4. RELIABILITY MODELLING

According to Louit, Pascual and Jardine (2009), a repairable system is one that can be brought back to its full operational capabilities by any means other than replacing the entire system. Hence, for a repairable system, reliability means the probability of not failing for a specific period. Reliability modelling for a repairable system means to model the distributions of times between failures, which can be done by many stochastic process models, for example, the renewal process (RP), the homogenous Poisson process (HPP), the branching Poisson process (BPP), the superposed renewal process (SRP), and the non-homogeneous Poisson process (NHPP).

4.1 Different Types of Repair

The term *repairable* may be classified into economically repairable and technically repairable. Although an item is repairable, the degree on how much the item can be repaired, or the effectiveness of a repair, is not discussed so far. If one looks at technically repairable, there are five cases in terms of the effectiveness of the repair.

- *Better-than-perfect repair*. Due to technological advances, the reliability of some item may be improved. As a result, if a failed system may be replaced with a system that has the same functionality as the failed one and that has higher reliability than the failed one, then the repair is a better-than-perfect repair.

- *Perfect repair*. If a failed item is replaced with an identical and new item, the repair is said to be perfect, or a perfect repair. In the reliability literature, perfect repair is also called a good-as-new repair. In Figure 4.1 below, the cross X denotes a failure; then the repair brings the maintained item back to its good-as-new status.

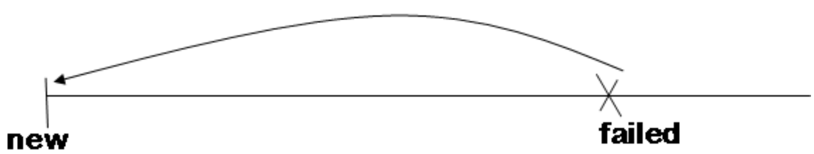


Figure 4.1: Perfect repair

- *Minimal repair*. If a repair restores the condition of a failed item to the condition immediately before the item failed, then the repair is said a minimal repair. Such a repair may be assumed when a component in a very complex system, which may be constituted of a large number of components, failed and is replaced with a new component. Similarly, Figure 4.2 shows a minimal repair case.

Figure 4.2: Minimal repair

- *Worse-than-minimal repair*. If a repair brings a maintained item to a status that is worse than the status just before the item was maintained, then such a repair is a worse-than-minimal repair. A worse-than-minimal repair may happen if the maintained item is intentionally damaged.

- *Imperfect repair*. If the effectiveness of a repair is between that of a minimal repair and that of a perfect repair, the repair is said an imperfect repair. Similarly, Figure 4.3 shows an imperfect repair case.

Figure 4.3: Imperfect repair

4.2 Failure Process Models

Many stochastic processes can be used to model the failure process of a repairable system. For the above five types of the effectiveness of repair, one may choose different stochastic processes to model them. For example, the renewal process can model the failure process of a system with perfect repair; the non-homogeneous Poisson process can model the failure process of a system with minimal repair, and there are various other models like the geometric process can model the failure process of a system with an imperfect repair.

4.2.1 Renewal Process

The time-between-failures of an item under perfect repair can be modelled by the *renewal process*, in which the time-between-failures are considered independently and identically distributed random variables (Yanez, Joglar and Modarres 2002). In other words, it usually presumes that the system is restored to its original state when it had undergone instant repair action. However, because many researchers consider this process as an ideal situation, the renewal process model tends to have limited applications when analysing repairable assets.

4.2.2 Non-Homogeneous Poisson Process

The minimal repair can be modelled by the Non-Homogeneous Poisson Process (NHPP), which has been used extensively to solve repairable reliability problems as it is considered as a well-developed stochastic process model in reliability engineering (Tanwar, Rai and Bolia 2014). The NHPP models help describe failure processes that possess certain trends such as reliability growth or deterioration. Saldanha, De Simone and e Melo (2001) introduced the use of the non-homogeneous Poisson point process to the study of the rates of occurrence of failures when they are time-dependent, and the times between failures are not independent or identically distributed.

4.3 Generalised Renewal Processes

It may be noted that repair can frequently be regarded as *imperfect repair*, on which many models have been developed. One of the most cited models is the generalised renewal process, introduced by Kijima (1989). The applications of the generalised model have been enormous. For example, in Veber, Nagode and Fajdiga (2008), a generalised renewal process is applied in order to bring repairable assets to one of the possible states following a repair. In order for the generalised renewal process to be possible, there is a need to assume that the time to first failure distribution and the quality of repair must be known and can be estimated from the available data (Veber, Nagode and Fajdiga 2008). Even if the generalised renewal process provides a solution, which is unbiased and consistent, for all distribution types, in order to accurately program this process, there is the need for a large sample of data, which increase the time to process this approach.

4.4 Parameter Estimation

In both scenarios, the non-homogeneous Poisson process (NHPP) with the power law will be used. In practical terms, the NHPP enables modelling of a trend in the number of failures to be found in an interval concerning the total age of the system. A widely used failure intensity of the NHPP is the power law intensity, which has the following form

$$\lambda(t) = \alpha t^{\beta} \tag{1}$$

where α and β are estimable parameters.

The NHPP with the power law has a flexible shape and can model a broad range of failure rates. Consequently, before conducting a more in-depth analysis in the research projects (that is, the vehicle and the boreholes projects), which are to optimize time and miles to replacement, there is the need to estimate the parameters for both times between failures (related to research question 1) and miles between failures (related to research question 2).

4.4.1 Times Between Failures

Assume there are m vehicles. Vehicle m has m_i failures, which are observed at times $t_{i,1}$,$t_{i,2}$,...,t_{i,m_i} (where $i = 1, 2, \ldots, m$), respectively. Denote $T_i = t_{i,m_i}$, then,

$$\hat{\alpha}_1 = \frac{\sum_{i=1}^{m} m_i}{\sum_{i=1}^{m} T_i^{\widehat{\beta_1}}} \tag{2}$$

To obtain $\hat{\alpha}_1$ from Eq. (2), one needs to obtain $\hat{\beta}_1$, first. Plugging in $\hat{\alpha}_1$ into the following quantity and minimising it, one can obtain $\hat{\beta}_1$

$$\left| \widehat{\beta_1} - \frac{\sum_{i=1}^{m} m_i}{\widehat{\alpha_1} \sum_{i=1}^{m} \left(T_i^{\widehat{\beta_1}} \ln T_i \right) - \sum_{i=1}^{m} \sum_{j=1}^{m_i} \ln(t_{i,j})} \right|. \tag{3}$$

In this project, we need to code the model (i.e., NHPP) into MS Excel. To solve the values

of $\hat{\alpha}_1$ and $\hat{\beta}_1$ may be very time consuming, which may not be an attractive property of the model. As such, we propose the following method to find $\hat{\alpha}_1$ and $\hat{\beta}_1$, respectively.

- set β_1 = 0.01, 0.03, 0.05, ..., 4.00, 4.005 respectively, and plug β_1 into Eq. (2) to obtain α_1,
- Then plug β_1 into Eq. (3) to choose the β_1 that minimises.

4.4.2 Miles Between Failures

Similarly, the parameters in Eq. (1) may be estimated based on miles between failures, as shown below.

Assume there are m vehicles. Vehicle m has m_i failures, which are observed at miles $y_{i,1}$,$y_{i,2}$,...,y_{i,m_i} (where $i = 1, 2, \ldots, m$), respectively. Denote $Y_i = y_{i,m_i}$, then,

$$\hat{\alpha}_2 = \frac{\sum_{i=1}^{m} m_i}{\sum_{i=1}^{m} Y_i^{\hat{\beta}_2}} \tag{4}$$

To obtain $\hat{\alpha}_2$ from Eq. (4), one needs to obtain $\hat{\beta}_2$, first. Plugging in $\hat{\alpha}_2$ into the following quantity and minimising it, one can obtain $\hat{\beta}_2$

$$\left| \hat{\beta}_2 - \frac{\sum_{i=1}^{m} m_i}{\hat{\alpha}_2 \sum_{i=1}^{m} \left(Y_i^{\hat{\beta}_2} \ln Y_i \right) - \sum_{i=1}^{m} \sum_{j=1}^{m_i} \ln(y_{i,j})} \right|. \tag{5}$$

Similarly, one can obtain $\hat{\alpha}_2$ and $\hat{\beta}_2$.

4.5 Maintenance Policies

Once α and β are obtained, the process to optimise time and miles can begin. The optimisation process will be done under a block replacement policy. This is a form of asset replacement policy that falls under the preventive replacement class. For example, if a system consists of a group of assets, a unit is always replaced upon failure or at a scheduled time periodically (for example, T, 2T, 3T...). The block replacement policy is considered to be easy to implement in practice, while keeping the system more reliable and up-to-date (in Sheu et al. 2014). This policy is commonly used when there are a large number of identical systems in service. For example, in the South East Water project, the identical vehicles in the Transport model are categorised into groups.

4.5.1 Block Replacement Policy

According to Ke and Yao (2016), the block replacement policy can be described as a type of preventive replacement policies where the systems or assets are always replaced when failed or at a scheduled time periodically.

Figure 4.4 below shows a case of block replacement policy. Between times t_0 and $2t_0$, although there is a failure, denoted by the symbol X, and a replacement upon this failure, at time $2t_0$, there will still be a new replacement. A real-world example may be: in the UK, there is an MOT test every year, although a car owner may have conducted a similar test during a year.

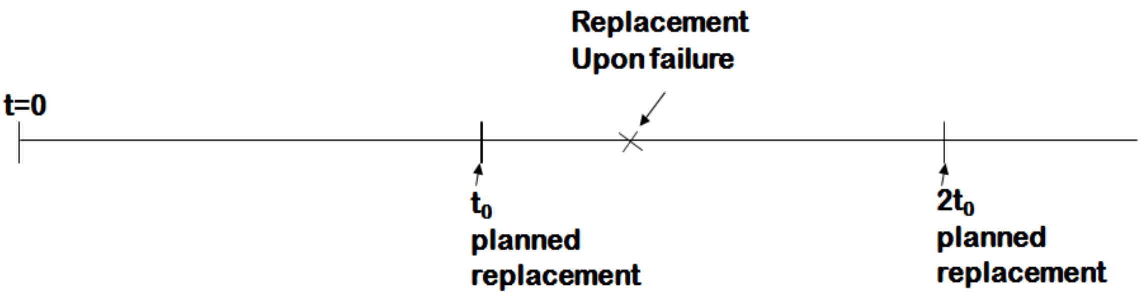


Figure 4.4: Block replacement policy

The preventive maintenance policies provide valuable strategies for reducing the cost of a system or asset caused by failure or when replacing (or repairing) the units. The primary objective of preventive maintenance is to minimise the average cost of operating a system in the long run. In order to do so, appropriate time-scheduled maintenance needs to be applied to the operations of the system, for example, by making use of block replacement policy and age replacement policy.

The following equations have been developed to show the integration of block replacement policy in order to answer the first two research questions for the transport model of South East Water project, namely the optimum replacement age and the optimum replacement miles.

Optimum Replacement Age

The aim is to minimise the following objective function to obtain the optimum time to replace a vehicle:

$$\frac{C_r + C_s\,\widehat{\alpha_1}\,t^{\widehat{\beta_1}}}{t} \tag{6}$$

Then the time to replace a model of vehicles is given by

$$t^* = \left(\frac{C_r}{C_s\,\widehat{\alpha_1}\,(\widehat{\beta}_1 - 1)}\right)^{\frac{1}{\widehat{\beta}_1}} \tag{7}$$

Where C_r is the cost of purchasing a new vehicle of this type/model and $C_s(t)$ is the average cost of service repair

Optimum Replacement Mile

The aim is to minimise the following objective function to obtain the optimum accumulative miles to replace a vehicle:

$$\frac{C_r + C_s\,\widehat{\alpha_2}\,t^{\widehat{\beta_2}}}{y} \tag{8}$$

Then the miles to replace a model of vehicles is given by

$$y^* = \left(\frac{C_r}{C_s\,\widehat{\alpha_2}\,(\widehat{\beta}_2-1)}\right)^{\frac{1}{\widehat{\beta}_2}} \tag{9}$$

Where C_r is the cost of purchasing a new vehicle of this type/model and $C_s(t)$ is the average cost of service repair.

4.5.2 Age Replacement Policy

An age replacement policy, on the other hand, can be described as a type of preventive replacement policies where the systems or assets are replaced after a pre-specified period after the last replacement.

Figure 4.5 below shows a case of age replacement policy. At time $w + t_0$, there is a failure, and a replacement followed. Then t_0 time units later, that is, at time $w + 2t_0$, there will be a replacement.

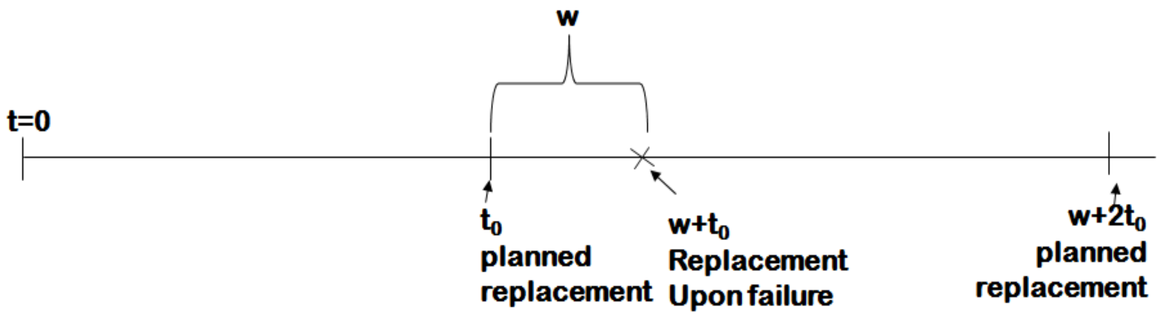


Figure 4.5: Age replacement policy

Since using the age replacement needs more detailed failure data, we skip its introduction in this chapter.

4.6 Implementation of Block Replacement Policy

As mentioned above, the block replacement policy is a preventive replacement policy in which assets are replaced when failed or at a specified time. Because it is easier to implement block replacement policy than age replacement policy, this section will illustrate the implementation of the block replacement policy in order to find out the optimum replacement age or miles for the South East Water vans. In order to test and answer the first two research questions for the Transport Model, Visual Basic (VB) codes in MS Excel have been used to implement Equation 2 to 9 that have been mentioned above.

Appendix 1 contains the codes used to obtain the optimum replacement age. Appendix 2 represents the codes used to obtain the optimum replacement miles. The findings of these codes will be explored in Chapter 5 Development of Decision Support System and Findings. However, this section will explore the VB codes.

4.6.1 Optimum Replacement Age

1) The first step when using VB codes to find the optimum replacement age of vehicles is to guarantee that all the data in the excel sheet are read. The following codes have been used to implement the first step:

- To activate the worksheet filled with the relevant data:

```
Worksheets("Age").Activate
```

- In order to read the number of vehicles in each column:

```
numCOL=ThisWorkbook.Sheets("Age").Cells(1,Columns.Count).End(xlToL
eft).    Column
numVehicles = numCOL
With ActiveSheet
LastCol = .Cells(1, Columns.Count).End(xlToLeft).Column
For i = 2 To LastCol
numServices_of_Vehicle = ActiveSheet.UsedRange.Rows.Count
totalnumServices=totalnumServices+WorksheetFunction.Sum(numServic
es_of_Vehicle)
Next i
MsgBox ("totalnumServices =") & totalnumServices
End With
```

- Please note that
    - numCOL and numVehicles are the total number of columns in the worksheet, which represents the total number of vehicles being tested.
    - LastCol is the last column with filled cells in the excel sheet.
    - numServices_of_Vehicle is the total number of services for each vehicle
    - totalnumServices is the total number of services for all vehicles.

2) The second step is to obtain the value for $\hat{\beta}_1$ as shown in Equation 3 above. In

order to set β_1 = 0.01, 0.03, 0.05, ..., 4.00, 4.005 respectively, the following codes are used:

```
For k = 1 To 800
beta1(k) = 0.005 + (1 + k)
```

3) After finding the value for β_1, it will be plugged in Equation 2 to find α_1. The following codes will give the value for α_1:

```
For i = 1 To numVehicles – 1
sum01 = sum01 + (TtoF(i) ^ beta1(k))
sum02 = sum02 + ((TtoF(i) ^ beta1(k)) * Math.Log(TtoF(i)))
Next i
 a = 1
For b = 2 To numCOL
For c = 1 To nrows(a)
sum03 = sum03 + Math.Log(t(b, c))
Next c
 a = a + 1
Next b
alpha1(k) = totalnumServices / sum01   'Equation1
TbetweenF(k) = Abs(beta1(k) - (totalnumServices / ((alpha1(k) * sum02)
- sum03))) 'Equation2
```

As shown in the precedent codes, α_1 will be obtained.

- Please note that
  - sum01 is T power by β_1.
  - sum02 is T power by β_1 times lnT.
  - sum03 is ln(ti, j).
  - a will represent the number of vehicles.
  - b and c are used for the for-loop for sum03.
  - TtoF(i) is time to failure, that is, it is the month in which a vehicle has experienced a failure and requires a service repair. For example, a flat tire.
  - TbetweenF(k) is time between failure, that is, the months between a vehicle's previous and recent failures.
  - alpha1(k) is α_1.
  - beta1(k) is β_1.

4) The next step will be to use plug β_1 found in the previous step in Equation 3 to find the minimum β_1, and this can be found by the codes below:

```
If TbetweenF(k) < middlevalue Then
middlevalue = TbetweenF(k)
selectedbeta = beta1(k)
selectedalpha = alpha1(k)
Else
middlevalue = middlevalue
selectedbeta = selectedbeta
selectedalpha = selectedalpha
End If
```

- Please note that
  - middlevalue is a big number used so that the first answer in the loop is stored no matter how much it is. In this case, 1,000,000 is used as the middlevalue.
  - selectedalpha and selectedbeta is the value of alpha and beta that will be used in equation 6 to find the optimum time to replace a vehicle.

5) If β_1 (selectedbeta) is greater than 1, then the optimum replacement age formula shown in Equation 7 can be coded as follows:

```
opt_replacement_age = (costReplacement / (costService * selectedalpha * (selectedbeta - 1))) ^ (1 / selectedbeta)
```

- Please note that
  - opt_replacement_age is t* in Equation 7, that is, the optimum time to replace a vehicle
  - costReplacement is the cost that will be incurred when replacing the vehicle. It will be the cost of purchasing a new van.
  - costService is the service costs incurred by the vehicle over the years.

However if β_1 (selectedbeta) is less than 1, it implies that the failure rate is decreasing, that is, the number of failures of the vehicles becomes fewer with time, and hence, there is no need to find the optimal time to replace the vehicle.

4.6.2 Optimum Replacement Mile

To find the optimum replacement mile, similar codes to find the optimum replacement age will be used. Step 1 and 2 for the optimum replacement age will also apply to find the optimum miles to replace a vehicle. For Step 3, instead of using the time to failure, miles to failure will be used. Miles to failure is the total mileage that a van had when it had a failure. The time between failures will be miles between failures in this calculation, that is, the difference between the miles that a van had for its previous failure to the miles it has for its current failure.

To find the optimum replacement miles (y*) as shown in Equation 9 above, the following codes will be used:

```
opt_replacement_miles = (costReplacement / (costService * selectedalpha * (selectedbeta - 1))) ^ (1 / selectedbeta)
```

- Please note that
  - opt_replacement_miles is y* in Equation 9, that is, the optimum mile to replace a vehicle

Similarly, in this case, if β_2 (selectedbeta) is less than 1, it implies that the failure rate is decreasing, that is, the number of failures of the vehicles reduces with time and consequently, eliminating the need to find the optimal miles to replace the vehicle.

4.7 Methodology for each research question

This section will present a breakdown of the specific method or combination of methods used to analyse and answer each research question.

1. <u>Research Question 1</u>: After how many years, will it be the optimum point to replace the vehicles?
   In order to get the optimum years to replace a vehicle, the Age Replacement Policy has been used. This policy has been extensively explained in Section 4.5.1 and Section 4.5.2. Section 4.6.1 presents the VB codes used in order to answer this research question by using the data collected from South East Water.

2. <u>Research Question 2</u>: After how many mileages, will it be the optimum point to

replace the vehicles?

Similarly, in order to answer this research question, the Age Replacement Policy has been applied, as explained thoroughly in Section 4.5.1 and Section 4.5.2. Section 4.6.2 presents the VB codes used to get the optimum mileages to replace a vehicle in South East Water.

3. Research Question 3: What is the predicted total whole life cost of the vehicles?

   In order to get the total whole life cost of the vehicles, firstly detailed calculations about the OPEX and CAPEX of the vehicles need to be made. A decision support system has been designed on Excel in order to analyse and answer this research question. Chapter 5 will thoroughly explain the steps involved in developing this computer program. More precisely, Section 5.1 explains the decision support system designed for the transport model. Figure 5.1.7 shows the specific spreadsheet used to calculate and analyse the total whole life cost of the Vehicles in South East Water.

4. Research Question 4: Whether the output of one borehole in the current year is less or greater than last year?

   A decision support system has been designed on Excel in order to answer the research questions for the borehole project. This research question will be explained methodically in Section 5.2.2. The overall analysis of the loss generated by each borehole has been represented in graphs in Figure 5.2.3.

5. Research Question 5: Whether there is a gradual or step change in the flow?

   Likewise, in order to answer this research question, the water flow for each borehole has been analysed and represented graphically in the decision support system designed for the borehole project, as explained in Chapter 5.2. For example, see Figure 5.2.5.

6. Research Question 6: When was the latest surveys performed at this borehole?

   In Chapter 5.2, this research question has been answered in the decision support system for the borehole project. The dashboard of the borehole model shows when surveys have been performed at a specific borehole. See Figure 5.2.2.

CHAPTER 5. DEVELOPMENT OF DECISION SUPPORT SYSTEM

This chapter will explain in detail the decision support systems that have been built in excel for both the transport and borehole model while providing an analysis of the findings generated from the models built. A decision support system is a computer program that will help managers in a company to solve complex business problems. The business problems, also referred to as research questions and analysis in this thesis, for both the transport and borehole models have been thoroughly explained in Chapter 3 Case Studies. Tools such as Visual Basic and Microsoft Excel have been used to model the business problems of South East Water. The models designed contain the data and the algorithms, such as mathematical processes, necessary to solve the problem.

The system runs the data through the algorithms and displays output formatted as information. The information is displayed through well-organised and visually appealing tables and graphs. This will enable the manager of the company to use the displayed information to tackle its problems. The models are built in a user-friendly way so that even a worker with less technical ability can use it. The excel files for the transport and borehole models contain all the necessary arithmetic, statistical and financial functions to solve the business problems of South East Water. Therefore, in the future, the users of the decision support system will be able to manually input and update the data in the system for further analysis.

5.1 Transport Model

The decision support system designed for the transport model is based on the research questions and analyses requested by South East Water, as explained in Section 3.1. For example, detailed calculations about the OPEX, whole life costs, fuel cost per mile and so on of the vehicles will be provided. The formulations of the optimum replacement age and mile, as explained in Chapter 4, have also been included in this decision support system. Section 5.1.1 will present an overview of the transport model while providing a brief explanation of each worksheet in the transport model‘s excel file. Section 5.1.2 will provide a more detailed explanation of each worksheet and also, analyse the results generated.

i. Overview of Transport Model

Figure 5.1.1 below shows the area designed to enable the users to navigate quickly through the pages in the spreadsheet, which is designed to tackle the problems of the transport model, by just clicking on the pages the user wishes to visit. The pages in the spreadsheet are presented by their unique ID, namely A to Z, as shown in the figure 5.1.1 below:

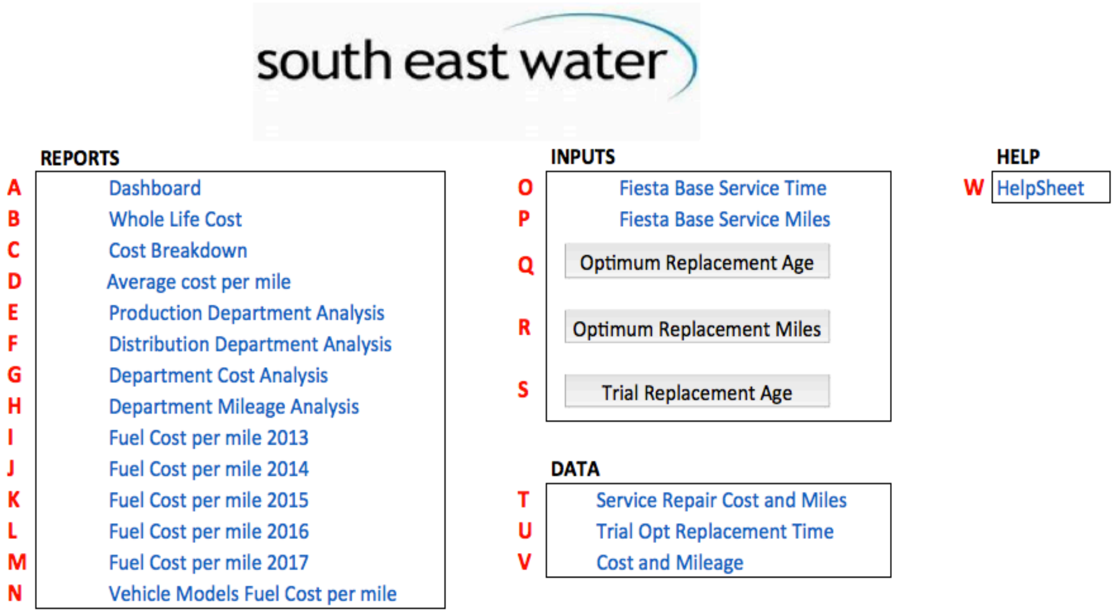


Figure 5.1.1: Overview of transport model

A. <u>Dashboard</u>

The dashboard allows the user to select the reports they would like to display, while also providing a summary of the findings.

B. <u>Whole Life Cost</u>

This worksheet provides the calculation of the whole life costs for each vehicle model as well as for the whole life costs for the production and distribution department.

C. <u>Cost Breakdown</u>

This worksheet provides a breakdown of all the costs involved in the Transport Model, such as fuel cost, service cost, cost of purchasing a new vehicle and so on.

D. <u>Average Cost per Mile</u>

This worksheet provides a graphical comparison of average cost per mile of the different vehicle models between the production and distribution department.

E. Production Department Analysis

This worksheet provides a detailed analysis the total and average cost and miles for all vans operating under the production department.

F. Distribution Department Analysis

This worksheet provides a detailed analysis the total and average cost and miles for all vans operating under the distribution department.

G. Department Cost Analysis

This worksheet provides a comparison between the costs for the vans operating under production department and distribution department.

H. Department Mileage Analysis

This worksheet provides a comparison between the miles used by the vans operating under production department and distribution department.

I. Fuel Cost per Mile 2013

This worksheet provides an analysis and graphically represents the cost per mile of all SEW vehicles for the year 2013.

J. Fuel Cost per Mile 2014

This worksheet provides an analysis and graphically represents the cost per mile of all SEW vehicles for the year 2014.

K. Fuel Cost per Mile 2015

This worksheet provides an analysis and graphically represents the cost per mile of all SEW vehicles for the year 2015.

L. Fuel Cost per Mile 2016

This worksheet provides an analysis and graphically represents the cost per mile of all SEW vehicles for the year 2016.

M. Fuel Cost per Mile 2017

This worksheet provides an analysis and graphically represents the cost per mile of all SEW vehicles for the year 2017.

N. Vehicle Models Fuel Cost per Mile

This worksheet provides a graph for the cost per mile of each vehicle model.

O. Fiesta Base Service Time

This worksheet provides the data regarding the age each Fiesta Base TDCI van obtained a service repair.

P. Fiesta Base Service Miles

This worksheet provides the data regarding the number of miles each Fiesta Base TDCI van obtained a service repair.

Q. Optimum Replacement Age

This control button allows the VB algorithms to generate the optimal replacement age of the Fiesta Base TDCI vans.

R. Optimum Replacement Miles

This control button allows the VB algorithms to generate the optimal replacement miles of the Fiesta Base TDCI vans.

S. Trial Replacement Age

This control button test whether the VB algorithms for the optimal replacement age on the data for a random vehicle is properly functioning.

T. Service Repair Cost and Miles

This worksheet provides the time, service repair cost and mileages for Fiesta Base TDCI vans.

U. Trial Opt Replacement Time

This worksheet provides the data regarding the age of a random vehicle obtained a service repair in order to test the VB codes of the optimum replacement age.

V. Cost and Mileage

This worksheet provides a breakdown for the cost and mileage for the production and distribution department as well as each vehicle model.

W. HelpSheet

This worksheet provides a brief explanation on each worksheet in the spreadsheet to facilitate the user when they are going through the pages.

ii. Breakdown of the Transport Model

This section will present detailed analyses about each worksheet in the transport model spreadsheet, while providing some screenshots as shown by the figures below:

A. Dashboard

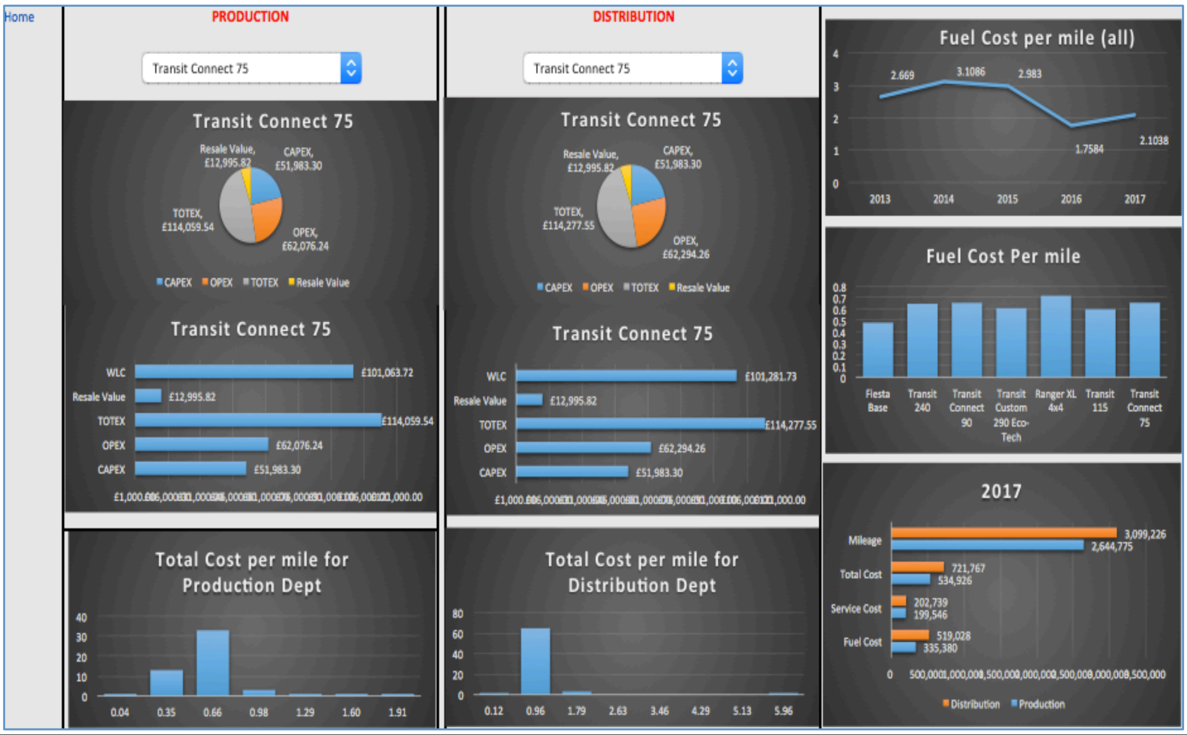


Figure 5.1.2: Dashboard for transport model

Figure 5.1.2 above shows a screenshot of the dashboard for the transport model. There are seven sections in this spreadsheet, which will be explained below:

1. <u>Production</u>

   In this section, there is a dropdown list for the seven vehicle models, namely Fiesta Base, Transit 240, Transit Connect 90, Transit Custom 290 Eco-Tech, Ranger XL 4x4, Transit 115 and Transit Connect 75 vans. By selecting one vehicle model, its value for OPEX, CAPEX, TOTEX, Resale Value and most importantly whole life cost for the production department will be generated.

2. <u>Distribution</u>

   Similarly, by selecting a specific vehicle model from the dropdown list, this section will provide graphical representations of the value of OPEX, CAPEX, TOTEX, Resale Value and whole life cost of the vehicles in the distribution department.

3. <u>Total Cost per Mile for Production Department</u>

   In this section, a chart illustrates the total cost per mile for the vehicles in the production department.

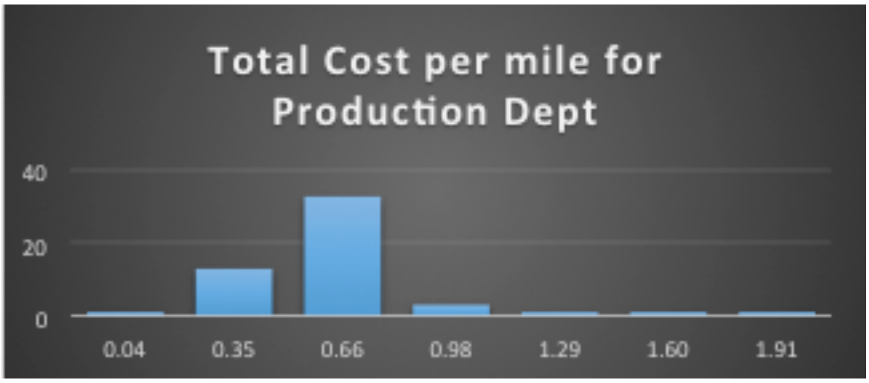


Figure 5.1.3: Total cost per mile for production department

   As mentioned in Chapter 3, there are 53 vans in the production department, and out of the 53 vans, 33 vans have a total cost per mile of £0.66, as shown in Figure 5.3 Total cost per mile for production department above.

4. <u>Total Cost per Mile for Distribution Department</u>

   Similarly, this section will show the total cost per mile for the vehicles in the distribution department. There are 70 vans in this department, but out of the 70, 65 vans have a total cost per mile of £0.96, as shown in Figure 5.1.4 Total cost per mile for distribution department below:

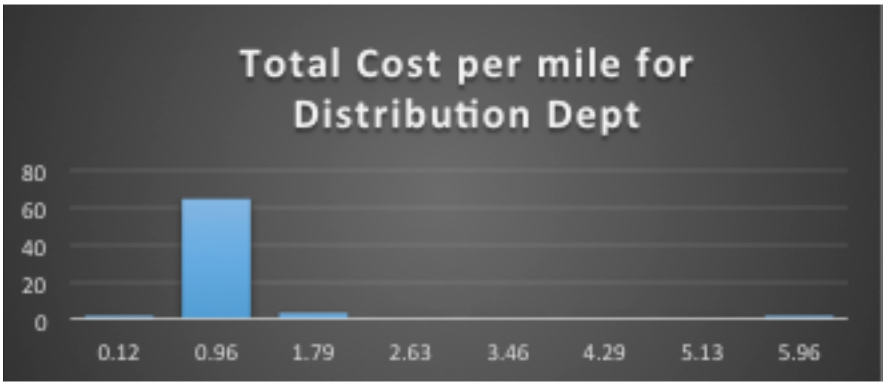


Figure 5.1.4: Total cost per mile for distribution department

5. <u>Fuel Cost per Mile (all)</u>

   This section provides a trend line for the fuel cost per mile of all the vehicles in South East Water from 2013 to 2017. This will enable the user to know the trends of the fuel cost per mile. In this case, the fuel cost per mile has a decreasing trend, as shown in Figure 5.1.5 below:

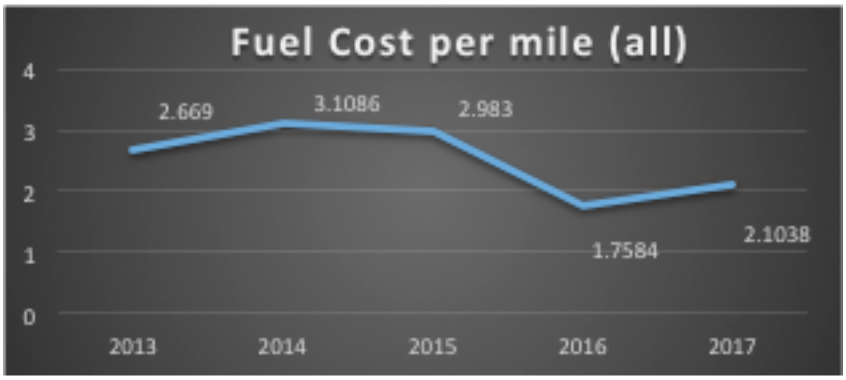


Figure 5.1.5: Fuel cost per mile (all)

In Figure 5.1.5 above, it can be seen that the fuel cost per mile has a sharp fall from 2015 to 2016. This graph will enable the user to pinpoint where there was a sharp increase or decrease and will therefore be able to find out the causes.

6. <u>Fuel Cost per Mile</u>

   On the other hand, this section provides the fuel cost per mile for the different vehicle models for the year 2017. This will enable the user to compare the fuel cost per mile for the different vehicle models and help in the decision process if there is the need to purchase a new vehicle.

7. <u>Comparison between Production and Distribution Department for the year 2017</u>

This graph represents a comparison between the costs and mileages of the production and distribution department, as shown in Figure 5.1.6 below:

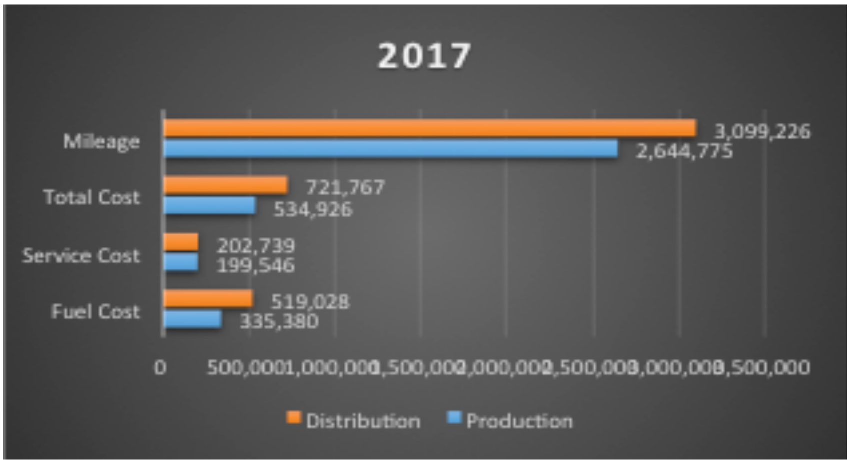
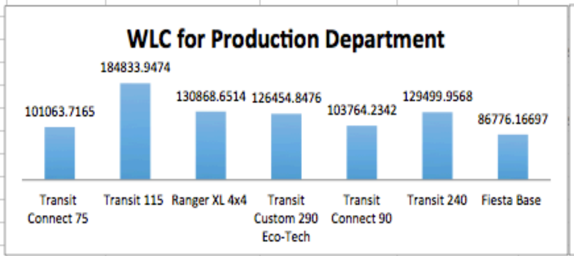


Figure 5.1.6: Comparison between production and distribution department

It can be seen that the distribution department has higher service, fuel and total costs when compared to the production department. Similarly, the vehicles in the distribution department have more mileages when compared to the production vehicles.

B. Whole Life Cost

Home	Production	Transit Connect 75	Transit 115	Ranger XL 4x4	Transit Custom 290 Eco-Tech	Transit Connect 90	Transit 240	Fiesta Base
	Capex	51983.2966	99852	69014.688	66492.5144	53526.4496	68232.5768	43818.9826
	Opex	62076.24402	109944.9474	79107.63542	76585.46182	63619.39702	78325.52422	53911.93002
	TOTEX	114059.5406	209796.9474	148122.3234	143077.9762	117145.8466	146558.101	97730.91262
	Resale Value	12995.82415	24963	17253.672	16623.1286	13381.6124	17058.1442	10954.74565
	WLC	101063.7165	184833.9474	130868.6514	126454.8476	103764.2342	129499.9568	86776.16697
	Distribution	Transit Connect 75	Transit 115	Ranger XL 4x4	Transit Custom 290 Eco-Tech	Transit Connect 90	Transit 240	Fiesta Base
	Capex	51983.2966	99852	69014.688	66492.5144	53526.4496	68232.5768	43818.9826
	Opex	62294.25665	110162.96	79325.64805	76803.47445	63837.40965	78543.53685	54129.94265
	TOTEX	114277.5532	210014.96	148340.336	143295.9888	117363.8592	146776.1136	97948.92525
	Resale Value	12995.82415	24963	17253.672	16623.1286	13381.6124	17058.1442	10954.74565
	WLC	101281.7291	185051.96	131086.664	126672.8602	103982.2468	129717.9694	86994.1796



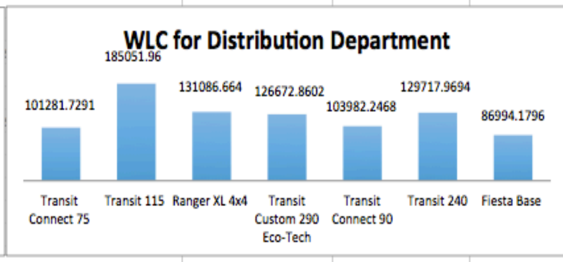


Figure 5.1.7: Whole life cost

This spreadsheet provides the value of CAPEX, OPEX, TOTEX, Resale Value and whole life costs for the different vehicle models. Graphical representations of the whole life costs are also provided. In South East Water case, the vans in the distribution department has a slightly higher whole life costs that the ones in the production department.

C. Cost Breakdown

Home

TRANSPORT MODEL	
Department	Distribution
Model	Transit Connect 90
Expected Opex	
Fuel Cost	£519,028.39
Service Repair Cost	£202,738.81
Expected Capex	
Cost of Vehicle	£53,526.45
Mileage	
Total Mileage	3099225.53
Average Mileage	10310.96
Summary	
Average Cost	£10,310.96
Total Cost	£63,837.41
Total Opex	£721,767.20
Average cost per mile	£0.7313

Vehicle Type	
Model	Transit 240
Average Cost	£10,448.66
Average Miles	50861.03
Average cost per mile	£0.6451

Expected TOTEX	
Cost of Vehicle	£775,293.65

Figure 5.1.8: Cost breakdown

This spreadsheet provides detailed information about the costs and mileages of the vehicles, as shown in Figure 5.1.8. The user will be able to select the specific department and vehicle model from two dropdown lists. The dropdown lists are the Department and Model cells (shown in red colour in the above figure). This will enable the user to find out the specific costs and mileages for the selected department and vehicle model.

D. Average Cost per Mile

Home

Model	Average Cost permile	Prod Average Cost per mile	Dist Average Cost per mile	Average Cost per mile (predicted)	AVERAGE COST PER MILE
Fiesta Base	0.479237994	0.64	0.69	0.5	0.5
Transit 240	0.645067657	0.64	0.69	0.5	
Transit Connect 90	0.653306972	0.64	0.69	0.5	
Transit Custom 290 Eco-Tech	0.606665966	0.64	0.69	0.5	
Ranger XL 4x4	0.715790447	0.64	0.69	0.5	
Transit 115	0.596973328	0.64	0.69	0.5	
Transit Connect 75	0.653995244	0.64	0.69	0.5	

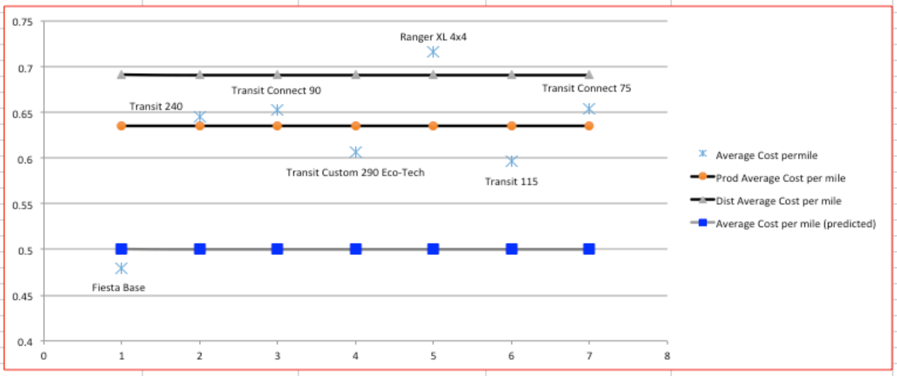


Figure 5.1.9: Average cost per mile

Figure 5.1.9 above shows the speadsheet that compares the average cost per mile for the production and distribution department. The graph in Figure 5.1.9 above shows whether the average cost per mile of the vehicle model is above or below the production or distribution average cost per mile. For example, Transit 240, Transit Connect 90 and Transit 75 vans have a higher average cost per mile than the production average cost per mile but are less than the distribution average cost per mile. This spreadsheet will also enable the user to insert a value in the blue cell that will move the blue trend line up or down depending on the value inserted.

E. Production Department Analysis

Vans	Fuel Cost	Service Cost	Total Cost	Mileage
1	5300.32	716	6,016	43,312.53
2	3698.92	2,104	5,803	30,910.79
3	5074.24	6,811	11,885	40,418.71
4	2059.84	816	2,876	20,189.89
5	2210.56	2,101	4,311	18,032.08
6	5636.30	2,286	7,922	38,925.01
7	5843.54	3,467	9,310	49,850.01
8	9749.70	7,627	17,377	50,877.73
9	3205.94	2,945	6,151	29,564.04
10	5962.86	3,608	9,571	59,108.62
11	4471.36	7,514	11,985	38,546.64
12	3877.90	4,933	8,811	27,350.66
13	5030.28	5,369	10,400	44,863.06
14	7787.20	2,141	9,929	53,333.84
15	4531.02	3,256	7,787	39,460.07
16	5576.64	4,343	9,919	45,939.14
17	1843.18	2,914	4,757	25,891.81

FOR 2017			
Fuel Cost	335,380	STD Cost	7405.779169
Service Cost	199,546	Variance Cost	54845565.1
Total Cost	534,926	STD Mileage	55179.32081
Mileage	2,644,774.59	Variance Mileage	3044757445
Average Cost	10092.94742		
Average Mileage	49901.40728		
Average Cost per mile	0.202257771		

Figure 5.1.10: Production department analysis

This spreadsheet provides the fuel cost, service cost and mileage information for each 53 vans in the production department. It will also provide the average cost, average mileage and average cost per mile of the production vehicles, which can be used for comparison between the two departments.

F. Distribution Department Analysis

Vans	Fuel Cost	Service Cost	Total Cost	Mileage
1	5476.16	3567.04	9043.20	39160.20
2	8983.54	2408.38	11391.92	60149.53
3	9724.58	998.52	10723.10	45224.16
4	5312.88	894.90	6207.78	33235.02
5	6945.68	4078.86	11024.54	45010.02
6	6490.38	2502.58	8992.96	55695.12
7	15615.22	2486.88	18102.10	56507.44
8	9203.34	2625.04	11828.38	55932.19
9	5724.22	1099.00	6823.22	35763.34
10	6022.52	2910.78	8933.30	40185.09
11	7143.50	4179.34	11322.84	37199.58
12	7055.58	3174.54	10230.12	45915.59
13	5746.20	244.92	5991.12	34997.81
14	9843.90	2339.30	12183.20	66423.56
15	8468.58	2320.46	10789.04	54792.06
16	[illegible]	[illegible]	[illegible]	[illegible]

FOR 2017			
Fuel Cost	519,028	STD Cost	3541.920104
Service Cost	202,739	Variance Cost	12545198.02
Total Cost	721,767	STD Mileage	32132.68941
Mileage	3,099,225.53	Variance Mileage	1032509729
Average Cost	10310.96005		
Average Mileage	44274.65043		
Average Cost per mile	0.232886312		

Figure 5.1.11: Distribution department analysis

This spreadsheet provides the fuel cost, service cost and mileage information for each 70 vans in the distribution department. It will also provide the average cost, average mileage and average cost per mile of the distribution vehicles, which can be used for comparison between the two departments. Distribution vehicles have a higher cost and mileage when compared to the vehicles in the production department.

G. Department Cost Analysis

Production	Distribution
6,016	9,043
5,803	11,392
11,885	10,723
2,876	6,208
4,311	11,025
7,922	8,993
9,310	18,102
17,377	11,828
6,151	6,823
9,571	8,933
11,985	11,323
8,811	10,230
10,400	5,991
9,929	12,183
7,787	10,789
9,919	9,316
4,757	8,356
7,662	8,811
6,958	9,269

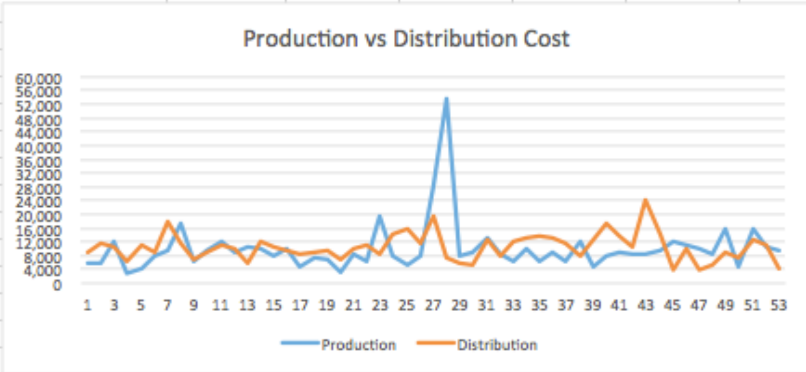


Figure 5.1.12: Department cost analysis

This spreadsheet provides a comparison between the total costs of all the vehicles in the distribution and production department. For example, a van in the production department has a cost of £6,016 but distribution department costs £9,043 per year. This will further demonstrate that running a distribution van will cost more than running a production one.

H. Department Mileage Analysis

Production	Distribution
43,312.53	39,160.20
30,910.79	60,149.53
40,418.71	45,224.16
20,189.89	33,235.02
18,032.08	45,010.02
38,925.01	55,695.12
49,850.01	56,507.44
50,877.73	55,932.19
29,564.04	35,763.34
59,108.62	40,185.09
38,546.64	37,199.58
27,350.66	45,915.59
44,863.06	34,997.81
53,333.84	66,423.56
39,460.07	54,792.06
45,939.14	48,949.77

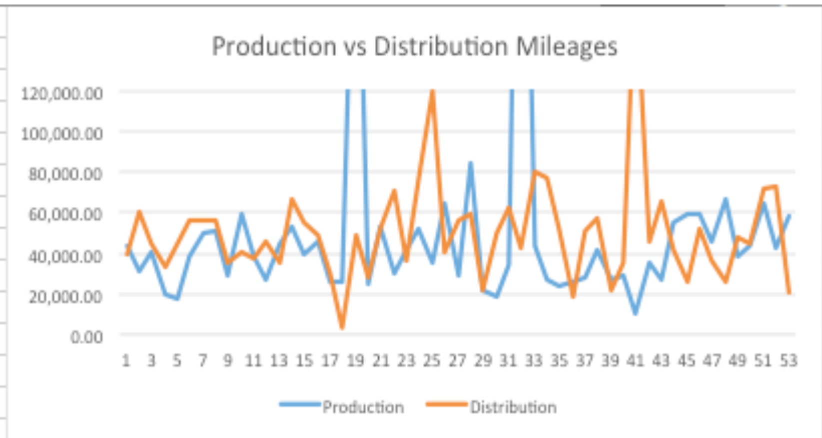


Figure 5.1.13: Department mileage analysis

Similarly, this spreadsheet will compare the mileages of a van operating under the two departments. For example, for the same period of time, a production van has 43,312 miles while a distribution van might have 39,160 miles. The comparison of the mileages is also illustrated graphically.

I. Fuel Cost per Mile in 2013

Home	FuelCost/mile 2013				Cost per mile for 2013
	0.672007709	Number of Classes	9	0.00	1
	0.617348845	Min	0.001955424	2.66	264
	9.21351847	Max	23.96047035	5.33	7
	2.253232921	Class Width	2.662057214	7.99	3
	0.307183866			10.65	4
	0.641792601			13.31	0
	0.121386324			15.97	1
	0.078066359			18.64	1
	0.303601985			21.30	0
	0.29602702			23.96	1
	0.34867097				
	0.505712936				
	0.280061748				
	0.770950651				
	0.272744629				
	0.077980632				
	0.041252129				
	0.088994831				
	0.311761901				
	0.295956294				
	0.170317811				
	0.32713888				
	0.290044808				
	0.830254758				
	0.14897665				

Figure 5.1.14: Fuel cost per mile 2013

This spreadsheet provides the fuel cost per mile of all the vehicles in both production and distribution department for the year 2013. In 2013, 264 vehicles have a fuel cost per mile of £2.66.

J. Fuel Cost per Mile in 2014

Home	FuelCost/mile 2014				Cost per mile for 2014
	0.930607534	Number of Classes	9	0.00	1
	0.620252649	Min	0.00047228	3.10	283
	9.151820802	Max	27.93368627	6.21	9
	1.784513179	Class Width	3.103690444	9.31	4
	0.44553822			12.42	1
	0.301151306			15.52	0
	0.005586244			18.62	0
	0.162053481			21.73	0
	0.258774846			24.83	0
	0.18884698			27.93	1
	0.441442352				
	0.444003917				
	0.143108476				
	0.64897409				
	0.047029391				
	0.038783021				
	0.041538271				
	0.114921649				
	0.207966022				
	0.223936511				
	0.284730822				
	0.031870619				
	0.328660602				
	0.777582274				
	0.364856002				
	0.422405724				
	0.191359569				

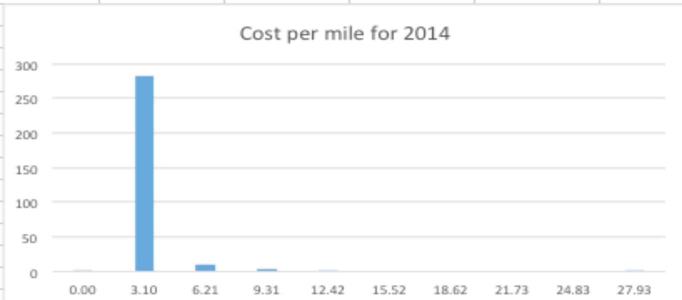


Figure 5.1.15: Fuel cost per mile 2014

This spreadsheet provides the fuel cost per mile of all the vehicles in both production and distribution department for the year 2014. In 2014, 283 vehicles have a fuel cost per mile of £3.10.

K. Fuel Cost per Mile in 2015

Home	FuelCost/mile 2015
	0.806761087
	0.700397655
	7.132250458
	1.3402851
	0.151803485
	0.3361465
	0.104261282
	0.087276435
	0.026488764
	0.152828483
	0.425409714
	0.394335682
	0.292500388
	0.436176427
	0.18928038
	0.03467481
	0.015427819
	0.1250043
	0.176902111
	0.146790321
	0.245542653
	0.159477104
	0.090753205
	0.828739003
	0.500153661
	0.083113197

Number of Classes	9
Min	0.00108808
Max	26.9311493
Class Width	2.992229025

	Cost per mile for 2015
0.00	1
2.99	288
5.99	9
8.98	4
11.97	0
14.96	1
17.95	1
20.95	0
23.94	0
26.93	1

Figure 5.1.16: Fuel cost per mile 2015

This spreadsheet provides the fuel cost per mile of all the vehicles in both production and distribution department for the year 2015. In 2015, 288 vehicles have a fuel cost per mile of £2.99.

L. Fuel Cost per Mile in 2016

FuelCost/mile 2016
0.097810545
0.182939684
1.982551742
0.326837008
0.35125123
0.551575631
0.032647472
0.13588517
0.322410575
0.289648744
0.209046926
0.332841677
0.358925289
0.122564399
0.057494722
0.048205525
0.046450375
0.066720403
0.164551399
0.15916872
0.276235484
0.054812503
0.062126357
0.784403171
0.358638278
0.321675017

Number of Classes	9
Min	0.000153868
Max	15.71686359
Class Width	1.74630108

	Cost per mile for 2016
0.00	1
1.75	292
3.49	11
5.24	2
6.99	1
8.73	1
10.48	1
12.22	0
13.97	1
15.72	1

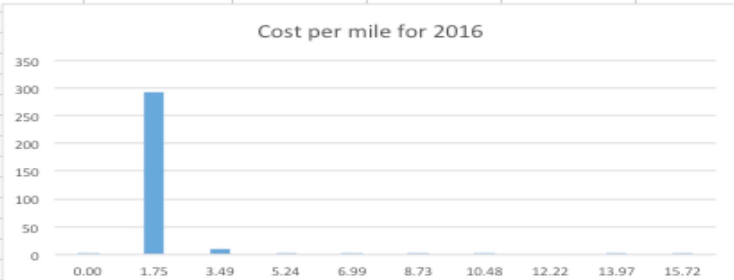


Figure 5.1.17: Fuel cost per mile 2016

This spreadsheet provides the fuel cost per mile of all the vehicles in both production and distribution department for the year 2016. In 2016, 292 vehicles have a fuel cost per mile of £1.75.

M. Fuel Cost per Mile in 2017

FuelCost/mile 2017				Cost per mile for 2017
0.690303207	Number of Classes	9	0.00	1
0.725370374	Min	0.001469915	2.10	293
10.73950747	Max	18.88556417	4.20	8
1.426428187	Class Width	2.098232695	6.30	4
0.14264663			8.39	1
0.132275414			10.49	1
0.032235372			12.59	1
0.074996334			14.69	0
0.242003854			16.79	1
0.111057032			18.89	0
0.081097132				
0.229419942				
0.199787639				
0.547571889				
0.212665874				
0.093282776				
0.030378736				
0.056277656				
0.330599855				
0.277326176				
0.060289491				
0.074654134				
0.185891801				
0.209174179				
0.463593448				

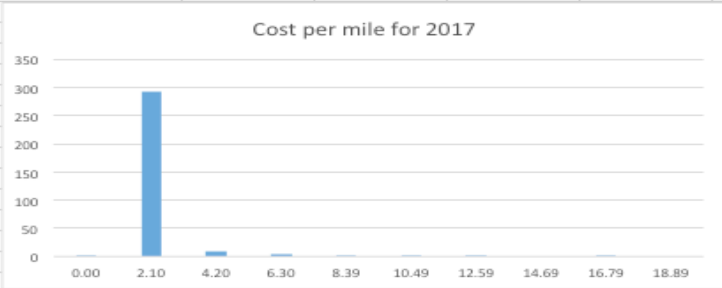


Figure 5.1.18: Fuel cost per mile 2017

This spreadsheet provides the fuel cost per mile of all the vehicles in both production and distribution department for the year 2017. In 2017, 293 vehicles have a fuel cost per mile of £2.10.

N. Vehicle Models Fuel Cost per Mile

Home	Model	Fuel Cost Per mile
	Fiesta Base	0.479237994
	Transit 240	0.645067657
	Transit Connect 90	0.653306972
	Transit Custom 290 Eco-Tech	0.606665966
	Ranger XL 4x4	0.715790447
	Transit 115	0.596973328
	Transit Connect 75	0.653995244

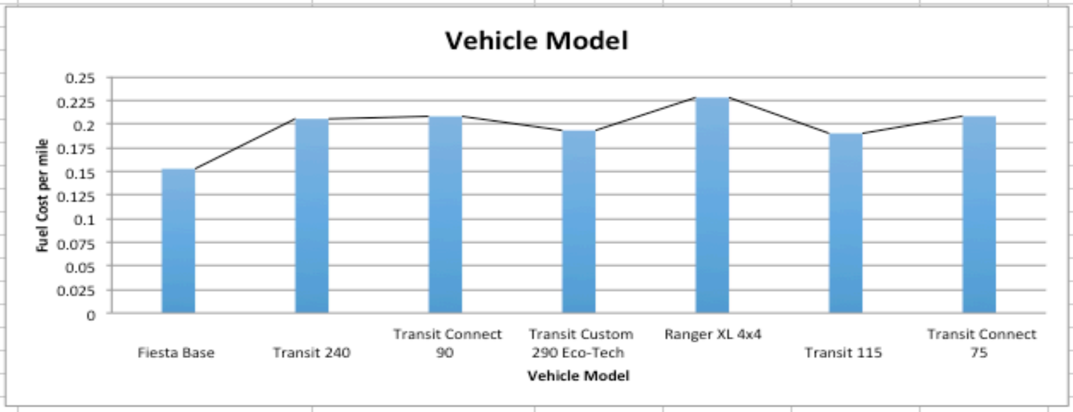


Figure 5.1.19: Vehicle models fuel cost per mile

This spreadsheet graphically represents the comparison between the fuel costs per mile of each vehicle model for the year 2017. As shown in Figure 5.1.19, Ranger XL 4x4 vans have higher fuel cost per mile when compared to the others, followed closely by Transit Connect 75 vans. Fiesta Base vans have the smallest fuel cost per mile among the other vehicle models.

O. Service time of Fiesta vehicles

A	B	C	D	E	F	G	H
Home	12	12	12	12	12	12	12
	24	24		24	24	24	24
	48	48				48	48
	72					72	
						84	
						96	

Figure 5.1.20: Fiesta base service time

This spreadsheet is used to store the data used in the VB codes explained in Chapter 4. In order to find the optimum replacement age of Fiesta Base vans, the data shown in Figure 5.1.20 will be used. For example, in Column B, van 1 has obtained a service repair after operating for 12, 24, 48 and 72 months. It can be said that over 4 years, the van obtained a service repair every year. However, Column D shows a van obtaining only one service repair after operating for 12 months. Each column will therefore represents a van and records the accumulated months it obtained a service repair. Moreover, this spreadsheet will enable the user to update the service repair data for each vehicle in the future. Hence, it will keep a record for future optimisation tool that can be developed.

P. Service miles of Fiesta vehicles

A	B	C	D	E	F	G
Home	30404.78	25564.62	12682.15	32054.06	27204.02	43468.65
	60809.55	51129.25		58620.97	34989.96	86937.31
	91214.33	75484.03				130405.96
	111404.22					173874.61
						217343.26
						242283.97

Figure 5.1.21: Fiesta base service miles

Similarly, this spreadsheet is used to store the data used in the VB codes to find the optimum replacement miles for the Fiesta Vans as described in Chapter 4. Column B shows a van obtaining a service repair after 30,404.78 miles, and undergoing through another repair at 60,809 miles, then 91,214 miles and finally at 111,404 miles. On the other hand, Column D shows that the van has a service repair only after 12,682 miles. Each column in this spreadsheet therefore represents a van and each row represents the accumulated miles of the van when it had a service repair. This spreadsheet will also keep a record of the mileages at which a van went through a service repair that can be updated for future optimisation techniques developed.

Q. Optimum Replacement Age

When clicking the control button named 'Optimum Replacement Age', as shown as Q in Figure 5.1.1, the following screen will pop up:

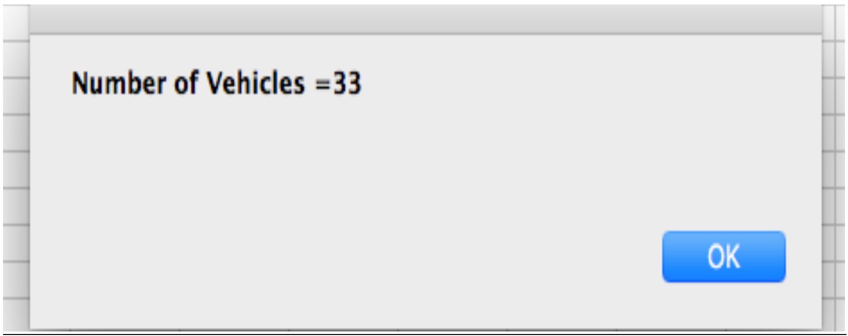


Figure 5.1.22: Number of vehicles

Figure 5.1.22 will show the number of vehicles in the worksheet that is activated to run the VB codes to calculate the optimum replacement age of a Fiesta Base van. In this case, in the worksheet (Figure 5.1.20), the time-to-failure for the 33 vans are stored. By clicking the OK button, the next screen will appear:

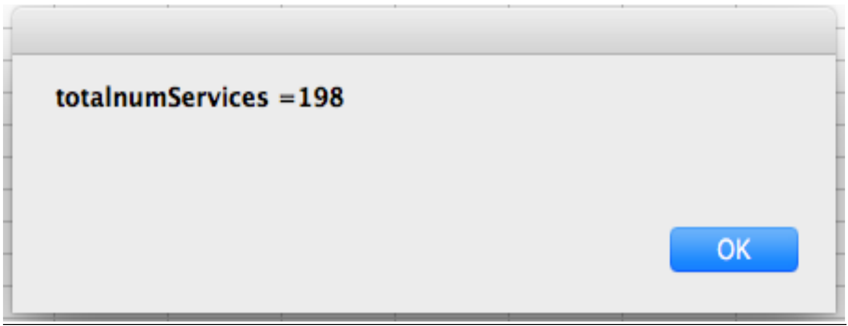


Figure 5.1.23: Total number of services

Figure 5.1.23 displays the total number of services that the 33 Fiesta Base vans had over the years. In this case, all the Fiesta Base vans had a total of 198 service repairs. Similarly, by clicking the OK button, the next screen will pop up:

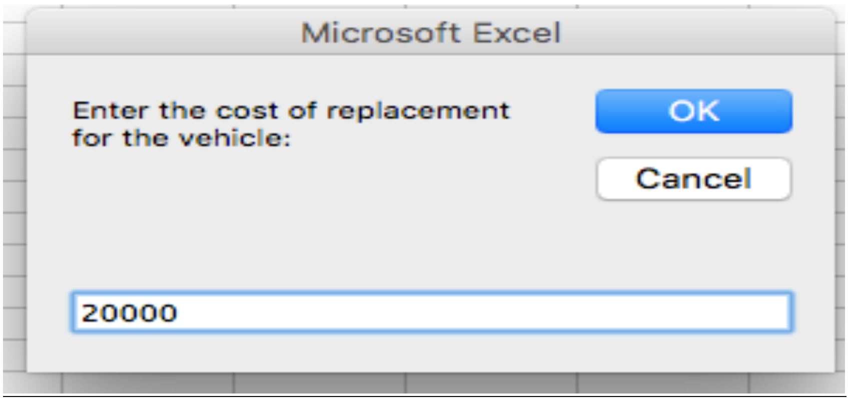


Figure 5.1.24: Replacement cost

To find the optimum replacement age of a vehicle, the cost of replacement plays a significant part of the formulation as shown in Chapter 4. Therefore, Figure 5.1.24 shows that the user will be able to enter the cost of replacing a vehicle. Because the purchasing costs for vans will vary over the years, this will enable the user to use this tool while taking into consideration the inflation rate. In Figure 5.1.24, it can be seen that the cost of replacement entered is 20,000. However, if the user input a replacement cost of 0 or less, the following screen will appear:

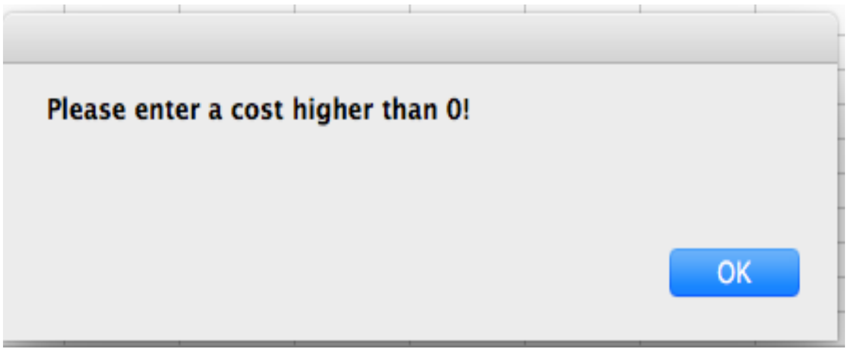


Figure 5.1.25: Error detection

Figure 5.1.25 will let the user know that a replacement cost higher than 0 needs to be entered in the box. When the user have correctly put the replacement cost, usually the optimum replacement age will be generated. However, for South East Water, as there is a lack of service repair data, the following screen will emerge:

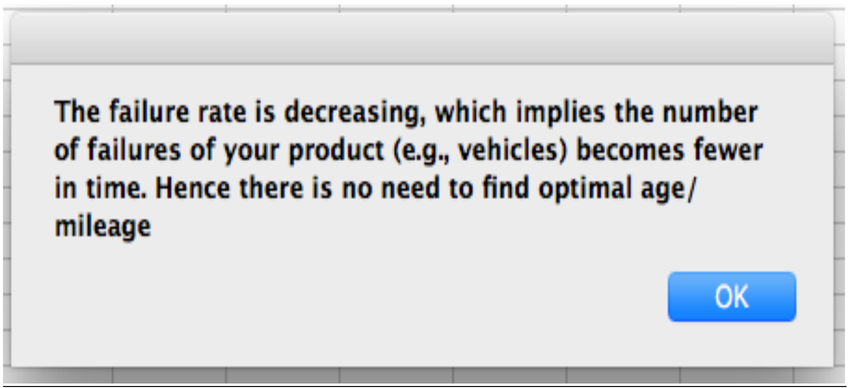


Figure 5.1.26: Results for optimum replacement age

As explained in Chapter 4, if the beta value is less than 1, it implies that the failure rate of the vehicle is decreasing and hence, there is no need to replace the vehicle and it might be more beneficial to repair and continue running it.

R. <u>Optimum Replacement Miles</u>

Similarly, when clicking the control button named 'Optimum Replacement Miles', as shown as R in Figure 5.1.1, the following screen will pop up:

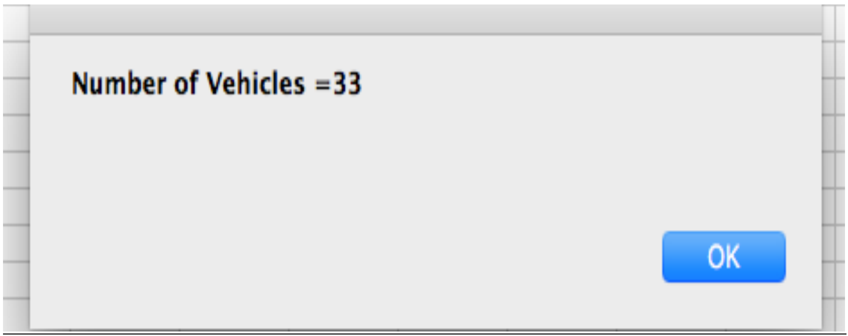


Figure 5.1.27: Optimum replacement miles

As explained, above this screen will show the number of vehicles recorded in the worksheet that the VB codes to calculate the optimum replacement miles are stored. This spreadsheet is Figure 5.1.21. By clicking OK, the following screen will pop up:

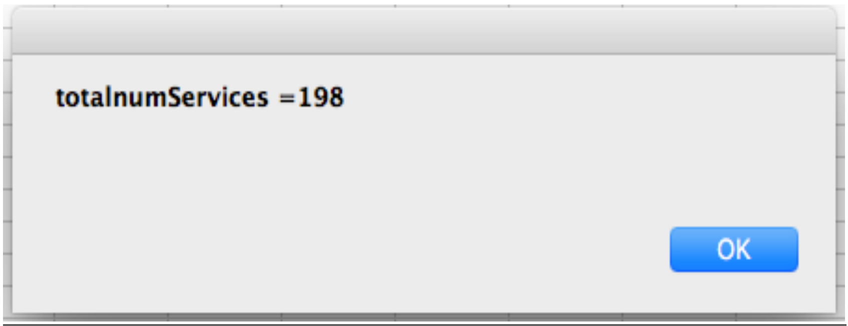


Figure 5.1.28: Total number of services

Figure 5.1.28 will provide the total number of services that the vans stored in the spreadsheet had gone through over the years. Again, by clicking OK, the next screen will appear:

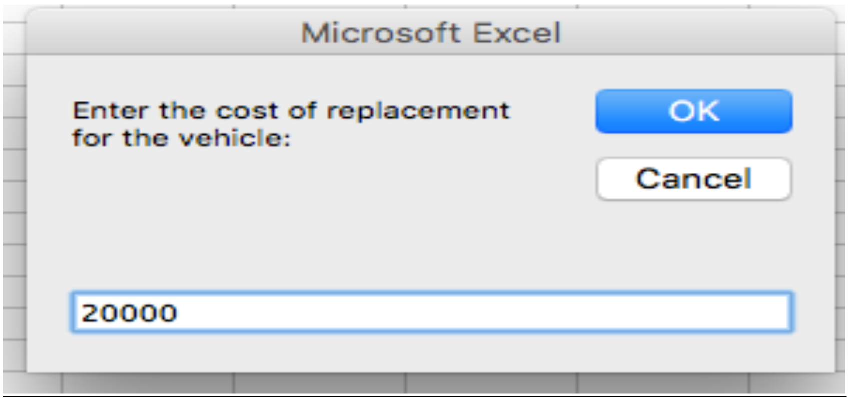


Figure 5.1.29: Cost of replacement

As previously explained, the user will have to input the cost of replacement manually as shown in Figure 5.1.29. If a value less or equal than 0 is entered, the following screen will pop up:

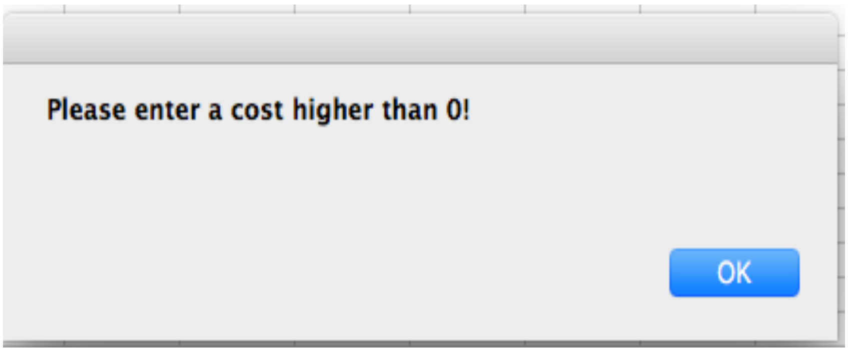


Figure 5.1.30: Error detected

This will give the user a reminder to enter a value greater than 0. When they have properly entered a cost of replacement, the optimum replacement miles will be given. However, there is a lack of data for the mileages in South East Water case, hence the following screen (Figure 5.1.31) will appear:

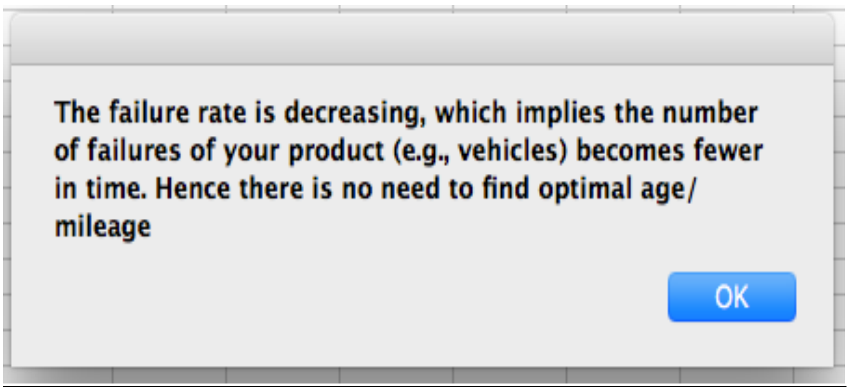


Figure 5.1.31: Results for optimum replacement miles

S. Trial Replacement Age

As explained in Chapter 5.1.1, the VB codes for the optimum replacement age have been tested against a random sample of data. By clicking the 'Trial Replacement Age', shown as S in Figure 5.1.1, the following screen will pop up:

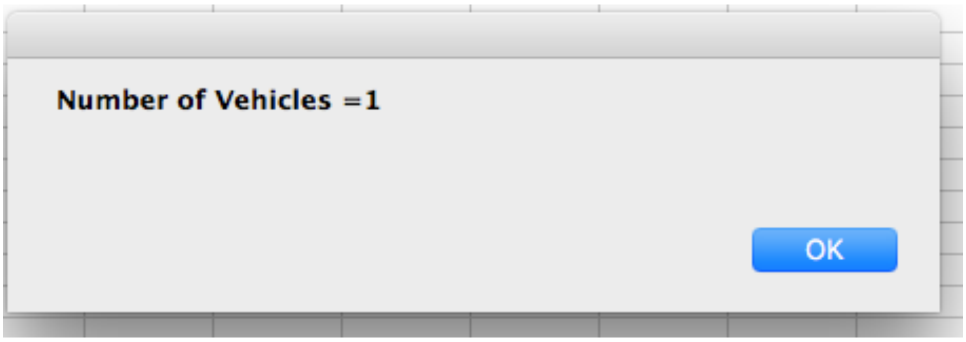


Figure 5.1.32: Number of vehicles in trial replacement age

Figure 5.1.32 shows the number of vehicles recorded in the worksheet activated for the data stored to test the VB codes. In this case, the service repair data of only one vehicle have been recorded. By clicking OK, the next screen will pop up:

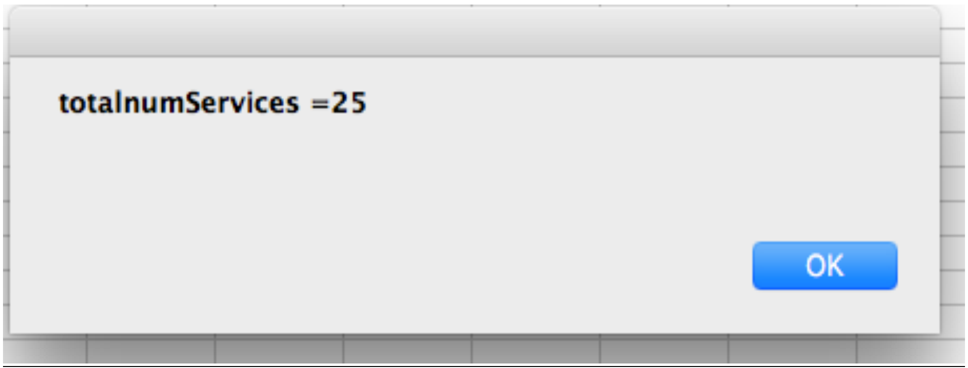


Figure 5.1.33: Total number of services in trial replacement age

In this case, the vehicle had a total of 25 repair services over the years, as shown in Figure 5.1.33. The next screen will then appear:

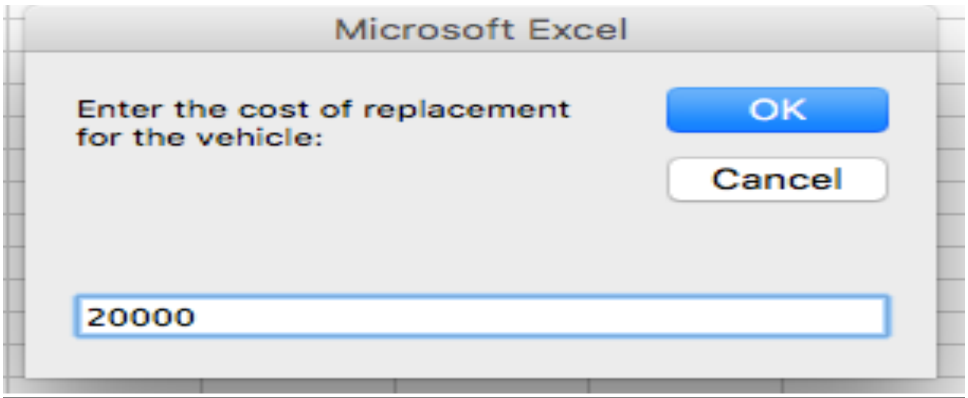


Figure 5.1.34: Cost of replacement in trial replacement age

For testing purposes, a cost of 20,000 has been entered as the replacing value of this vehicle, as shown in Figure 5.1.34.

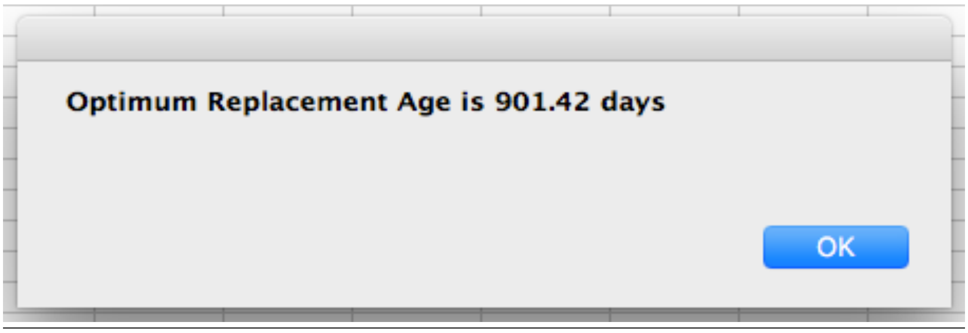


Figure 5.1.35: Results for trial replacement age

The optimum time to replace this vehicle is after 901.42 days, as shown in Figure 5.1.35. Hence, this trial test will confirm the validity of the VB codes.

T. Service Repair Cost and Miles

Home	1)						
			Times	Dec-14	Dec-15	Dec-16	Dec-17
Average Service Repair			Age	12	24	48	72
921.59			Miles	30404.78	30404.78	30404.78	20189.89
1707.113333		Service repair	Cost	345.40	1208.90	1315.66	816.40
618.58							
872.92							
1350.20	2)						
1392.066667			Times	Dec-15	Dec-16	Dec-17	
684.52			AGE	12	24	48	
2967.30			Miles	25564.62	25564.62	24354.78	
1343.92		Service repair	Cost	3033.24	1099.00	989.10	
558.92							
1503.28							
1158.66	3)						
3145.23			Times	Dec-17			
1920.11			AGE	12			
1378.46			Miles	12682.146			
569.91		Service repair	Cost	618.58			

Figure 5.1.36: Service repair cost and miles

Figure 5.1.36 shows the spreadsheet that stored the data for the service repair age, costs and mileages for the Fiesta Vans. The average service repair cost for each van has also been recorded in this spreadsheet. These data will be used in the formulation of the optimum replacement age and miles described in Chapter 4.

U. Trial Opt Replacement Time

Home	637
	677
	1074
	1110
	1164
	1217
	1314
	1377
	1593
	1711
	1836
	1861
	1865
	1966
	2150
	2317
	2398
	2444
	2462
	2494
	2713
	3118
	3138
	3386
	3526

Figure 5.1.37: Trial opt replacement time

This spreadsheet records the data for the trial replacement age formulation. As mentioned above, the 25 services repair costs of one vehicle is recorded in this workbook, as shown in Figure 5.1.37.

V. Cost and Mileage

Home				
Department	Fuel Cost	Department	Service Cost	Department
Production	335380.26	Production	199545.95	Production
Distribution	519028.39	Distribution	202738.81	Distribution
Model	Cost of Vehicle	Model	Average Cost	Model
Fiesta Base	43818.98	Fiesta Base	4828.06	Fiesta Base
Transit 240	68232.58	Transit 240	10448.66	Transit 240
Transit Connect 90	53526.45	Transit Connect 90	8987.94	Transit Connect 90
Transit Custom 290 Eco-Tech	66492.51	Transit Custom 290 Eco-Tech	9701.97	Transit Custom 290 Eco-Tech
Ranger XL 4x4		Ranger XL 4x4	8927.44	Ranger XL 4x4
Transit 115		Transit 115	4703.72	Transit 115
Transit Connect 75		Transit Connect 75	8086.13	Transit Connect 75
Model	Cost of Vehicle			
Fiesta Base	43818.98			
Transit 240	68232.58			
Transit Connect 90	53526.45			
Transit Custom 290 Eco-Tech	66492.51			
Ranger XL 4x4	69014.69			
Transit 115	99852.00			
Transit Connect 75	51983.30			

Figure 5.1.38: Cost and Mileage

Figure 5.1.38 will feed the data for the dropdown lists shown in Figure 5.1.8. Data such as fuel costs, service cost, cost of vehicles, average cost (for each vehicle model and each department), average cost per mile (for each vehicle model and each department) and the average mileage (for each vehicle model and each department) have been stored on this worksheet.

W. HelpSheet

Home	This worksheet provides quick navigation through the pages in this spreadsheet. Simply click on the page you want to visit
Dashboard	The dashboard allows the user to select the reports they would like to display, while also providing a summary of the findings.
WLC	This worksheet provides the calculation of the WLC for each vehicle model as well as the production and distribution department
Cost_Breakdown	This worksheet provides a breakdown of all the costs involved in the Transport Model
Production_Department	This worksheet provides a detailed analysis the total and average cost and miles for all vans operating under the production department. The worksheet contains 2 parts: Part 1: Column C: Index No for each van Column D: Operating Cost for each van Column E: Mileage for each van Part 2: Total: Total cost and Total miles for all vans Average: Average cost and Averagel miles for all vans Average cost per mile: Average cost per mile calculated for the production department
Distribution_Department	This worksheet provides a detailed analysis the total and average cost and miles for all vans operating under the distribution department. The worksheet contains 2 parts: Part 1: Column C: Index No for each van Column D: Operating Cost for each van Column E: Mileage for each van Part 2: Total: Total cost and Total miles for all vans Average: Average cost and Averagel miles for all vans Average cost per mile: Average cost per miles calculated for the distribution department

Figure 5.1.39: Helpsheet for transport model

As mentioned above, this worksheet will provide detailed explanations of each tab in the transport model decision support system. It will also explain the main column and rows that are important for the user's understanding.

5.2 Borehole Model

The decision support system designed for the borehole model is based on the research questions and analyses requested by South East Water, as explained in Section 3.2. For example, the overall analysis of the loss generated by each borehole will be calculated and graphically represented. Detailed analyses for each of the 16 boreholes will be given. Section 5.2.1 will present an overview of the borehole model while providing a brief explanation of each worksheet in the borehole model's excel file. Section 5.2.2 will provide a more detailed explanation of each worksheet and also, analyse the results generated.

5.2.1 Overview of Borehole Model

Figure 5.2.1 below shows the area designed to enable the users to navigate quickly through the pages in the spreadsheet, which is designed to tackle the performance analyses of the borehole model, by just clicking on the pages the user wishes to visit. The pages in the spreadsheet are presented by their unique ID, namely A to Z, as shown in the figure 5.2.1 below:

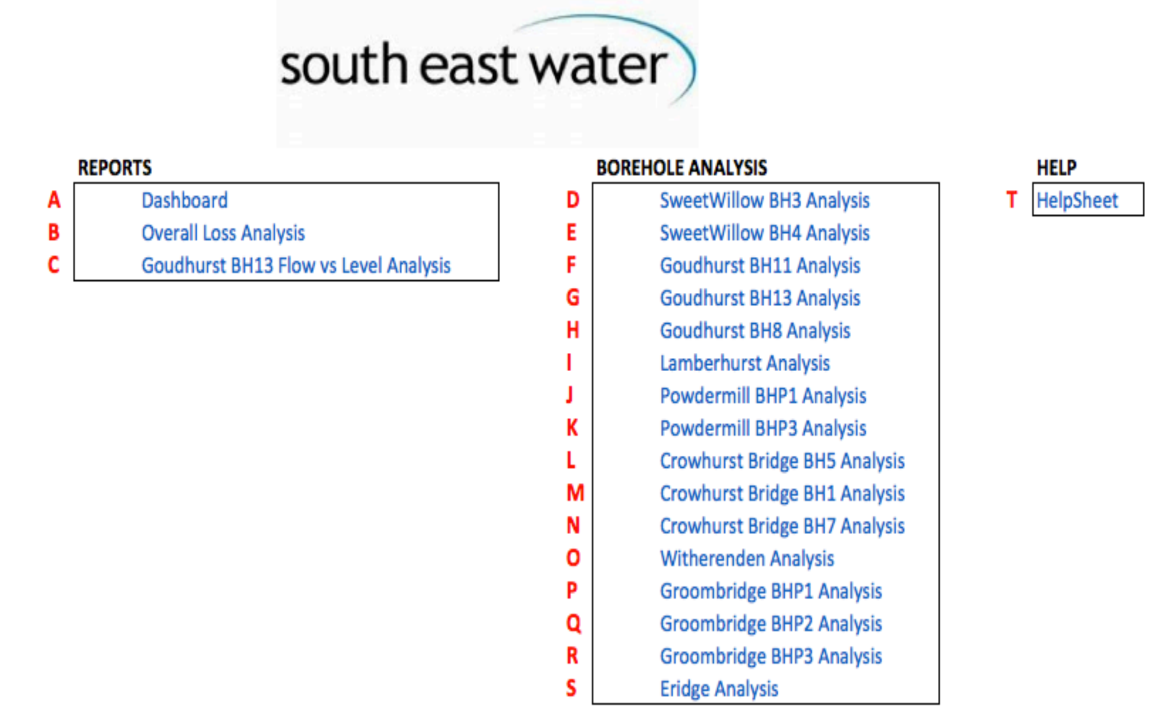


Figure 5.2.1: Overview of borehole model

A. Dashboard
The performance dashboard allows the user to select the reports they would like to display, while also providing a summary of the findings.

B. Overall Loss Analysis
This worksheet provides an analysis of the overall loss percentage for all the boreholes from 2010 to 2018.

C. Goudhurst BH13 Flow vs Level Analysis
This worksheet provides a comparison of the water flow and flow level of Goudhurst BH13 over the period of 2010 to 2018.

D. To S. Borehole Analyses
This worksheet analyses whether the output of each borehole respectively is greater or less over the years and also the changes in the water flow from 2010 to 2018. Therefore, this section will answer three research questions (Question 4, 5 and 6) concerning the performance condition of the boreholes.

E. HelpSheet
This worksheet provides a brief explanation on each worksheet in the spreadsheet to facilitate the user when they are going through the pages.

5.2.2 Breakdown of Borehole Models

This section will present detailed analyses about each worksheet in the borehole model spreadsheet, while providing some screenshots as shown by the figures below:

A. Dashboard

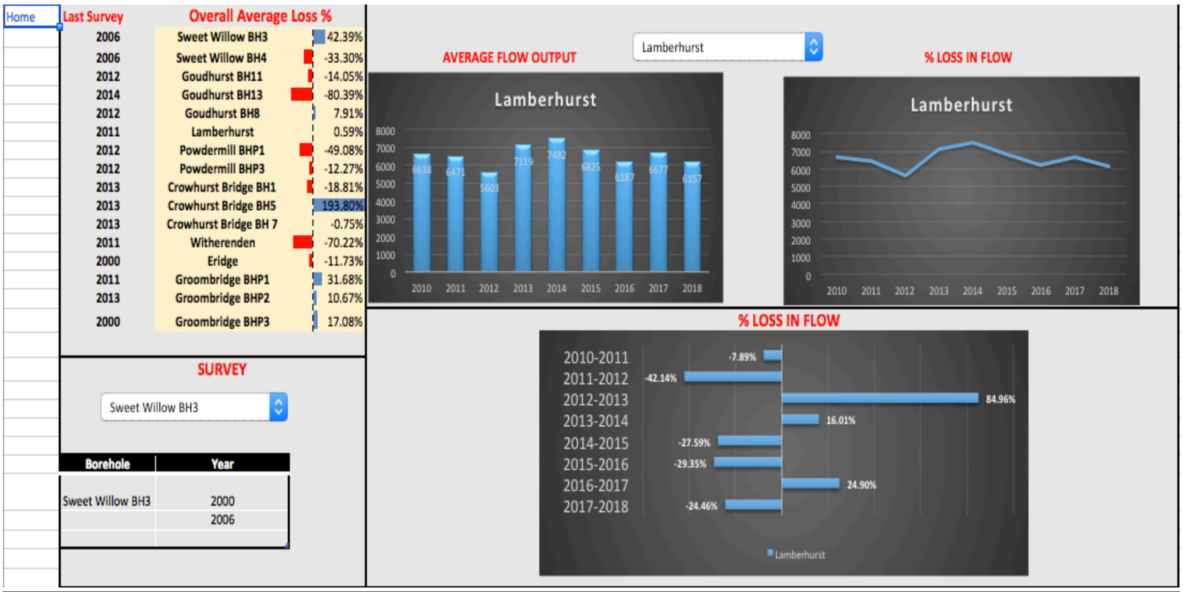


Figure 5.2.2: Dashboard for borehole model

Figure 5.2.2 above shows a screenshot of the dashboard for the borehole model. There are three sections in this spreadsheet, which will be explained below:

1. <u>Overall Average Loss Percentage</u>

   In this section, the overall flow loss percentage, from the year 2010 to 2018, for the 16 boreholes are listed. The blue bar indicates an increase in the overall flow, while the red bar pinpoints boreholes experiencing a decrease in the overall flow. The year in which the latest survey performed at each borehole is listed in the column 'Last Survey'.

2. <u>Borehole Performance</u>

   By selecting a borehole site from the dropdown list in this section, three charts will be generated to show the performance of the selected borehole. Information about the borehole's flow output for each year as well as the percentage loss in flow compared to previous years will be graphically represented in this section.

3. <u>Survey</u>

In this section, by selecting a borehole from the dropdown list, the years in which a survey was performed in this borehole will be listed in the table.

B. Overall Loss Analysis

Year	Sweet Willow BH3	Sweet Willow BH4	Goudhurst BH11	Goudhurst BH13	Goudhurst BH8	Lamberhurst	Powdermill BHP1	Powdermill BHP3	Crowhurst Bridge BH1	Crowhurst Bridge BI
2010	1907.210807	4880.614987	6929.935519	4798.312557	9820.287216	6638.159641	3036.819704	3751.515	6027.858	1572.669
2011	2194.784681	3345.079658	5391.345658	2937.862701	5750.873089	6471.347333	2902.019814	4120.308	5900.688	4997.781
2012	1909.92383	3529.561023	4160.473458	1999.395086	4323.752315	5602.940163	3123.295407	3214.857961	5960.034	5065.605
2013	1904.497915	3792.717954	7630.151358		10314.83446	7118.972047	3662.496257	3878.685257	6523.821	5006.259
2014	2175.793786	3537.699831	6672.457148		8868.872849	7482.034739	3247.922111	2820.630962	5421.681	5243.643
2015	2205.636511	3155.172511	6358.45912	943.1775647	10658.66227	6824.596987	3530.239407	3883.772111	5430.159	5146.146
2016	2707.533956	3236.561362	7049.254674	943.1775647	10701.05124	6186.784277	2690.917407	3840.534257	5428.633023	4913.001
2017	2715.673022	3255.552	5956.541689	940.8225575	10597.4317	6677.40972	1546.387407	3291.159961	4894.180088	4620.51
2018	2902.867148	2750.941533	477.2769504	943.1775647	10526.78239	6157.34672	3649.779257	3161.446407	5154.624	4756.158

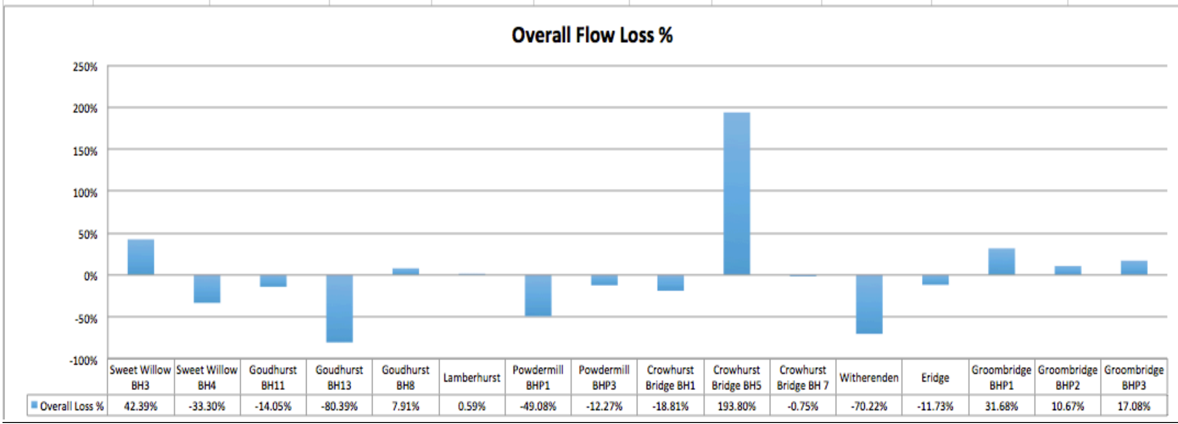


Figure 5.2.3: Overall loss analysis

This spreadsheet will provide the median flow rate of each borehole for the year 2010 to May 2018. From this data, the calculation of percentage loss flow of a borehole compared to the previous year has been done. Also, the overall flow loss percentage of each borehole is calculated and represented in a chart as shown in Figure 5.2.3. The overall flow loss percentage is the difference between the median flow rates of 2018 to the flow rate in 2010. This will enable the user to know how much did the flow rate in a borehole increase or decrease from 2010 till 2018. The top four worst performers are Sweet Willow BH4, Goudhurst BH13, Powdermill BHP1 and Witherenden. It will be beneficial for South East Water to further investigate why these four boreholes are performing worst when compared to the others.

C. Goudhurst BH13 Flow vs Level Analysis

Goudhurst BH13 Level vs Flow

	Flow	Level
2010	130309450.8	1722906
2011	103568504.4	1991245
2012	38704031.18	1102197
2013	155852890	3304905
2014	103480004.9	2430196
2015	22912527.57	1414293
2016	50931187.78	5642420
2017	33923765.58	5616383
2018	12506736.83	832779.8

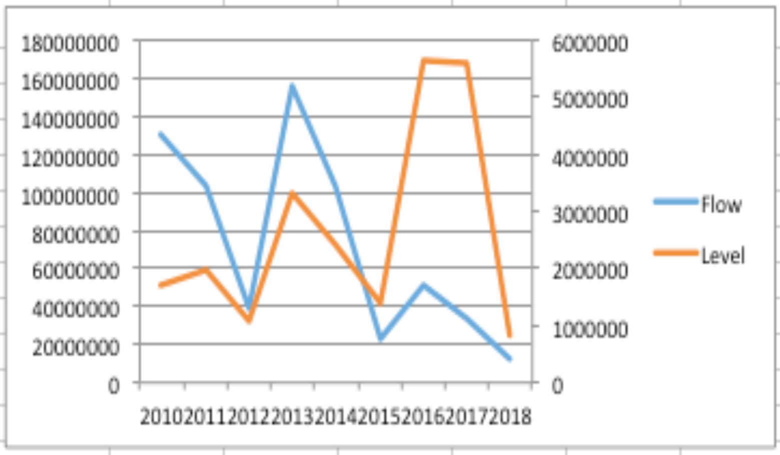


Figure 5.2.4: Goudhurst BH13 flow vs level analysis

Only Goudhurst BH13 has water level data, as there is a lack of data for the water level for the other boreholes. Therefore, this spreadsheet will show a comparison between the flow and water level of this borehole from 2010 to 2018, as illustrated in Figure 5.2.4. It can be seen that the water level is mostly moving in the same direction as the flow over the years.

D. Sweet Willow BH3 Analysis

In this spreadsheet, statistics for the year 2010 to 2018 deriving from SPSS will be provided, in order to know the mean and the percentiles of the water flow for Sweet Willow BH3. The lists of surveys performed in this borehole will also be given. Moreover, graphs generated from the 15 minutes water flow data collected for each year will be presented. This will be similar for spreadsheets E to S (Figure 5.2.5 to Figure 5.2.20).

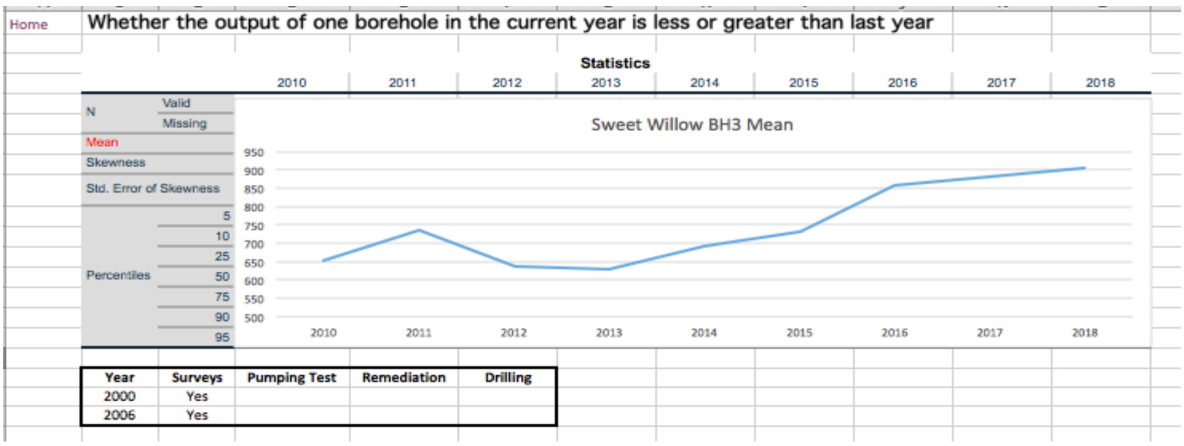


Figure 5.2.5: SweetWillow BH3 analysis

As shown in Figure 5.2.5, the latest surveys performed at Sweet Willow BH3 are in 2000 and 2006. It can be seen that mean flow in this borehole is experiencing an increasing trend over the years.

E. Sweet Willow BH4 Analysis

Sweet Willow BH4 can be seen to be experiencing a decreasing trend over the year in terms of flow output. The latest survey performed at this borehole is in 2006, as shown in Figure 5.2.6 below:

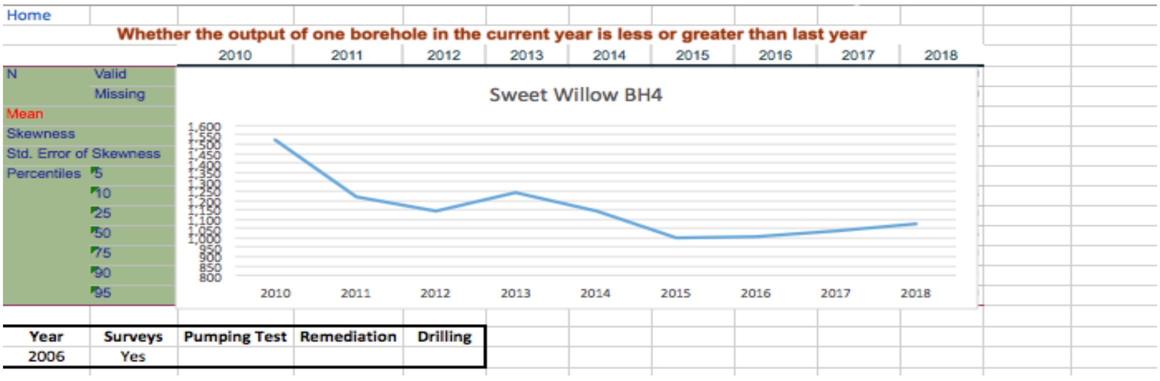


Figure 5.2.6: SweetWillow BH4 analysis

F. Goudhurst BH11 Analysis

Goudhurst BH11 can be seen to be experiencing a sharp decrease in its flow output after 2017. The latest surveys performed at this borehole are in 2003 and 2012, as shown in Figure 5.2.7 below:

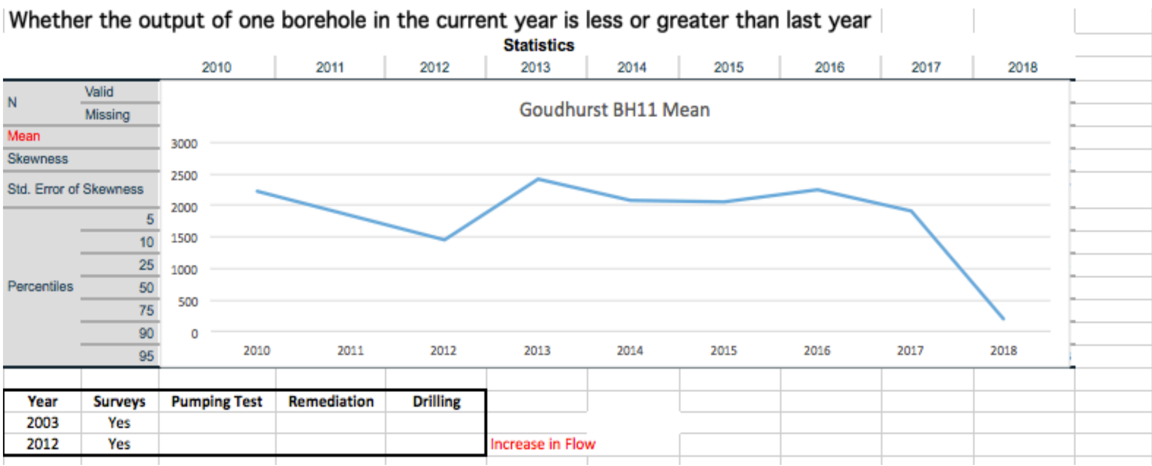


Figure 5.2.7: Goudhurst BH11 analysis

G. Goudhurst BH13 Analysis

Goudhurst BH13 can be seen to be experiencing a continuous decrease in its flow output over the years. There is a lack of water flow data for the year 2013 and 2014 for this borehole. The latest survey performed at this borehole is in 2014, as shown in Figure 5.2.8 below:

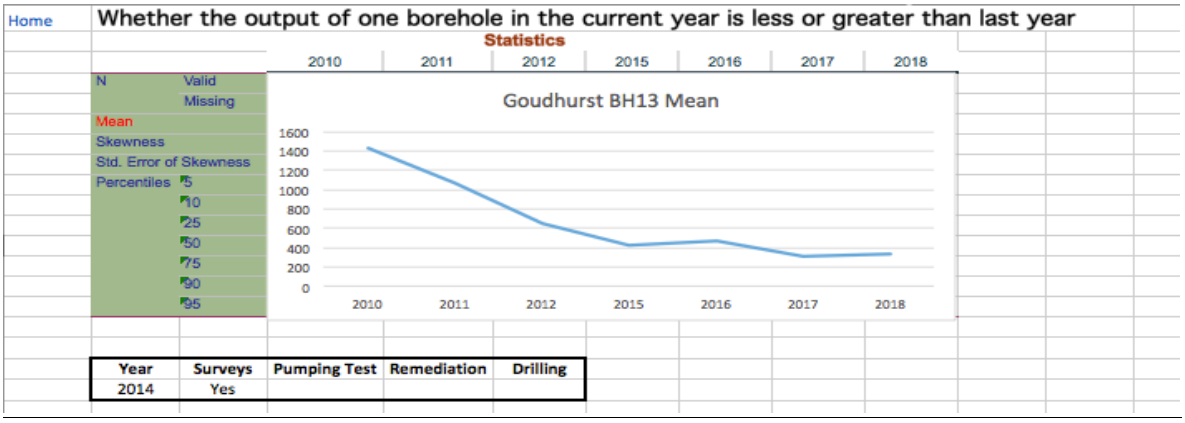


Figure 5.2.8: Goudhurst BH13 analysis

H. Goudhurst BH8 Analysis

Goudhurst BH8 has experience a sharp increase after 2012, then the flow output is fluctuating steadily over the years 2014 to 2018. The latest surveys performed at this borehole are in 2008 and 2012, as shown in Figure 5.2.9 below:

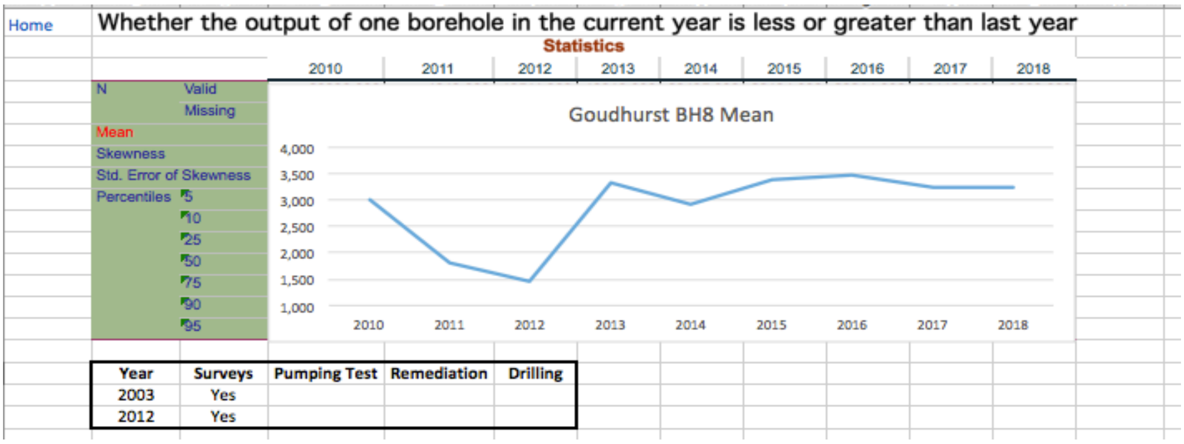


Figure 5.2.9: Goudhurst BH8 analysis

I. Lamberhurst Analysis

Lamberhurst experienced a sharp increase in its flow output in 2014, but then gradually decreased. The latest survey performed at this borehole is in 2011, as shown in Figure 5.2.10 below:

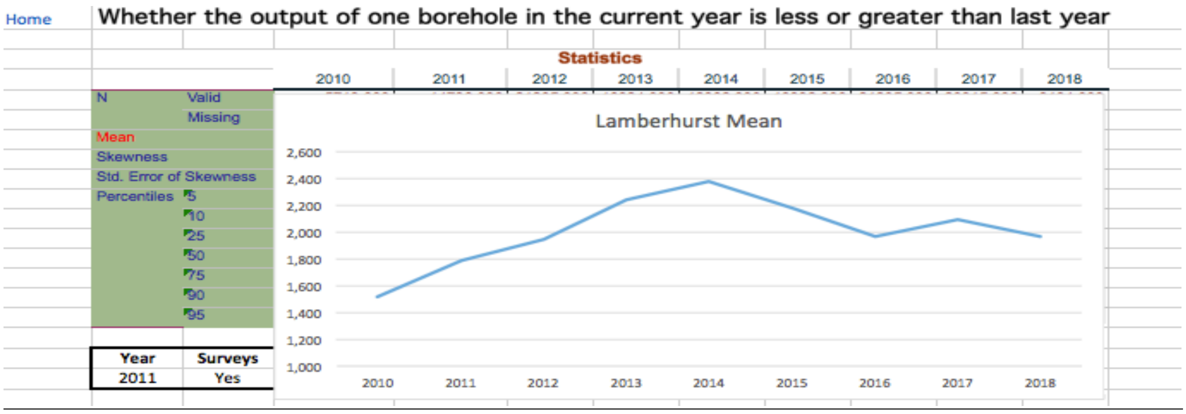


Figure 5.2.10: Lamberhurst analysis

J. Powdermill BHP1 Analysis

Powdermill BHP1 experienced a sharp decrease in its flow output in 2017, but then increased in 2018. The latest surveys performed at this borehole are in 2011 and 2012, as shown in Figure 5.2.11 below:

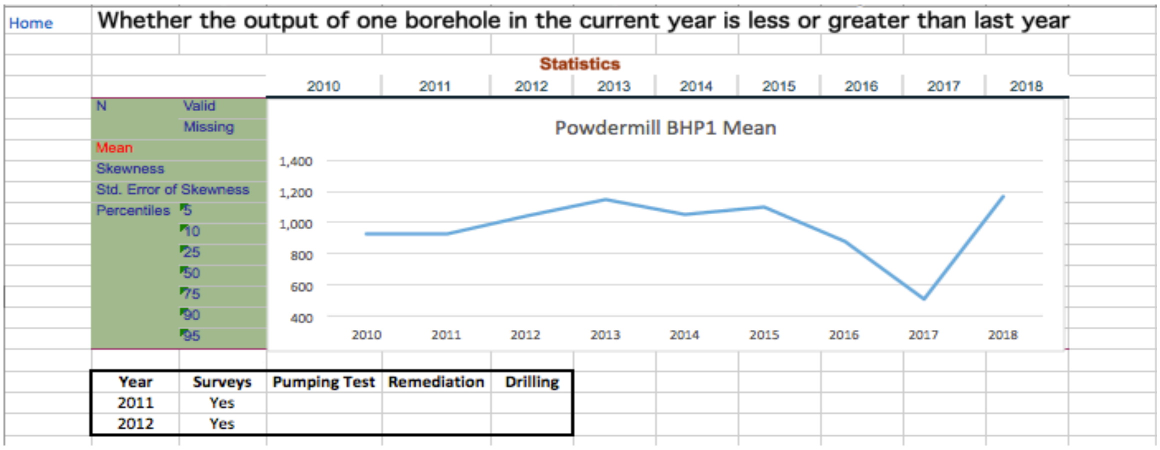


Figure 5.2.11: Powdermill BHP1 analysis

K. Powdermill BHP3 Analysis

Powdermill BHP3 experienced a sharp decrease in its flow output in 2014, but then gradually decreased, and again abruptly fell in 2017. The latest survey performed at this borehole is in 2012, as shown in Figure 5.2.12 below:

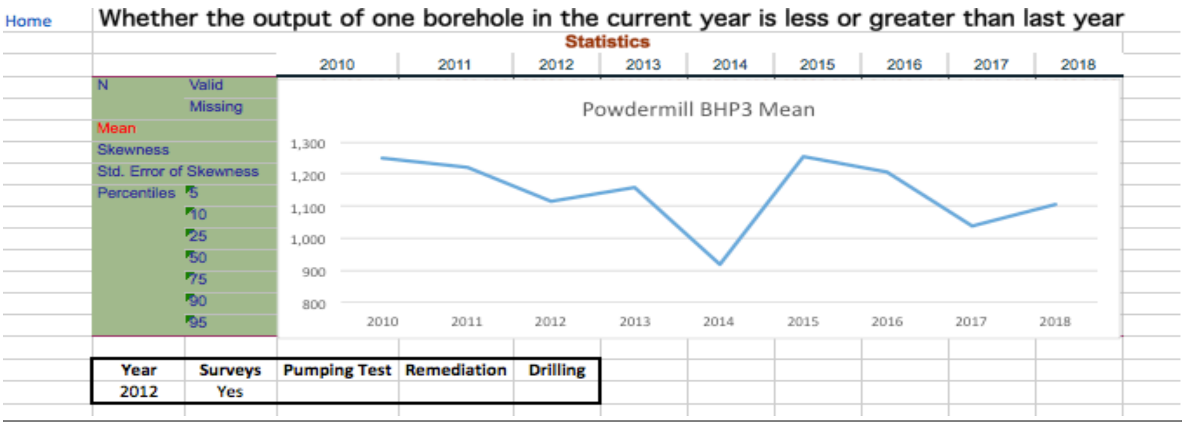


Figure 5.2.12: Powdermill BHP3 analysis

L. Crowhurst Bridge BH5 Analysis

Crowhurst Bridge BH5 experienced a steady trend in its flow output over the years 2012 to 2018. The latest survey performed at this borehole is in 2013, as shown in Figure 5.2.13 below:

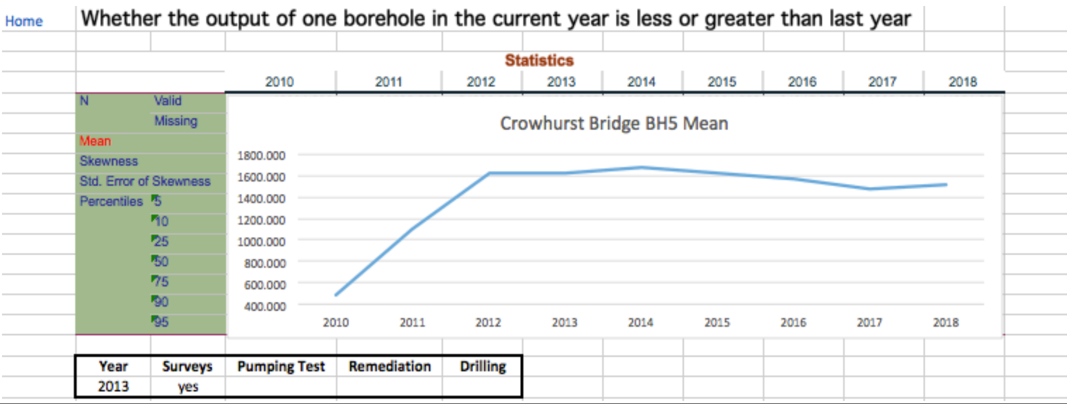


Figure 5.2.13: Crowhurst bridge BH5 analysis

M. Crowhurst Bridge BH1 Analysis

Crowhurst Bridge BH1 experienced a decreasing trend in its flow output after 2014. The latest surveys performed at this borehole are in 2007 and 2013, as shown in Figure 5.2.14 below:

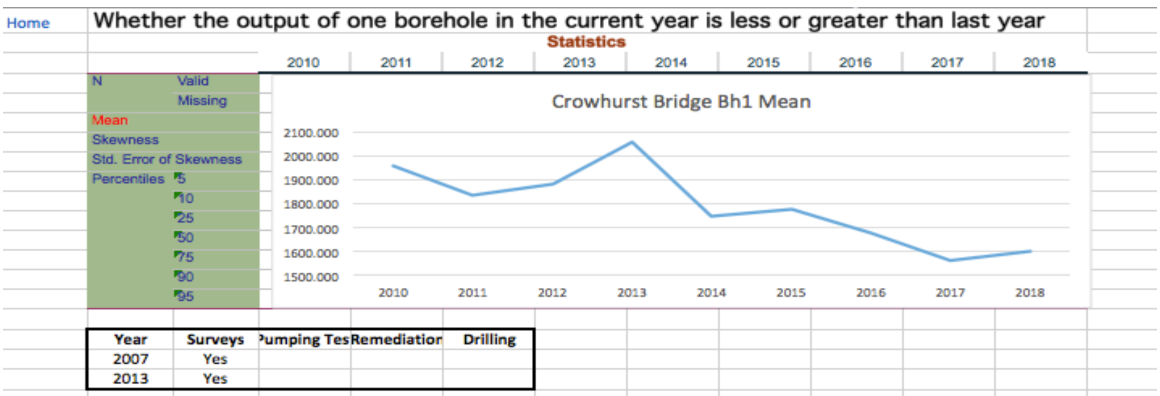


Figure 5.2.14: Crowhurst bridge BH1 analysis

N. Crowhurst Bridge BH7 Analysis

Crowhurst Bridge BH7 experienced a sharp decrease in its flow output in 2016, but then gradually increased. The latest survey performed at this borehole is in 2013, as shown in Figure 5.2.15 below:

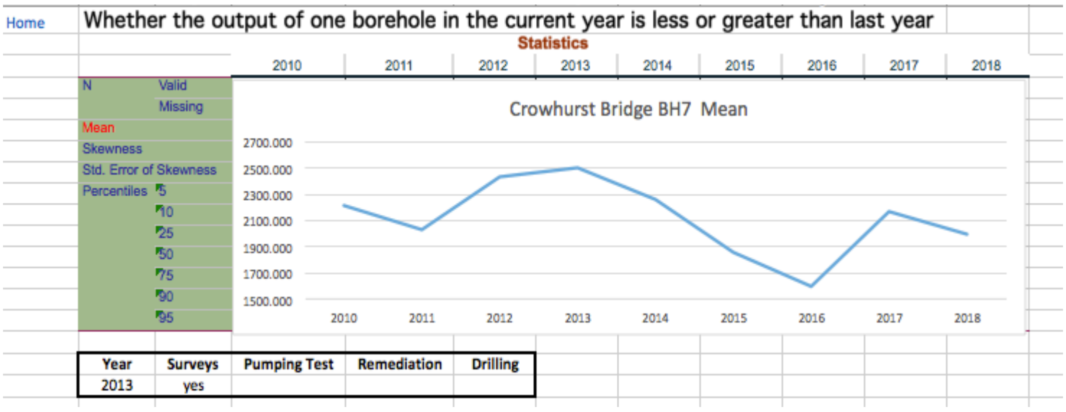


Figure 5.2.15: Crowhurst bridge BH7 analysis

O. Witherenden Analysis

Witherenden experienced a decreasing trend in its flow output over the years. The latest survey performed at this borehole is in 2011, as shown in Figure 5.2.16 below:

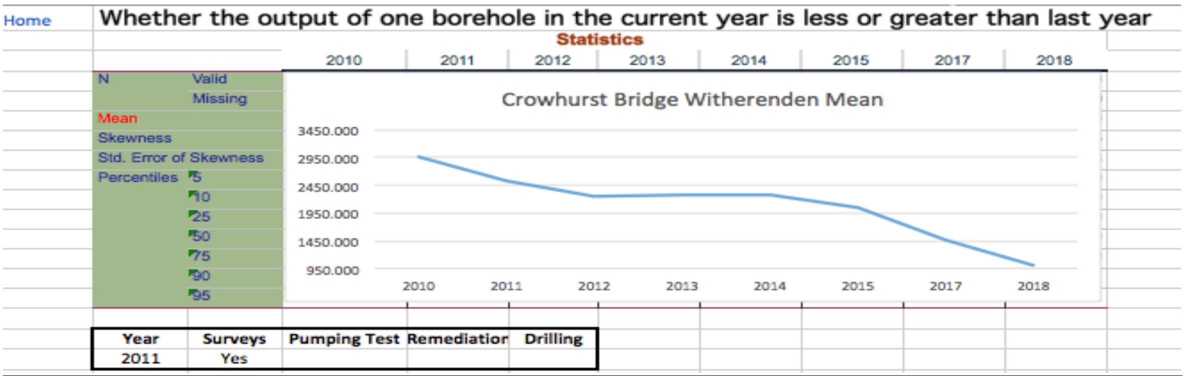


Figure 5.2.16: Witherenden analysis

P. Groombridge BHP1 Analysis

Groombridge BHP1 experienced a sharp decrease in its flow output in 2017, but then gradually increased in 2018. The latest surveys performed at this borehole are in 2000 and 2011, as shown in Figure 5.2.17 below:

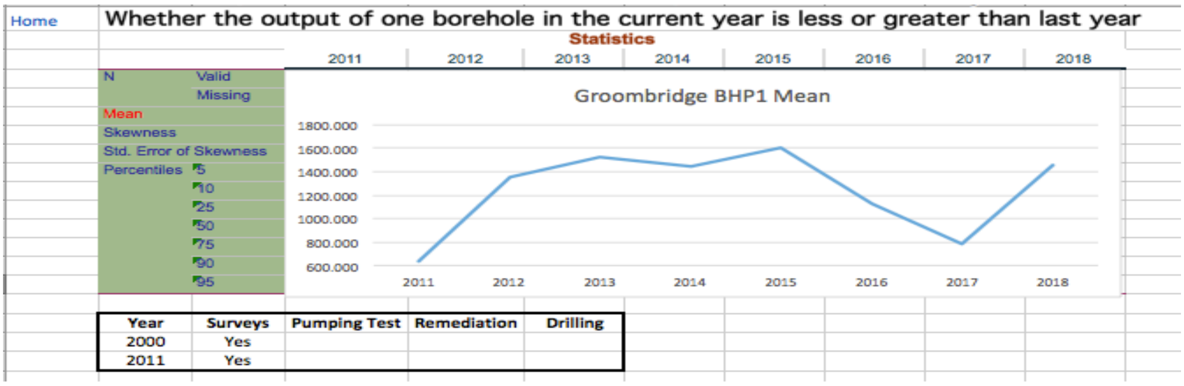


Figure 5.2.17: Groombridge BHP1 analysis

Q. Groombridge BHP2 Analysis

Groombridge BHP2 experienced a sharp increase in its flow output in 2012, but then gradually decreased. The latest survey performed at this borehole is in 2013, as shown in Figure 5.2.18 below:

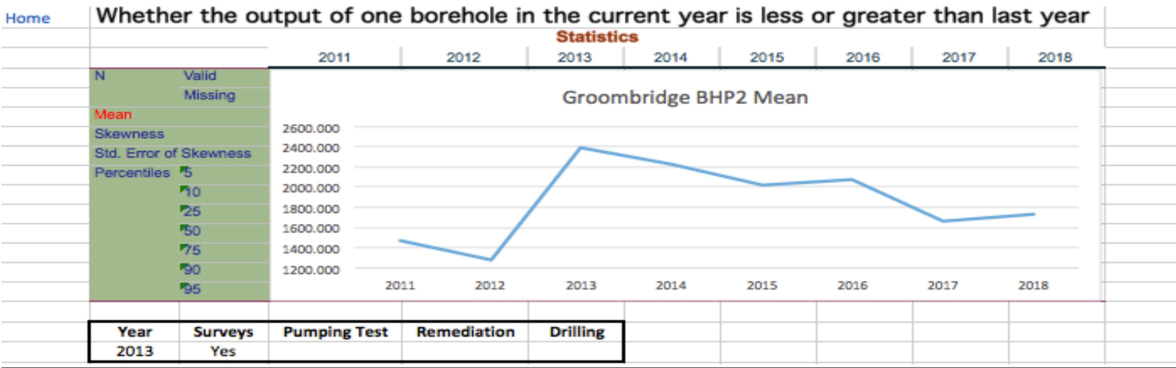


Figure 5.2.18: Groombridge BHP2 analysis

R. Groombridge BHP3 Analysis

Groombridge BHP 3 experienced a sharp decrease in its flow output in 2015, but then gradually increased. The latest survey performed at this borehole is in 2000, as shown in Figure 5.2.19 below:

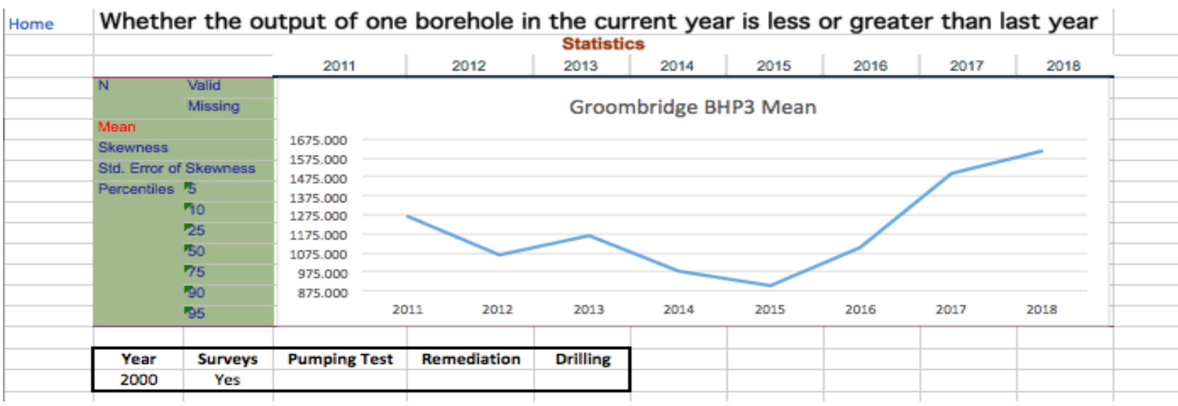


Figure 5.2.19: Groombridge BHP3 analysis

S. Eridge Analysis

Eridge experienced a sharp increase in its flow output in 2013, but then gradually decreased. The latest survey performed at this borehole is in 2000, as shown in Figure 5.2.20 below:

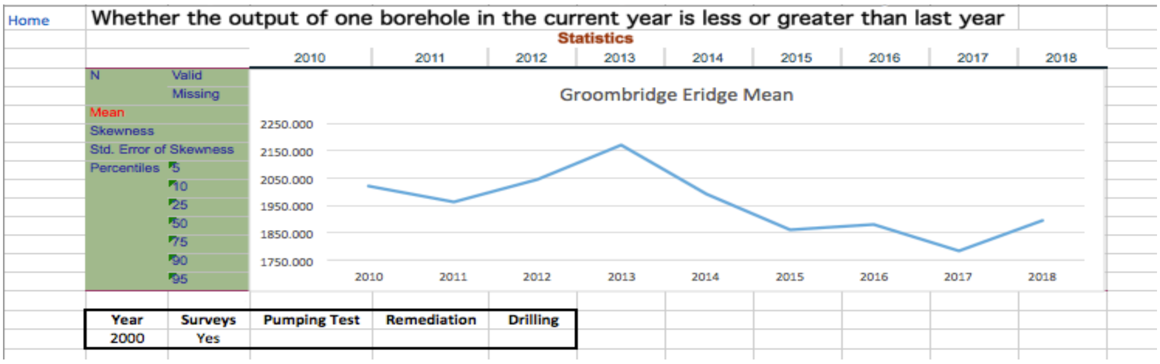


Figure 5.2.20: Eridge analysis

T. HelpSheet

This worksheet will provide detailed explanations of each tab in the borehole model decision support system, as shown in Figure 5.2.21. It will also explain the main column and rows that are important for the user's understanding.

Home	This worksheet allows the user to nativate quickly through the pages in this spreadsheet. Simply click on the page that you wish to visit
Dashboard	The dashboard allows the user to select the reports they would like to display, while also providing a summary of the findings.
Overall_Loss_Analysis	This worksheet provides an analysis of the overall loss % for all the boreholes from 2010 to 2018.
SweetWillowBH3	This worksheet analyses whether the output of SweetWillow BH3 is greater or less over the years and it also the changes in the water flow from 2010 to 2018
SweetWillowBH4	This worksheet analyses whether the output of SweetWillow BH4 is

Figure 5.2.21: Helpsheet for borehole model

CHAPTER 6. CONCLUSION AND RECOMMENDATIONS

6.1 Conclusions

This thesis conducted a comprehensive literature review on reliability modelling with a focus on water asset management. Data on the failures of vehicles and boreholes were then collected from the project funder, South East Water and analysed. An MS-Excel decision support system was developed, whereby its main findings include

- On the transport model, it can be seen that vans in the distribution department have a slightly higher cost and miles when compared to the ones in the production department.
- On the borehole models, it can be seen that the top four worst performers are Sweet Willow BH4, Goudhurst BH13, Powdermill BHP1 and Witherenden. These boreholes are experiencing a sharp decrease in their flow output.

6.2 Recommendations

One specific solution in order to understand why the four boreholes mentioned above are performing poorly when compared to the other boreholes is to do a survey at each borehole. For example, a pumping test can be performed in order to determine how productive the borehole is. This test will also establish whether the water flowing out of the borehole is meeting the consumers' expectations. This pumping test will enable South East Water to evaluate the performance of the boreholes.

Another solution to know why these four boreholes are experiencing a severe loss in their flow output is to perform a borehole remediation. This procedure will test the reliability and efficiency of the boreholes throughout their operational life. For example, one example of why a borehole might be performing poorly is that there might be iron build-ups on the boreholes' pumps, and this might be solved using a borehole remediation techniques such as make use of chemicals to clean up the borehole in order to improve its performance.

It is said *that data is golden assets*. Nevertheless, it seems that data collection may be improved in South East Water. On both projects, we found that many data that could be collected are unavailable. The data may be on some computers but need collecting and collating.

This project developed a decision support system in order to answer the six research questions. However, the lack of data made it impossible to answer the first and second research question.

The data collected for the transport model have been able to generate the following findings:

- The operating expenditure (OPEX) of the vehicles,
- The capital expenditure (CAPEX) of the vehicles,
- The total cost per mile for each department,
- A comparison between the cost of operating a vehicle in two different department and
- The whole life cost for the different vehicle models (Research Question 3).

However, the data provided by South East Water are not enough to answer the first and second research question. Therefore, for future modelling and optimisation, that is to know the optimum point to replace a vehicle, the following data would be useful for the Transport Model:

1. Time to each failure and miles to each failure of a vehicle
2. Failure mode: what caused each failure
3. Cost of repair
4. Time of preventive maintenance and its associated cost
5. Type of repair/preventive maintenance

With these above data, an optimum replacement regime can be produced. In other words, we will be in a position to find the optimum replacement age or miles for a vehicle model (Research Question 1 and 2).

The decision support system for the borehole project, designed by using the data provided by South East Water, have provided the following findings:

- Average flow output of each borehole,
- Percentage loss in flow of each borehole,
- Overall water loss percentage,
- A comparison between the flow and water level of a borehole,

- The year in which a survey were performed in each borehole, and
- An evaluation of each borehole's performance.

This project has been able to answer the three research questions (Research Question 4, 5 and 6) for the borehole model.

However, if the following data are collected without any errors being generated, a more sophisticated model can be built for the borehole model:

1. Water level
2. Flow output
3. Types and details of maintenance
4. Associated maintenance costs

For example, a maintenance policy based on the gamma process may be developed to find the optimum intervention time for a borehole.

Therefore, it is can be concluded that South East Water need to start collecting more data, as mentioned above, and also, reduce the errors in their current data collection system, in order to allow future researchers to design more sophisticated measures and models that will enable them to run their company more efficiently.

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APPENDICES

Appendix 1 – Optimum Replacement Age

```
Sub Opt_age()

Dim numCOL, finalalpha1, finalbeta1  As Integer
Dim numVehicles As Integer
Dim LastCol As Long
Dim numServices_of_Vehicle As Long
Dim totalnumServices As Integer
Dim alpha1() As Double
Dim beta1() As Double
Dim TbetweenF() As Double
Dim middlevalue As Double
Dim k As Integer
Dim h As Double
Dim TtoF() As Double ' time to failure
Dim a As Integer 'to represent number of vehicles
Dim sum01 As Double 'T power by beta1
Dim sum02 As Double 'T power by beta1 times ln T
Dim sum03 As Double 'ln(ti,j)
Dim nrows() As Integer 'number of rows for each vehicle
Dim b As Integer 'using in for-loop of sum03
Dim c As Integer 'using in for-loop of sum03
'Dim t(100, 100) As Double 'the small t in eq.2
Dim e As Double 'using to calculate ln
Dim selectedbeta As Double
Dim selectedalpha As Double
Dim costReplacement, costService As Integer
Dim opt_replacement_age As Double

'READ DATA

Worksheets("Age").Activate

numCOL = ThisWorkbook.Sheets("Age").Cells(1, Columns.Count).End(xlToLeft).Column 'to read the number of vehicles
numVehicles = numCOL

MsgBox ("Number of Vehicles =") & numVehicles - 1


With ActiveSheet
    LastCol = .Cells(1, Columns.Count).End(xlToLeft).Column 'to read the number of the filled cells in each column

    For i = 2 To LastCol
      numServices_of_Vehicle = ActiveSheet.UsedRange.Rows.Count '.Cells(Rows.Count, i).End(xlUp).Row   'I as variable column Number
      totalnumServices = totalnumServices + WorksheetFunction.Sum(numServices_of_Vehicle)
    Next i
```

```
MsgBox ("totalnumServices =") & totalnumServices
End With

ReDim TtoF(numVehicles)
ReDim nrows(numVehicles)
ReDim t(numVehicles, 100)

' store everything TtoF (last row of each vehicle), nrows (for the small t) and small t values
a = 1 'to count the correct amount of columns

With Range("A1")

For i = 2 To numVehicles

Cells(1, i).Select

'checking whether there is the cell value in the following cell or not

If IsEmpty(ActiveCell.Offset(1, 0)) = False Then

TtoF(a) = ActiveCell.End(xlDown).Value 'reading the last value in each column --> Time to Failure
'MsgBox ("TtoF(a)=") & TtoF(a)
nrows(a) = Range(ActiveCell, ActiveCell.End(xlDown)).Rows.Count 'number of rows in columns
'MsgBox ("nrows(a) =") & nrows(a)

   For b = 2 To numVehicles
      For c = 1 To nrows(a)

      t(b, c) = Cells(c, b).Value 't(i,j) --> reading each cells in every row and column
      'MsgBox ("t(b, c)=") & t(b, c)
      Next c
   Next b

Else

'if there is no following after the selected cell

TtoF(a) = ActiveCell.Value

'MsgBox ("TtoF(a)=") & TtoF(a)

nrows(a) = 1

t(a, 1) = Cells(1, a).Value
'MsgBox ("t(a, 1)=") & t(a, 1)

End If

a = a + 1

Next i
```

```
End With

'///--///
'calculation bit

ReDim beta1(800)
ReDim alpha1(800)
ReDim TbetweenF(800)

'using the big number so that the first answer will be stored no matter how much is it
middlevalue = 1000000
selectedbeta = 0
selectedalpha = 0


h = 0 'for the step 0.02
e = 2.718 ' e equals to 2.718 regarding mathematics

For k = 1 To 800 ' the number of beta1 from 0.01 to 4

beta1(k) = 0.005 + h

   sum01 = 0
   sum02 = 0
   sum03 = 0

   For i = 1 To numVehicles - 1

      sum01 = sum01 + (TtoF(i) ^ beta1(k)) 'summation bit from the first eq
      'MsgBox ("sum01 =") & sum01
      sum02 = sum02 + ((TtoF(i) ^ beta1(k)) * Math.Log(TtoF(i))) 'summation bit from the second eq.
      'MsgBox ("sum02=") & sum02

   Next i

   a = 1
      For b = 2 To numCOL
         For c = 1 To nrows(a)

         sum03 = sum03 + Math.Log(t(b, c)) 'summation bit from the second eq.
         'MsgBox ("sum03=") & sum03
         Next c
         a = a + 1
      Next b

   alpha1(k) = totalnumServices / sum01   'Equation1

   TbetweenF(k) = Abs(beta1(k) - (totalnumServices / ((alpha1(k) * sum02) - sum03)))  'Equation2

   'checking the value to find the minimum one
```

```
    If TbetweenF(k) < middlevalue Then

    middlevalue = TbetweenF(k)
    selectedbeta = beta1(k)
    selectedalpha = alpha1(k)

    Else
    middlevalue = middlevalue
    selectedbeta = selectedbeta
    selectedalpha = selectedalpha

    End If

    h = h + 0.005
Next k

   'MsgBox ("selectedbeta  is " & selectedbeta)
   'MsgBox ("selectedalpha  is " & selectedalpha)
'print out the minimum one
'MsgBox ("the minimum TbetweenF is" & current_answer)

'///--///

'finding the t*

Dim response1 As Integer
Dim optimal_1 As Double

response1 = InputBox("Enter the cost of replacement for the vehicle:")

If response1 > 0 Then

costReplacement = response1


ElseIf response1 <= 0 Then

MsgBox "Please enter a cost higher than 0!"

response1 = InputBox("Enter the cost of replacement for the vehicle:")
costReplacement = response1

End If

'MsgBox ("cost entered: " & costReplacement)

costService                                                          =
WorksheetFunction.Average(Worksheets("ServiceRepair").Range("A4:A36"))

'MsgBox ("cost entered: " & costService)

If selectedbeta <= 1 Then
```

```
MsgBox ("The failure rate is decreasing, which implies the number of failures of your product (e.g., vehicles) becomes fewer in time. Hence there is no need to find optimal age/mileage")

Else
opt_replacement_age = (costReplacement / (costService * selectedalpha * (selectedbeta - 1))) ^ (1 / selectedbeta)
optimal_2 = WorksheetFunction.RoundDown(opt_replacement_age, 2)
MsgBox ("opt_replacement_age is " & optimal_2 & "days")
End If

End Sub
```

Appendix 2 – Optimum Replacement Miles

```
Sub Opt_Miles()

Dim numCOL, finalalpha2, finalbeta2  As Integer
Dim numVehicles As Integer
Dim LastCol As Long
Dim numServices_of_Vehicle As Long
Dim totalnumServices As Integer
Dim alpha2() As Double
Dim beta2() As Double
Dim TbetweenF() As Double
Dim middlevalue As Double
Dim k As Integer
Dim h As Double
Dim TtoF() As Double ' time to failure
Dim a As Integer 'to represent number of vehicles
Dim sum01 As Double 'T power by beta1
Dim sum02 As Double 'T power by beta1 times ln T
Dim sum03 As Double 'ln(ti,j)
Dim nrows() As Integer 'number of rows for each vehicle
Dim b As Integer 'using in for-loop of sum03
Dim c As Integer 'using in for-loop of sum03
Dim t() As Double 'the small t in eq.2
Dim e As Double 'using to calculate ln
Dim selectedbeta As Double
Dim selectedalpha As Double
Dim costReplacement, costService As Integer
Dim opt_replacement_miles As Double

'READ DATA

Worksheets("Mileages").Activate

numCOL = ThisWorkbook.Sheets("Mileages").Cells(1, Columns.Count).End(xlToLeft).Column 'to read the number of vehicles
numVehicles = numCOL

MsgBox ("Number of Vehicles =") & (numVehicles - 1)
```

```
With ActiveSheet
      LastCol = .Cells(1, Columns.Count).End(xlToLeft).Column 'to read the
number of the filled cells in each column

      For i = 2 To LastCol
        numServices_of_Vehicle = ActiveSheet.UsedRange.Rows.Count
'.Cells(Rows.Count, i).End(xlUp).Row   'I as variable column Number
      totalnumServices = totalnumServices +
WorksheetFunction.Sum(numServices_of_Vehicle)
      Next i
MsgBox ("totalnumServices =") & totalnumServices
End With

ReDim TtoF(numVehicles)
ReDim nrows(numVehicles)
ReDim t(numVehicles, 100)

' store everything TtoF (last row of each vehicle), nrows (for the small t) and small t
values
a = 1 'to count the correct amount of columns

With Range("A1")

For i = 2 To numVehicles

Cells(1, i).Select

'checking whether there is the cell value in the following cell or not

If IsEmpty(ActiveCell.Offset(1, 0)) = False Then

TtoF(a) = ActiveCell.End(xlDown).Value 'reading the last value in each column
'MsgBox ("TtoF(a)=") & TtoF(a)

nrows(a) = Range(ActiveCell, ActiveCell.End(xlDown)).Rows.Count 'number of
rows in columns
'MsgBox ("nrows(a) =") & nrows(a)

   For b = 2 To numVehicles
      For c = 1 To nrows(a)

      t(b, c) = Cells(c, b).Value 't(i,j) --> reading each cells in every row and column
      'MsgBox ("t(b, c)=") & t(b, c)
      Next c
   Next b

Else

'when there is no following values after the selected cell

TtoF(a) = ActiveCell.Value

'MsgBox ("TtoF(a)=") & TtoF(a)
```

```
nrows(a) = 1

t(a, 1) = Cells(1, a).Value
'MsgBox ("t(a, 1)=") & t(a, 1)

End If

a = a + 1

Next i

End With

'///--///
'calculation bit

ReDim beta2(200)
ReDim alpha2(200)
ReDim TbetweenF(200)


middlevalue = 1000000
selectedbeta = 0
selectedalpha = 0


h = 0 'for the step 0.02

For k = 1 To 200 ' the number of beta1 from 0.01 to 4

beta2(k) = 0.01 + h

   sum01 = 0
   sum02 = 0
   sum03 = 0

   For i = 1 To numVehicles - 1

      sum01 = sum01 + (TtoF(i) ^ beta2(k)) 'summation bit from the first eq
      'MsgBox ("sum01 =") & sum01
      sum02 = sum02 + ((TtoF(i) ^ beta2(k)) * Math.Log(TtoF(i))) 'summation bit
from the second eq.
      'MsgBox ("sum02=") & sum02

   Next i

   a = 1
      For b = 2 To numVehicles - 1
         For c = 1 To nrows(a)

         sum03 = sum03 + Math.Log(t(b, c)) 'summation bit from the second eq.
         'MsgBox ("sum03=") & sum03
         Next c
         a = a + 1
```

```
      Next b

   alpha2(k) = totalnumServices / sum01   'Equation1

   TbetweenF(k) = Abs(beta2(k) - (totalnumServices / ((alpha2(k) * sum02) -
sum03)))  'Equation2

   'checking the value to find the minimum one
   'Print out; the; minimum; one
   'MsgBox ("the minimum TbetweenF is" & TbetweenF(k) )

   If TbetweenF(k) < middlevalue Then

   middlevalue = TbetweenF(k)
   selectedbeta = beta2(k)
   selectedalpha = alpha2(k)

   Else
   middlevalue = middlevalue
   selectedbeta = selectedbeta
   selectedalpha = selectedalpha

   End If

   h = h + 0.02
Next k

  'MsgBox ("selectedbeta  is " & selectedbeta)
   'MsgBox ("selectedalpha  is " & selectedalpha)

'///--///

'finding the t*

Dim response1 As Integer
Dim optimal_1 As Double

response1 = InputBox("Enter the cost of replacement for the vehicle:")

If response1 > 0 Then

costReplacement = response1


ElseIf response1 <= 0 Then

MsgBox "Please enter a cost higher than 0!"

response1 = InputBox("Enter the cost of replacement for the vehicle:")
costReplacement = response1

End If

'MsgBox ("cost entered: " & costReplacement)
```

```
costService =
WorksheetFunction.Average(Worksheets("ServiceRepair").Range("A4:A36"))

'MsgBox ("cost entered: " & costService)

If selectedbeta <= 1 Then
MsgBox ("The failure rate is decreasing, which implies the number of failures of
your product (e.g., vehicles) becomes fewer in time. Hence there is no need to find
optimal age/mileage")

Else

opt_replacement_miles = (costReplacement / (costService * selectedalpha *
(selectedbeta - 1))) ^ (1 / selectedbeta)
optimal_1 = WorksheetFunction.RoundDown(opt_replacement_miles, 2)

MsgBox ("opt_replacement_miles is " & optimal_1 & "miles")

End If
End Sub
```