University of Southern Queensland

Faculty of Sciences and Engineering

A Reliability Centered Maintenance program incorporating probabilistic based simulation

A dissertation submitted by

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Abstract

This research project aims to outline the current literature regarding existing Reliability Centered Maintenance (RCM) methodology and to use this methodology as a foundation for implementing RCM in the development of Preventative Maintenance (PM) programs for on-road vehicle fleets. RCM processes are centered on qualitative data and do not readily consider the available quantitative data. The use of probabilistic modelling allows for the consideration of quantitative data which may allow for a more well-rounded PM programming. The reviewed literature points to the importance of integrating quantitative data into the RCM process.

The data for the current project was obtained from maintenance records, failure records and component failure analysis reports and in consultation with subject matter experts (SME). A hybrid RCM methodology was then applied as guided by the literature to include quantitative data. This process includes the use of probabilistic methods of analysis to forecast and develop a number of preventative maintenance plans. The hybrid methodology was adapted into a 11-step process to allow for ease of use.

These results ultimately provide the utility company with the ability to perform an RCM analysis and to gain a quantitative output on how to model and forecast PM programs. This will further allow for more fluid and informed maintenance decisions to be made in similar fields and recommendations to be made for the application of a modified RCM methodology. There was a realization that the probabilistic modelling not only assisted in the modelling of the systems and components, but it could also assist in the assessment of organisational processes. Modelling outcomes of the organisational process meant that there was greater flexibility in cost savings when the options of maintenance were limited.

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Signature

October 22, 2020

Date

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Nomenclature

Cooling system	Responsible for the dissipation of rejected heat energy from the engine
Criticality	Considers failure effect, worst case probability and MTTF
Diesel particulate filter (DPF)	In an exhaust after treatment system used to eliminate diesel particulate matter generated by the combustion process in diesel engines
Essential or primary function	The intended purpose of the asset and why it was acquired, commonly defined by issues such as carrying or storing capacity, lifting capability, speed, output
Exhaust gas recirculation (EGR)	System used to dilute the intake air charge with "dead" gas in an effort to reduce the Oxides of Nitrogen emission by lowering combustion heat
Failure cause	Typically, one or more components fail resulting in MSI failure
Failure mechanism	Typically, one or more mechanisms of each failure cause
Failure mode	The way in which failure occurs
Functional failures	Identifying all of the failed states associated with each function
Functional Significant Items (FSIs)	Analysis items that are critical with respect to the functional failures
Gauges and indicators	Functional failures related to gauges and indicators revolve around protection and control of the asset
Hidden-failure consequences	Those which have no direct impact, but increase the likelihood of a multiple failure
Information functions	Condition monitoring functions (i.e. alarms)
Interface functions	Functions of the interface between the item and other items

Maintenance cost significant items (MSI) and systems	Items/systems with high failure rates, high repair costs, low maintainability, long lead times for spare parts or external maintenance
MATLAB	Is a multi-paradigm numerical computing environment
Mean time between failure (MTBF)	Predicted average elapsed time between inherent failures
Mean time to failure (MTTF)	Average amount of operation time of an asset before failure
% MTTF	Marginal MTTF for each failure mechanism
Mean time to repair (MTTR)	Average amount of time to repair failed component
Monte-Carlo	Used to model the probability of different outcomes
Non-operational consequences	Those which involve only the direct cost of repair
Off-line functions	Intermittent or infrequent use
On-line functions	Operations occurring continuously or often
On-condition maintenance	Are done so because the individual unit is remains in service 'on the condition' that it keeps meeting the relevant standards
Operating context	An asset fails to fulfil its function in its operating contexts it is considered the definition of a functional failure, this is why it is important to define the operating context precisely
Operational consequences	Those which involve an indirect economic loss as well as the direct cost of repair
Partial and total failure	This relates to a complete or partial loss of function
Preventative Maintenance (PM)	Maintenance performed on a component that helps prevent failure
Proactive tasks	Undertaken before a failure occurs with the objective of preventing a failed state from occurring
Protective functions	Intended to protect people, equipment and environment
Recommended maintenance interval	The interval between maintenance task

Safety consequences	Those which involve possible loss of the equipment and its occupants
Schedule restoration tasks	Are often assigned to components where the probability of their failure becomes greater after a certain operating age and restoration restores the components resistance to failure
Secondary or auxiliary functions	Functions that are required to support essential/primary functions, such as comfort, safety, environmental compliance, efficiency, protection
Subject matter expert (SME)	Individual with expertise in a specific subject
Superfluous functions	Items designed for a context different than the context of actual operation
System	A set of components or subsystems that provide a fundamental function for the plant operation
Upper and lower limits	Assets sometimes incorporate upper and lower limits; these limits need to be treated separately if a functional failure has occurred
Worst case probability	Probability of worst-case outcome regarding equipment failure

Chapter 1

Introduction

1.1. Chapter Overview

This chapter provides an overview of the project through a discussion of the aims and objectives as well as the scope of the project and the expected outcomes.

1.2. Research Aims and Objectives

This project aims to establish a modified maintenance assessment and optimization program for on-road vehicle fleets by incorporating probabilistic methods of analysis into traditional and existing Reliability Centered Maintenance (RCM) methodology. It will assist in providing a more efficient Preventative Maintenance (PM) program with the potential to reduce costs of service.

The following objectives have been proposed to achieve these aims:

- To conduct a review of the literature relevant to RCM, probabilistic modelling and optimization
- To develop and identify a method of identifying changing maintenance requirements
- To identify areas of weaknesses and opportunities within the data from the company's maintenance system
- To identify the system and or sub-systems for study, the failure modes and their consequences, data collection and choosing models in cooperation with subject matter experts
- To identify the maintenance plans with high probability of producing best reliability in the future, based on the past data and using optimization tools and acceptable models
- To translate, present and discuss the results and benefits of such RCM
- To present technical details encountered in design, set up and the operation of a Hybrid RCM Program in a large public utility company

1.3. Project Feasibility Analysis and Justification

RCM processes are centered on qualitative data and do not readily consider the quantitative data that is often available. Rausand (1998, p. 121) outlined a more rigorous progress which seeks to integrate the qualitative and quantitative data to provide a better-rounded PM program as a result of the RCM process. Few have implemented this process despite the benefits of a more complete approach.

This project will seek to begin to lessen the gap between the known reliable processes for developing a PM program and what is currently occurring in existing maintenance systems. The literature will be used as a guide to identify weakness and opportunity within the available data for optimization of fleet maintenance programs.

Based on the existing literature, this project is justified based on the lack of implementation of the RCM process to its full capacity and is feasible in the utility company setting as the required data is already being obtained and is available for analysis and evaluation to create a more effective PM program. Further to the completion of the study, the implementation of the RCM process will have occurred and will allow for identification of short falls as well as effective steps in the process. As well, it will provide a foundation for other similar companies to implement the RCM process.

1.4. Project Scope

The scope of this project is to provide a theoretical foundation for implementation of an RCM program to the fleet of a public utility company using actual data and modelling programs. The real time implementation will be limited as the maintenance plans generally take time to implement while it must consider a company's many operating objectives in addition to the technical specifications required, as a result this is considered a limitation to the project.

1.5. Outcomes and Benefits

RCM is an established methodology, used in many industries to preserve the state of the asset. A modified RCM, based on the literature, will be the primary methodology used in this project. The researcher seeks to improve upon the RCM process by integrating probabilistic modelling into the RCM methodology. This is an opportunity to look critically at the existing RCM process and literature suggestions on the integration of more quantitative data to the process.

The expected outcomes of the project include:

- Improved understanding of suitability of the data currently obtained in a company's maintenance system for completing the RCM process and developing a PM plan
- Increased understanding of the RCM process with the integration of quantitative data through probabilistic modelling
- Improved understanding of how the enhanced RCM process may be applied in the practical setting of fleet maintenance management
- Further develop the knowledge around the design, set up and completing of a hybrid RCM program

The benefits of the above outcomes will lend further knowledge to the industry to assist in creating more effective PM plans based on the expanded RCM process. The project is meant to lay the foundation for future research on the implementation of this expanded hybrid RCM process to further optimize PM planning.

1.6. Chapter Summary

This chapter has outlined the aims and objectives, scope of the project and the expected outcomes of the current project on expanding the RCM process and optimizing PM planning. The subsequent chapters will provide the foundation of the research through a review of the literature, methodology, analysis and discussion of the project findings.

Chapter 2

Literature Review

2.1 Chapter Overview

A literature review was conducted on the topic of Reliability Centered Maintenance (RCM) with a focus on the use of peer reviewed literature to outline it's use in various industries and to define and explain the RCM methodology. A summary is then provided of potential methods of data analysis that may be considered for the project data. This is followed by an outline of probabilistic modelling which can be used to repetitively evaluate a deterministic model using sets of random numbers as inputs. Despite the current literature and awareness around RCM, the processes are not being implemented to the full capacity in the selected public utility company, thus there is a need to provide guidance on the implementation of a RCM program.

2.2 Reliability Centered Maintenance (RCM) Defined

Reliability Centered Maintenance (RCM) is a method for developing maintenance practices aimed at improving the reliability of a system or asset within the scope of a particular operating context as defined by the asset owner. Developed in the aviation industry to address deficiencies in scheduled maintenance programs, RCM has become one of the standard techniques used for developing PM programs in a variety of industries (Rausand 1998, p. 121). The airline industry had observed that the traditional approach to PM, which was to assume that every item on a piece of equipment has a 'right age' required for overhauling, was not sufficient at preventing failures (Moubray 2001, p. 318). The American Federal Aviation Agency who was responsible for regulating maintenance practices became concerned that controlling failure rates through content or frequency of scheduled overhauls was not possible (Moubray 2001, p. 319). This realization led to a joint task force being formed to investigate the capabilities of PM. The task force aimed to analyze the factors that affect reliability and when low reliability levels were identified, provide a system of actions that would rectify low reliability (Deshpande & Mahant 2013, p. 177, Moubray 2001, p. 319).

Standards Australia (2011) describes RCM as "a method to identify and select failure management policies to efficiently and effectively achieve the required safety, availability and economy of operation". Moubray (2001, p. 7), states that a fuller definition of RCM could be "a process used to determine what must be done to ensure that any physical asset continues to do whatever its users want it to do in its present operating context". Further, Rausand (1998, p. 121) describes RCM as "a systematic consideration of system functions, the way functions can fail, and a priority-based consideration of safety and economics that identifies applicable and effective PM tasks".

At the core of the RCM methodology are the seven questions about the asset or system under review (Moubray 2001, p. 7, Rausand 1998, p. 122).

1. What are the functions and associated performance standards of the asset in its present operating context?
2. In what ways does it fail to fulfil its functions?
3. What causes each functional failure?
4. What happens when each failure occurs?
5. In what ways does each failure matter?
6. What can be done to predict or prevent each failure?
7. What should be done if a suitable proactive task cannot be found?

Whilst RCM has proven to be a significant tool in many industries that seek to improve their maintenance programs and improve uptime, there are naturally limitations to the process. The researcher has identified what they see as gaps or weaknesses in the RCM methodology. RCM tends to rely largely on qualitative input as a way of analysing and making decisions along the process, whilst this has been an obvious success, integrating a form of quantitative analysis could be beneficial to an RCM program.

Moubray (2001, p. 253) suggests that in the absence of actuarial data the questions must be answered based on judgement and experience. This judgement and experience are knowledge gained from experience in the field of work which is based on the data the individual recalls. Having a mechanism which allows the RCM group to explore the human judgement and experience aspect of data could aid in the decision process for a maintenance plan. Rausand (1998, p. 130) states that one of the problematic steps in the RCM process is the selection of maintenance intervals, noting that this step relies on several probabilistic concepts which can be difficult to fully understand and interpret. Rausand (1998, p. 130) also notes that through the other steps of the RCM process, the practitioners may realize the importance of using models and data to select optimal intervals. For example, the question, 'what can be done to predict or prevent each failure?' has been identified as a question that could potentially be enhanced by probabilistic modelling. Developing an effective RCM program lies in effectively combining the intuitive and statistical approaches (Baird & Chalifoux 1999, p. 14).

2.2.1 RCM Objectives

The chief objectives of RCM are to realize the inherent reliability capabilities of equipment and to preserve an assets specific function or functions through a systematic process. This process is capable of creating an effective maintenance system that:

- Has greater maintenance cost effectiveness
- Improves operating performance
- Enables a longer useful life of expensive items
- Creates a comprehensive database
- Ensures greater safety and environmental integrity (Moubray 2001, p. 312-314, Nowland & Heap 1978, p. 2)

Many company's employ maintenance plans that are a combination of manufacturer's recommendations, a company's standards and historical data. If a maintenance program has already been created, the purpose of performing an RCM analysis is often to eliminate inefficient PM tasks (Moubray 2001, p. 19).

2.2.2 Reliability-Centered Maintenance Methodology

The seven basic questions, noted above, provide a general outline of the RCM analysis; however, this project intends to provide a hybrid methodology that consists of RCM and probabilistic modelling. Rausand (1998, p. 122) outlines a more detailed approach to using an RCM analysis in a sequence of activities as follows:

1. Study Preparation
2. System selection and definition

3. Functional failure analysis (FFA)
4. Critical item selection
5. Data collection and analysis
6. Failure modes, effects and criticality analysis (FMECA)
7. Selection of maintenance actions
8. Determination of maintenance intervals
9. Preventative maintenance comparison analysis
10. Treatment of non-critical items
11. Implementation
12. In-service data collection and updating

Each of these steps are discussed in detail below.

2.2.2.1 Step 1: Study Preparation

The RCM process is best served when it is carried out by a project or review group, this is necessary as it is not possible for one specific discipline to answer all questions alone (Moubray 2001, p. 17). A facilitator leads the group through the task of defining and clarifying the objectives and the scope of the analysis (Rausand 1998, p. 122). The facilitator is an individual who has been trained in RCM and whose role is to ensure the analysis is carried out at the right level with all system boundaries defined and ensures no important items have been overlooked (Moubray 2001, p. 17, Rausand 1998, p. 123). Due to time restrictions of the current project this step will not be completed to this depth. However, the analysis that is to be carried out will be well defined by the researcher.

2.2.2.2 Step 2: System Selection and Definition

Defining the level at which to analyze and the system to analyze is a critical step when performing and RCM analysis (Rausand 1998, p. 123). Smith & Hinchcliffe (2003, p. 75) describe the levels of analysis in four general categories:

- Part: the smallest component that can be disassembled from the equipment assembly without damage
- Component: an assembly of parts that perform a significant function

- System: a set of components or subsystems that provide a fundamental function for the plant operation
- Plant: an assembly of equipment that takes raw input materials and processes them into output products

It is recommended that an RCM analysis be carried out with the systems that would benefit most from analysis due to limitation in resources (Rausand 1998, p. 123). Rausand (1998, p. 123) recommends beginning analysis at the system level to assist in defining the performance standards. This is supported by Moubray (2001, p. 84) stating that it is easier to define functions and performance expectations as well as the failure consequences.

2.2.2.3 Step 3: Functional Failure Analysis (FFA)

The general role of an asset is that the asset owner requires it to do something, many maintenance specialists incorrectly believe that preventative maintenance is all about preserving the inherent reliability or built in capability of any asset. The role of an asset in the business operating environment is an important fact and as a result when an asset is maintained, "the state which we wish to preserve must be one in which it continues to do whatever its users want it to do" (Moubray 2001, p. 21).

After the selection of a specific system in the previous step, Rausand (1998, p. 123) recommends the functional failure analysis be determined by three objectives:

1. *Identify and describe the system's required functions and performance criteria.*
   It is important to identify all of the system's functions to ensure a successful RCM analysis. Moubray (2001, p. 8) suggests defining primary and secondary functions in contrast to Rausand (1998, p. 123) who proposes defining a system or asset by eight separate functions.

   The classification of functions acts as a checklist.

   - Essential or primary function: the intended purpose of the asset and why it was acquired, commonly defined by issues such as carrying or storing capacity, lifting capability, speed, output

- Secondary or auxiliary functions: functions that are required to support essential/primary functions, such as comfort, safety, environmental compliance, efficiency, protection (Moubray 2001, p. 8, Rausand 1998, p. 123)
- Protective functions: intended to protect people, equipment and environment
- Information functions: condition monitoring functions (i.e. alarms)
- Interface functions: functions of the interface between the item and other items
- Superfluous functions: items designed for a context different than the context of actual operation
- On-line functions: operations occurring continuously or often
- Off-line functions: intermittent or infrequent use (Rausand 1998, p. 123)

This step in the process frequently requires the greatest time commitment, sometimes up to a third of the total RCM analysis process (Moubray 2001, p. 8). The added positive of this step is that it challenges the team carrying out the analysis to study the assets functions sometimes in great detail and in the process end up learning a considerable amount about how the equipment works.

Netherton (2002, p. 63) describes the asset function description task as having four characteristics:

- The operating context is defined. This requires stating the relevant features of the environment in which the asset operates. The assets production targets, the features of the surrounding environment or whether the asset is operated continuously.
- Listing all primary, secondary and protective functions. Often an RCM process is carried out by focussing on the primary functions and not placing enough attention on the secondary and protective functions.
- Any statement which is used to describe the function should comprise of a verb, an object and a performance standard.
- The asset owner needs to define the performance standard relating to their operating context and not rely on the manufacturers stated performance standards.

2. *Describe input interfaces required for the system to operate.*
   System functions are divided into sub-functions on an increasing level of detail and input interfaces to a function are represented by block diagrams.

3. *Identify the ways in which the system might fail to function through functional failure analysis (FFA).*
   Functional failures are defined by the characteristic of identifying all of the failed states associated with each function. This is an important step as it allows the researcher to discover how the functions might fail and aims to identify all relevant functional failures (Rausand 1998, p. 124, Smith & Hinchcliffe 2003, p. 97). If the performance standards were defined well then, describing a functional failure should be a simple task (Netherton 2002, p. 63, Standards Australia 2011, pp. 21-22). These performance standards apply to individual functions, if this is done then (Moubray 2001, p. 47) describes a functional failure as "the inability of any asset to fulfil a function to a standard of performance which is acceptable to the user". A FFA worksheet may be used to record the identified functional failures (Rausand 1998, p. 124).

   There are differing views in the literature on how to classify failures. Rausand (1998, p. 124) classifies failures as sudden failures and gradual failures. Moubray (2001, p. 46) however discusses four different aspects of functional failure:
   1. Partial and total failure: this relates to a complete or partial loss of function
   2. Upper and lower limits: assets sometimes incorporate upper and lower limits; these limits need to be treated separately if a functional failure has occurred
   3. Gauges and indicators: functional failures related to gauges and indicators revolve around protection and control of the asset
   4. The operating context: an asset fails to fulfil its function in its operating contexts it is considered the definition of a functional failure, this is why it is important to define the operating context precisely

   Smith and Hinchcliffe (2003, p. 97) emphasize the loss of function, not the loss of equipment. The Standard SAE JA1011 states that functional failures in an RCM process has one characteristic, it identifies all of the failed states associated with each function (Nowland, 1978).

2.2.2.4 Step 4: Critical Item Selection

Critical item selection involves identifying Functional Significant Items (FSIs) which are the "analysis items that are critical with respect to the functional failures" (Rausand 1998, p. 125). FSIs in simple systems may be identified without the use of a formal analysis. However, in systems with increasing complexity or systems with redundancy there may be a need for a formal assessment. Reliability block diagrams, fault tree analysis or probabilistic modelling programs like Monte Carlo simulations may be suitable for analysing FSI within complex systems (Rausand 1998, p 125). The researcher will utilize Monte Carlo simulations to analyze FSIs in the current project.

Maintenance cost significant items (MSI) and systems are those with high failure rates, high repair costs, low maintainability, long lead times for spare parts or external maintenance are to be identified along with FSIs (Rausand 1998, p. 125).

2.2.2.5 Step 5: Data Collection and Analysis

Discussion of the literature regarding data collection and analysis is discussed below in Section 2.3.

2.2.2.6 Step 6: Failure Modes, Effects and Criticality Analysis (FMECA)

Using the MSIs determined in Step 4, dominant failure modes are identified and analysed by identifying the following:

- MSI
- Operational mode
- Function(s)
- Failure mode: the way in which failure occurs
- Effect of failure/severity class: ranked in four classes, Safety of personnel (S), Environmental impact I, Production availability (A), Material loss/cost (C)
- Worst case probability: probability of worst-case outcome regarding equipment failure
- MTTF
- Criticality: considers failure effect, worst case probability and MTTF
- Failure cause: typically, one or more components fail resulting in MSI failure
- Failure mechanism: typically, one or more mechanisms of each failure cause

- %MTTF: marginal MTTF for each failure mechanism
- Failure characteristic: gradual, aging or sudden failure
- Maintenance action: decision logic in Step 7 is used to determine appropriate maintenance action
- Failure characteristic measure: condition indicators are listed for gradual failures and aging parameter describe aging failures
- Recommended maintenance interval: determined in Step 8, the interval between maintenance tasks

Defining a Failure Mode

A failure mode is any event which can cause a functional failure, there may be one or more failure modes for each functional failure. An RCM process aims to identify all failure modes. One way to achieve this is to firstly list the failures and then record the failure modes which could cause each functional failure (Moubray 2001, pp. 53-54, Netherton 2002, p. 60). In describing the failure mode there should be enough detail to apply and appropriate failure management strategy but not so much detail that the analysis becomes excessive.

There are five important characteristics of failure modes that stem from an RCM process (Netherton 2002, p. 64):

1. The process identifies all failure modes that could likely cause each functional failure. The RCM working group should be careful not to list failure modes that cannot stand up to scrutiny.
2. The method used by the RCM group identifying failure modes should be in line with what is acceptable to the asset owner and the operating context.
3. When a failure mode is identified, it is required to be at an appropriate level. An appropriate level is one where an appropriate failure management policy can be implemented, that is, ones that are technically feasible and worth doing.
4. All failure modes need to be included; historical, present, those that are being prevented by maintenance and those that are reasonably likely to occur.

"Any event or process that is likely to cause a functional failure, including deterioration, design defects, and human error whether caused by operators or maintainers (unless human error is being actively addressed by analytical processes apart from RCM)" (Netherton 2002, p. 64). This statement by Netherton (2002, p. 64) encourages the investigation into a failure mode to be looked at from all aspects, not just once specific viewpoint such as design or maintenance.

Failure Effects

To assess whether a proposed maintenance action is worth doing it is necessary to understand what would occur if the failure took place, that is, to define the effects of the failure. Failure effects describe what happens when a failure occurs and failure consequences describes how the failure matters, it is important to distinguish between the two (Moubray 2001, p. 73, Netherton 2002, p. 62).

Two characteristics to describe the failure effects (Netherton 2002, p. 64) include:

1. A description of what would happen if no specific task were assigned to prevent or identify failure.
2. The description includes all required information to support the evaluation of the consequences of failure.

The first characteristic is to assist the RCM working group in determining if any task is required at all to prevent failure. It is not always the case that failures need to be prevented. For example, a household lightbulb, in almost all cases the bulb is allowed to fail as its failure effect is not severe.

The second characteristic is a description that allows the RCM working group to build a scenario of possible outcomes from the failure mode. This is information that will be used to determine if a failure effect has been developing for some time, if serious or fatal injury may occur, or if damage to the environment or hindered operations may occur (Netherton 2002, p. 64).

Failure Consequences

Netherton (2002, p. 67) states that, "the consequences of a failure determines the priority of the maintenance activities or design improvement required to prevent its occurrence".

Within the RCM methodology, the consequences of failure dictate the priority of the maintenance activities or the need for redesign. For serious failure consequences significant efforts will be taken to prevent the failure or to anticipate them, as opposed to minor consequences where little to no proactive action will be taken. The consequences of failure are taken to be more important than technical characteristics (Moubray 2001, p. 91, Netherton 2002, p. 67).

Both Moubray (2001, p. 91) and Netherton (2002, pp. 66-67) group failure consequences into the following four categories:

- Safety consequences: which involve possible loss of the equipment and its occupants
- Operational consequences: which involve an indirect economic loss as well as the direct cost of repair
- Non-operational consequences: which involve only the direct cost of repair
- Hidden-failure consequences: which have no direct impact, but increase the likelihood of a multiple failure

The following decision diagram may be used to help select the appropriate level of maintenance or repair.

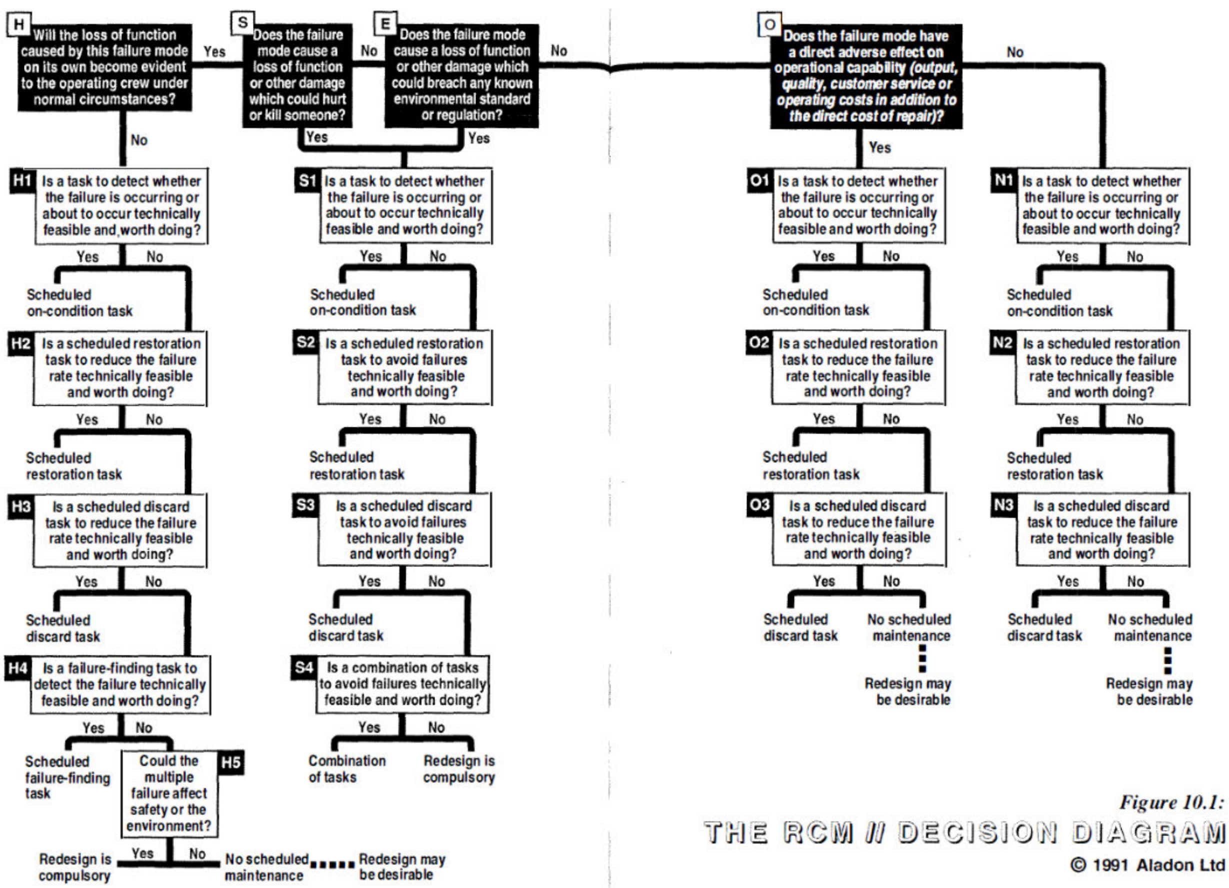

Figure 1: RCM Decision Diagram (Moubray 2001, pp. 200-201)

Standards Australia (2011, pp. 25-26) group failure consequences into the following categories:

- Evident, safety and environmental
- Evident, operational/economic
- Hidden, safety and environmental
- Hidden, operational/economic

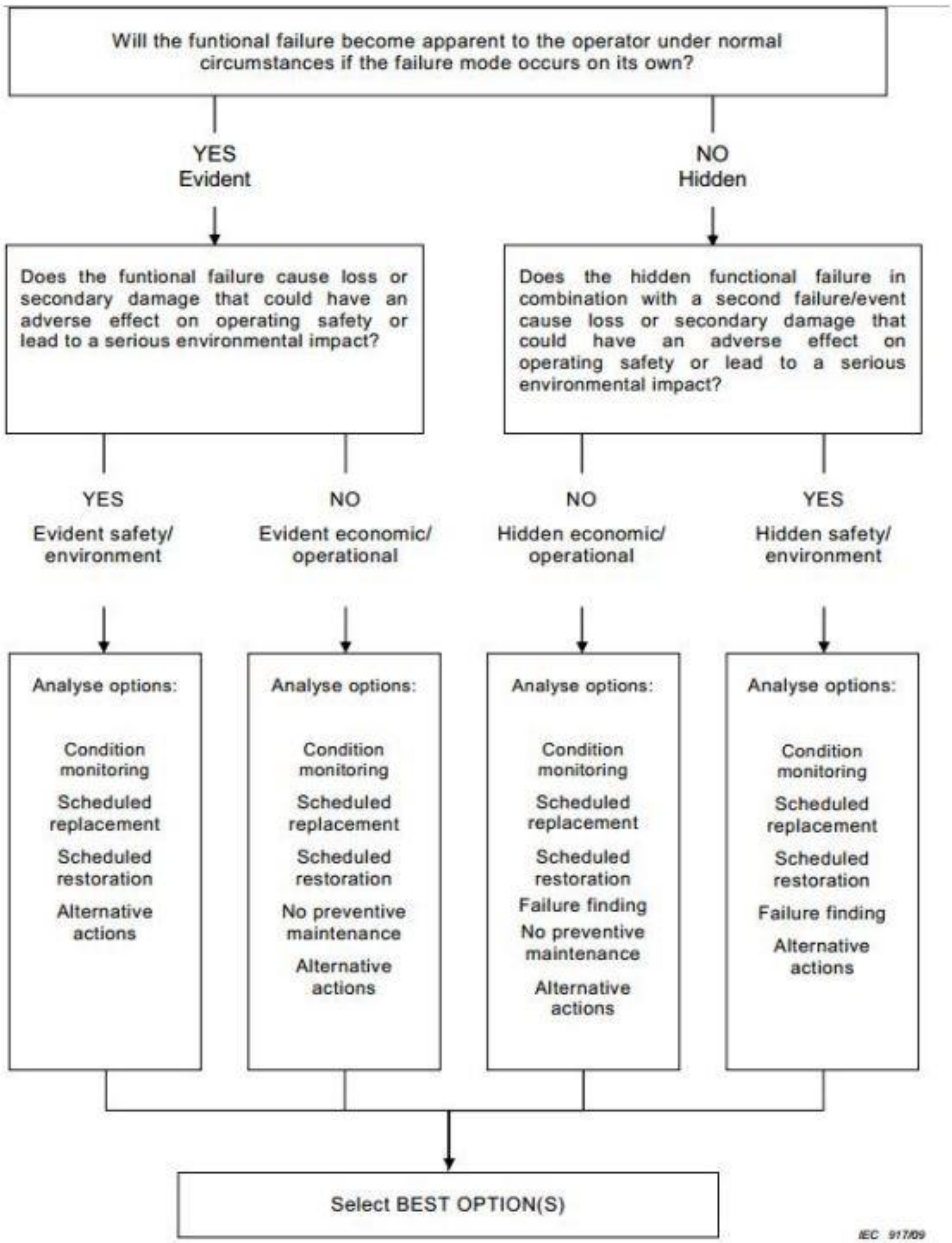

Figure 2: Group failure consequences (Standards Australia 2011, p. 25)

Evident Failures

Evident failures are defined by the characteristic where they will inevitably become evident on its own. These types of failures are most often detectable by signs of physical damage, warning lights, smoke, and loss of control or production losses. An example of this would be a pumping system that has a standalone pump, if the pump were to fail it would be evident to the operating crew. Whilst the failure does not have to become evident immediately, it does have to become evident on its own (Moubray 2001, p. 92-93).

Hidden Failures

Hidden failures under normal operating conditions are not detectable without a failure finding activity. Hidden failures often have a lack of symptoms to alert operating crews to the failure. The system can continue to operate as normal due to redundancy or fail safe within the system. The example of the pumping system above could become a hidden failure if there was a built-in stand-by pump that took over after the main pump failed. This is where a failure finding task would be required (Moubray 2001, p. 113).

Safety Consequences

Failure modes that are attributed to the safety and wellbeing of human beings are the top priority in an RCM analysis. As described by Moubray (2001, p. 94), "a failure mode has safety consequences if it causes a loss of function or other damage which could hurt or kill someone".

Environmental Consequences

Any failure mode with environmental consequences is considered in RCM due to the legal requirements of the assets operating context be it corporate, municipal, regional, national and international regulations. Environmental consequences are also important from a company's perspective with respect to society's environmental expectations (Moubray 2001, p. 91, Netherton 2002, p. 66).

Operational Consequences

Failure modes that have operational consequences are an important consideration due to their effect on the company's ability to continue its operation. Operational consequences have an impact on output, operating costs, revenue and product quality. When a company is seeking to mitigate the effects of operational consequences, it requires two considerations:

1. How much the failure costs each time it occurs, in terms of its effect on operational capability plus repair costs
2. How often it happens (Moubray 2001, p. 105)

The RCM analysis group should be careful not to place too much emphasis solely on whether a task is technically feasible or not, the consideration of whether a task is worth doing should carry significant weight. For failure modes that carry operational consequences, proactive tasks are worth doing if over a period of time the task costs less than the cost of the operational consequences plus the cost of repair. There are instances where a proactive task cannot be found that prevents the failure consequence, in these circumstances Moubray (2001, p. 105) suggests it might be feasible to change the design in the asset.

Non-operational Consequences

Non-operational consequences have a magnitude that are simply measured in economic cost associated with the cost of repair, they do not affect operation, safety or the environment (Netherton 2002, p. 67). For failure modes having non-operational consequences, an assessment of whether a task is worth completing depends on whether the cost of the proactive task costs less over a period of time than the cost of failures it is required to prevent (Moubray 2001, p. 109).

When examining failures with non-operational consequences Moubray (2001, p. 109) suggests considering the following two points:

- Secondary Damage: There are failure modes that have the potential to cause considerable secondary damage if not anticipated or have an effective preventative strategy. Therefore, it is recommended that a suitable proactive task be sought on the grounds that the proactive task does not cost more than the cost of repair.
- Protected Functions: If the function is protected by redundancy, then a suitable maintenance program must be applied to the protective device.

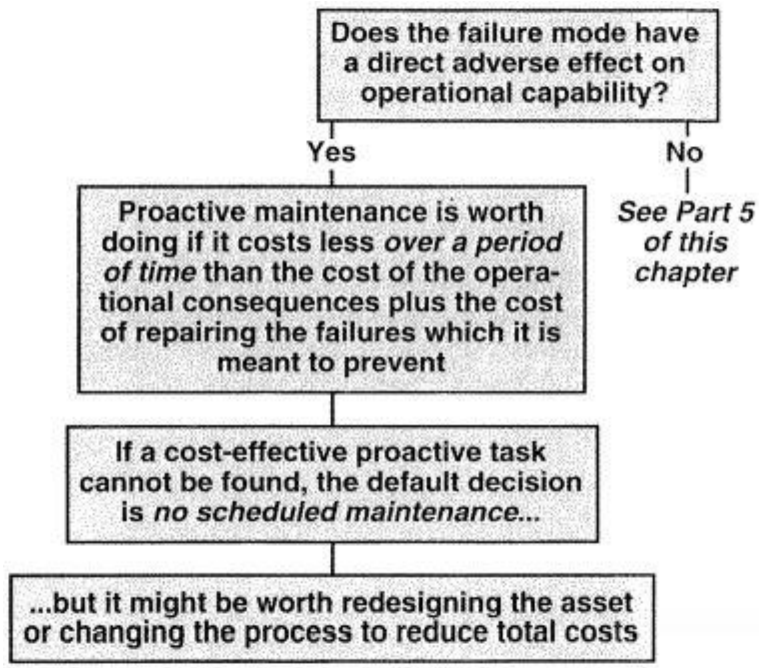

Figure 3: Developing Maintenance Strategy for Failure (Moubray 2001, p. 109)

2.2.2.7 Step 7: Selection of Maintenance Actions

Decision logic based on dominant failure modes from the FMECA is used to determine the effectiveness of a PM task versus corrective maintenance following deliberate run to failure. The primary reasons for a PM task are to; prevent a failure, detect onset of a failure or discover a hidden failure (Rausand 1998, p. 127). The maintenance actions may include; scheduled on-condition task, scheduled overhaul, scheduled replacement, scheduled function test or run to failure.

All failures may not be prevented with PMs. An item may need to be modified if a failure mode cannot be addressed by an applicable PM task. In the case of failure as it relates to safety or environment, typically redesign is mandatory and will be suggested. Additionally, a cost-benefit will be performed while considering operation and economic consequences.

Proactive Maintenance Task Selection

Proactive tasks are undertaken before a failure occurs with the objective of preventing a failed state from occurring. Various terms are often associated with proactive tasks, such as 'predictive' and ‘preventative’, however, Moubray (2001, p. 129) states that RCM uses the terms scheduled restoration, scheduled discard and on-condition maintenance.

Having already assessed whether a task is economically feasible, proactive maintenance task selection focusses on whether a task is technically feasible. Determining if a proactive task is technically feasible depends on the characteristics of the failure mode and of the task (Moubray 2001, p. 129).

There are two dominate issues relating to task selection from a technical standpoint:

- The relationship between the age of the item and how likely it is to fail
- What happens to the item once failure has started to occur

Schedule Restoration Tasks

Schedule restoration tasks are often assigned to components where the probability of their failure becomes greater after a certain operating age and restoration restores the components resistance to failure. Characteristics that cause the need for schedule restoration tasks are usually direct wear, fatigue, corrosion, oxidation and evaporation (Moubray 2001, p. 133). These characteristics are grouped into age related failures.

A restoration task must meet the following criteria to be considered applicable (Nowland & Heap 1978, p. 57):

- There must be an identifiable age at which the item shows a rapid increase in the conditional probability of failure
- A large proportion of the units must survive to that identifiable age
- It must be possible to restore the original failure resistance of the item by reworking it

Moubray (2001, p. 134) agrees saying that for a schedule restoration task to be considered technically feasible it must meet these criteria:

- A point at which there is an increase in the conditional probability of failure
- Be reasonably sure what the life of the component is

Moubray (2001, p. 134) also adds a caveat to these points stating that if the failure has a safety or environmental consequence then all of the units must survive until the scheduled restoration age.

Schedule Discard Tasks

Schedule discard tasks carry many of the characteristics of schedule restoration tasks. They are only technically feasible if there is a direct relationship between failure and operating age.

On Condition Maintenance

While many failures modes are not age related, some failure modes provide an indication that failure is likely to occur sometime in the future. Tasks described as on-condition are done so because the individual unit is remains in service 'on the condition' that it keeps meeting the relevant standards (Moubray 2001, p. 144, Nowland & Heap 1978, p. 51).

Components often provide signs that it is in the final stages of failure and identifying this at an appropriate time interval may allow timely repair. The *P – F curve* (Figure 4) is a tool used to describe and illustrate the path to failure. Point 'P', potential failure, is often the point in the failure process that the impending failure becomes detectable. If the failure is not detected and rectified then the component continues to deteriorate, usually at an accelerate rate until it reaches point 'F', functional failure.

On-condition tasks must be carried out at intervals less than the P – F interval. Moubray (2001, p. 146) describes this as the 'warning interval' or the lead time to failure. Inspections carried out at intervals longer than the P – F interval risk a chance of missing the impending failure.

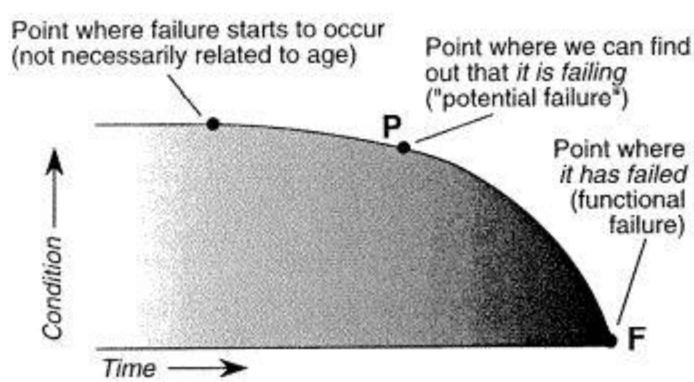

Figure 4: P – F curve (Moubray 2001, p. 144)

2.2.2.8 Step 8: Determination of Maintenance Intervals

The optimal interval with which to perform a PM tasks will require consideration of the failure rate, likely consequences, cost of failure meant to be prevented with a PM and risk of PM task (Rausand 1998, p. 128). Maintenance optimization models have been created by statisticians and scientists and assume only single units and that the cost of a single unit failure can be quantified. In reality, maintenance intervals are performed in packages of tasks rather than as a single unit. It is also important to consider that due to the concerns with maintenance optimization models the implementation of maintenance intervals ends up following manufacturers' recommendations and past experience resulting in increased frequency of maintenance (Rausand 1998, p. 128). These considerations will be made when determining maintenance intervals in the current project.

2.2.2.9 Step 9: Preventative Maintenance Comparison Analysis

Maintenance tasks must meet two requirements:

- Applicability: it may eliminate or reduce impact of failures
- Cost-effectiveness: the cost must not be more than the failure it is meant to prevent

The cost of a PM task must consider the risk and cost related to failures induced by maintenance, risk to personnel, risk of increasing another components failure, the cost of physical resources, limitation of physical resources while in use, unavailability during maintenance and absence of protective functions. This must be compared to the cost of failure. Cost of failure may include; consequences of failure including safety or regulation violations, significance of not performing PM task without failure and emergency repair premiums (Rausand 1998, p. 129). These guidelines will assist in achieving the preventative maintenance comparison.

2.2.2.10 Step 10: Treatment of Non-Critical Item

Non-critical items which were not selected in Step 4 as MSIs are briefly evaluated for cost to determine ability to continue the program (Rausand 1998, p. 129).

2.2.2.11 Step 11: Implementation

Implementation of the RCM analysis results requires organizational and technical maintenance support functions and requires the consideration of risk associated with the maintenance task as accidents typically occur due to lack of maintenance or during the maintenance process (Rausand 1998, p. 129). Investigation and recommendations into the practicality of implementing RCM process findings into fleet maintenance management of utility company will be completed.

2.2.2.12 Step 12: In-Service Data Collection and Updating

Operating and maintenance experience should be utilized and integrated into the RCM analysis to achieve the full benefit of the process (Rausand 1998, p. 130).

Three time perspectives will be used to update the process:

- Short-term interval adjustment: update of failure information and reliability estimates to revise previous analysis results
- Medium term task evaluation: review of maintenance actions selected in Step 7 with integration of maintenance experience to further identify causes of significant failure yet to be defined
- Long-term revisions of the initial strategy: considers all steps in the RCM process and the entire operation as it relates to the outside world (Rausand 1998, p. 130).

2.3 Data

Throughout the RCM analysis process there is a requirement for various data to be collected, analyzed and used to make sound decisions. One of the main objectives of this project is to use the data captured from operation and gained from an RCM process to aid in the decision making process via probabilistic modelling. Reliability data helps to inform the decision making on critical systems and components by mathematically describing failure processes and thus guides maintenance task schedules (Rausand 1998, p. 125).

In the context of reliability engineering, typically more emphasis is placed on time to failure data or life data (O'Connor 2012, p. 70). Some of the literature focuses on reliability data such as mean time to failure (MTTF), mean time to repair (MTTR) and failure rate function (z(t)), where failure rate will be an increasing function of time signifying that the item is deteriorating (Rausand 1998, p. 125). However, some of the literature cautions and even warns against the reliance on historical information about failure and technical history data. John Moubray, a respected expert on the subject of RCM, says that there is an "almost mystical faith which we place in the relationship between age and failure" (Moubray 2001, p. 250). Moubray (2001, p. 250) suggests from a maintenance viewpoint these patterns are fraught with practical difficulties, conundrums and contradictions. Despite the cautions of historical failure data and the age-failure relationship, it is still necessary to quantitatively use this data. Moubray (2001, p. 253) states that the principal use of actuarial analysis in maintenance is to analyze reliability issues where there are uncertain relationships between age and failures which have substantial economic consequences but no safety consequences.

Moubray (2001, pp. 253-254) places these failures into two categories:

- Failures that have large numbers of identical items where the functions are identical. The failure might only have a small impact if taken as a single event but when taken as a cumulative effect can be a significant economic consideration. For example, vehicle components in large fleets.
- Less common failures that are still thought to be age related and where the preventative maintenance and the cost of failure are both very high.

Netherton (2002, p. 69) confirms that the use of historical data is important as the various steps in the RCM review require this historical data about; failures, the assets performance and how it degrades over time, costs pertaining to operation and maintenance and the performance of the PM program.

One of the objectives of this project is to successfully integrate the use of historical data into the RCM process. Whilst some of the literature cautions against the reliance of data while undertaking an RCM analysis this project does not intend to rely solely on data. The project however aims to explore the benefits of using data, data analysis and probabilistic modelling to complement the RCM process. RCM presents itself as a predominately qualitative analysis and in the researcher's experience one of the issues that comes with the qualitative approach with respect to maintenance is that of management 'buy in'.

Tracking the performance of the maintenance program is just one area where data, statistics, analysis and probabilistic modelling may be useful. Moubray (2002, p. 258) notes that monitoring the performance of the maintenance function is an essential aspect of maintenance management. One of the established measures of the performance of an asset and the maintenance program is the 'mean time between failure' (MTBF).

2.3.1 Data Analysis

Attaining data relating to a specific asset, failure or function is the first step in the process of making use failure history, asset performance or the performance of the maintenance function. Once collected, the data will be analyzed. In reliability engineering, statistical data analysis is the process of finding the best statistical distribution based on the observed failure data (O'Connor 2012, p. 70).

Analyzing life data is commonly carried out using the Weibull distribution or Weibull analysis. The life data analysis process requires the following steps:

1. Gather life data for the product
2. Select a lifetime distribution against which to test data
3. Generate plots and results that estimate the life characteristics of the product, such as the reliability, failure rate, mean life, or any other appropriate metrics (O'Connor 2012, p. 70).

Life data may be grouped into different classifications, for example distance travelled, cycles, time, on/off switches and so on. The accuracy and credibility of any parameter estimations are dependent on the quality, accuracy and completeness of the supplied data (O'Connor 2012, p. 70).

2.3.1.1 The Weibull Distribution

The Weibull distribution is commonly used in reliability engineering, as it is able to be applied to life data modelling in a wide range of situations. The distributions cover a large variety of distribution parameters and is known to have a flexibility for describing hazard rates (O'Connor & Kleyner 2011, p. 78). The Weibull distribution is often used when there is a need to model the failure characteristics of components with varying failure rates.

The application of a Weibull analysis to failure analysis includes:

- Plotting the data
- Interpreting the plot
- Predicting future failures
- Evaluating various plans for corrective actions
- Substantiating engineering changes that correct failure modes (Abernethy 1933, p. 2)

When applying the Weibull analysis, care should be taken with respect to the data problems and deficiencies, these include:

- Censored data
- Nonzero time origin
- No failures
- Extremely small samples
- Strengths and weaknesses of the method
- Mixture of failure modes

Whilst these data problems can be an issue, there are methods to overcome these deficiencies (Abernethy 1933, p. 2).

Two Parameter Weibull Cumulative Failure Distribution Function

In accordance with its name, this distribution is defined by two parameters:

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)\hat{}\beta\right]$$

Where:

- F(t) represents the cumulative failures,
- t is time,
- β is the 'shape' parameter,

η is the 'scale' parameter, or 'characteristic life'. It represents the time at which 63.2% of the population will have failed (O'Connor & Kleyner 2011, p. 78).

Failure Distribution

The slope or shape of the Weibull plot, β, indicates which class of failure exists

- $\beta < 1.0$ gives an indication of infant mortality
- $\beta = 1.0$ indicates random failures independent of age
- $\beta > 1.0$ gives an indication of wear out failures

The Weibull plot (Figure 5) is used to illustrate the onset of failure in whatever might be modelled, for example it can give a determination on the time at which 1% of the population will have failed. The characteristic life η is defined as the age at which 63.2% of the units will have failed or it can be called the B63.2 life (Abernethy 2006, p. 1.7).

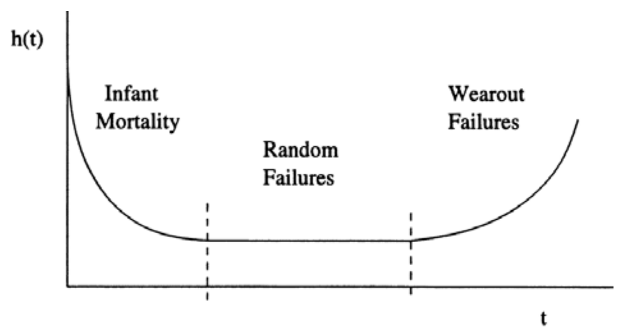

Figure 5: Bathtub curve (Klutke, 2003)

Weibull Results

Weibull analysis provides the engineer with reasonably accurate failure analysis and can provide failure forecasts with extremely small samples (Abernethy 2006, p. 1.3). This gives the advantage of being able to find solutions for problems without having to wait for more data to accumulate from damage. The Weibull analysis also provides graphical information in the form of a plot. The plot is typically laid out with the horizontal axis being a life parameter for example, cycles or operating time and the vertical axis being the cumulative percentage failed.

How the Weibull plot provides the user information for analysis is through parameter, the slope of the line β and the characteristic life η. The slope of the line beta can provide information with respect to the physics of failure whilst the characteristic life η typically indicates time to failure (Abernethy 2006, p. 1.3).

Maintenance Planning Weibull

For maintenance planning activities, the Weibull plot is extremely useful. In particular, in RCM the slope β allows the maintenance planning engineer to assess whether they should schedule inspections or overhauls (Abernethy 2006, p. 1.6).

2.3.1.2 Monte Carlo Simulation

Monte Carlo simulation is a method that has the ability to simulate reality, aiding in the decision process when the future outcomes are uncertain. Monte Carol simulation has the ability to simulate real systems by accounting for randomness and applying hundreds or thousands of scenarios.

Probabilistic Modelling

Monte Carlo simulation is a tool that is widely used for modelling phenomena with uncertain inputs, it is used in many applications such as reliability, availability and logistics forecasting, load-strength interface analysis, probabilistic design (O'Connor & Kleyner 2012, p. 108).

The basic definition of Monte Carlo simulation can be summarised as a method for repetitively evaluating a deterministic model using sets of random numbers as inputs (Thomas et al. 2009, pp. 158-159). When running a Monte Carlo simulation, random variables need to be generated that follow an arbitrary statistical distribution. The inputs are randomly generated from probability distributions to simulate the process of sampling from an actual population. Thus, a distribution is chosen for each input that best represents the current state of knowledge (Bergkvist & Orjas 2014, p. 34, O'Connor & Kleyner 2012, p. 108). The generated data after a simulation can be represented in a histogram, a basic statistic format or fitted into a probability distribution function.

Depending on the complexity and scope of the selected problem to be modeled, there are some basic steps in performing a Monte Carlo simulation:

Step 1: Define the problem and the overall objectives of the study. Evaluate the available data and outcome expectations.

Step 2: Define the system and create a parametric model, $y = (x1, x2, \dots , xq)$.

Step 3: Design the simulation. Quantities of interest need to be collected, such as the probability distributions for each of the inputs. Define how many simulation runs should be used. The number of runs is affected by the complexity of the model and the sought accuracy of the results.

Step 4: Generate a set of random inputs, $xi1$, $xi2$, … , xiq.

Step 5: Run the deterministic system model with the set of random inputs, evaluate the model and store the results.

Step 6: Repeat steps 4 and 5 for I = 1 to m.

Step 7: Analyze the results statistics, confidence levels, histograms, best fit distribution or any other statistical measure (O'Connor & Kleyner 2012, p.113).

2.4 Chapter Summary

The current chapter provided a review of the literature surrounding RCM. Section 2.2 reviewed the definition and objectives of RCM process and introduced the seven basic questions with which the RCM process is meant to achieve. The literature highlights the lack of quantitative analysis in the heavily qualitative analysis in the basic seven step process. The literature introduces a hybrid methodology that consists of the basic RCM process and probabilistic modelling. This twelve-step process is sequentially outlined in Section 2.2.

The chapter concludes with a discussion of the collection of the data and the use of the Weibull Distribution and Monte Carlo Simulation for the analysis of data. The use of probabilistic modelling in RCM simulation and the ability of Monte Carlo Simulation to simulate real systems by accounting for randomness and applying hundreds or thousands of scenarios is discussed in the literature however the implementation of it is limited in current RCM programs. The literature points to the importance of integrating this for a more complete RCM program.

Chapter 3

Reliability-Centered Maintenance Analysis Planning and Preparation

3.1 Chapter Overview

Chapters 3 through 5 document the modified RCM process as developed by the author following the assessment of existing literature and the noted need for incorporation of quantitative data into the RCM process. The RCM methodology presented follows a 11-step process from identifying the systems of interest to analyzing and establishing a maintenance plan. This modified process seeks to bridge the identified gaps in the current literature.

Chapter 3 details a modified step wise process of the first four steps of the hybrid approach of RCM and probabilistic modelling as outlined in Chapter 2. This includes the following steps:

1. Preliminary analysis system selection
2. Study of equipment and work environment
3. Functional failure
4. Failure mode

3.2 Step 1: Preliminary Analysis System Selection

3.2.1 Assemble RCM Working Group

Assemble RCM working group consistent with the recommendations laid out in section 2.2.2.1 of the literature review. As an overview this should involve:

- A Team of approximately 4 – 5 individuals who come from different but relevant departments of the operations
- Led by an RCM facilitator with relevant knowledge and training on the subject
- At least one person from maintenance and one from operations

3.2.2 Establish Working Group Rules and Develop a Plan

The RCM working group are required to:

- Identify and document rules for the analysis team to follow
- Identify assumptions
- Set goals, address budgets, make procedures, determine facilities to be used and document meetings

3.2.3 System Selection

The RCM working group will need to decide on the overall level of analysis required, this may be discussed and decided upon with recommendations from the group and management. RCM may be carried out on an operations entire fleet or production line or carried out on selected critical assets. The methods employed in this project were:

- Collect failure data for analysis
- Perform Pareto analysis to identify high cost assets
- Consultation with SME to discuss the merit of selected assets

The following three figures demonstrate the Pareto analysis conducted on failures, cost of repair and time to repair. Figure 6 demonstrates that failures occurred most with exhaust/emissions, cooling and brakes (air) systems. The highest cost of repair as demonstrated in Figure 7 was seen with exhaust/emission systems. And the greatest time to repair was found with exhaust/emissions systems as depicted in Figure 8.

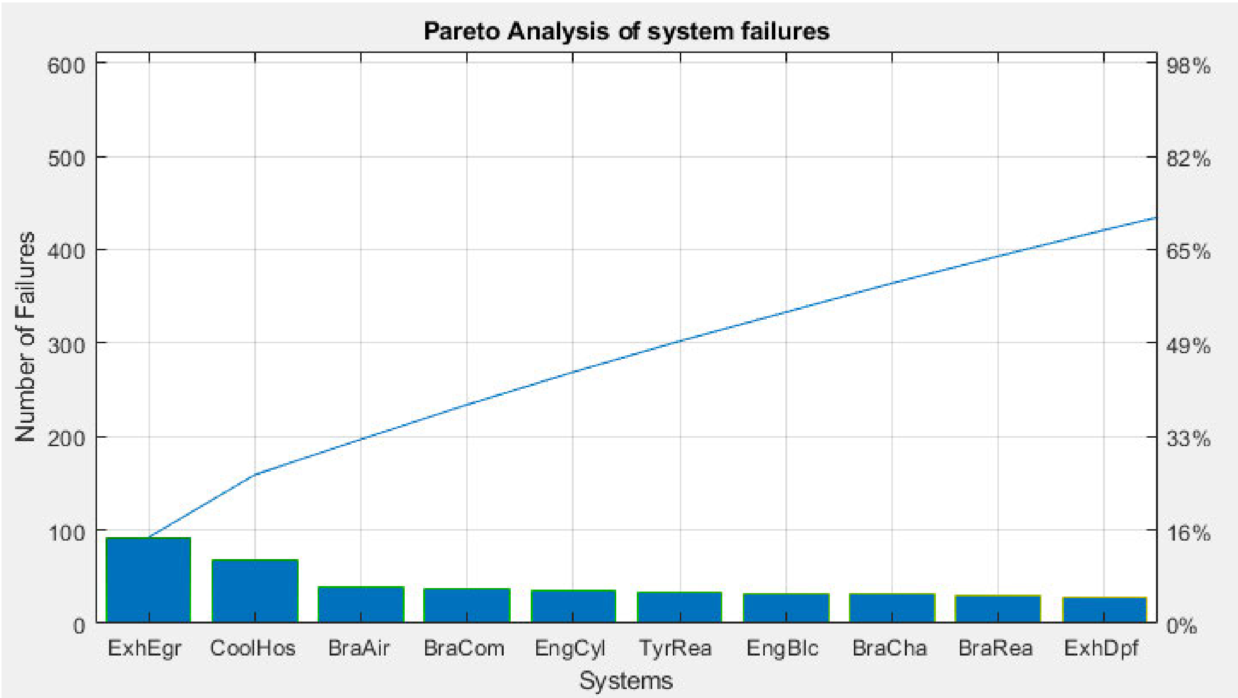

Figure 6: Pareto analysis of failures

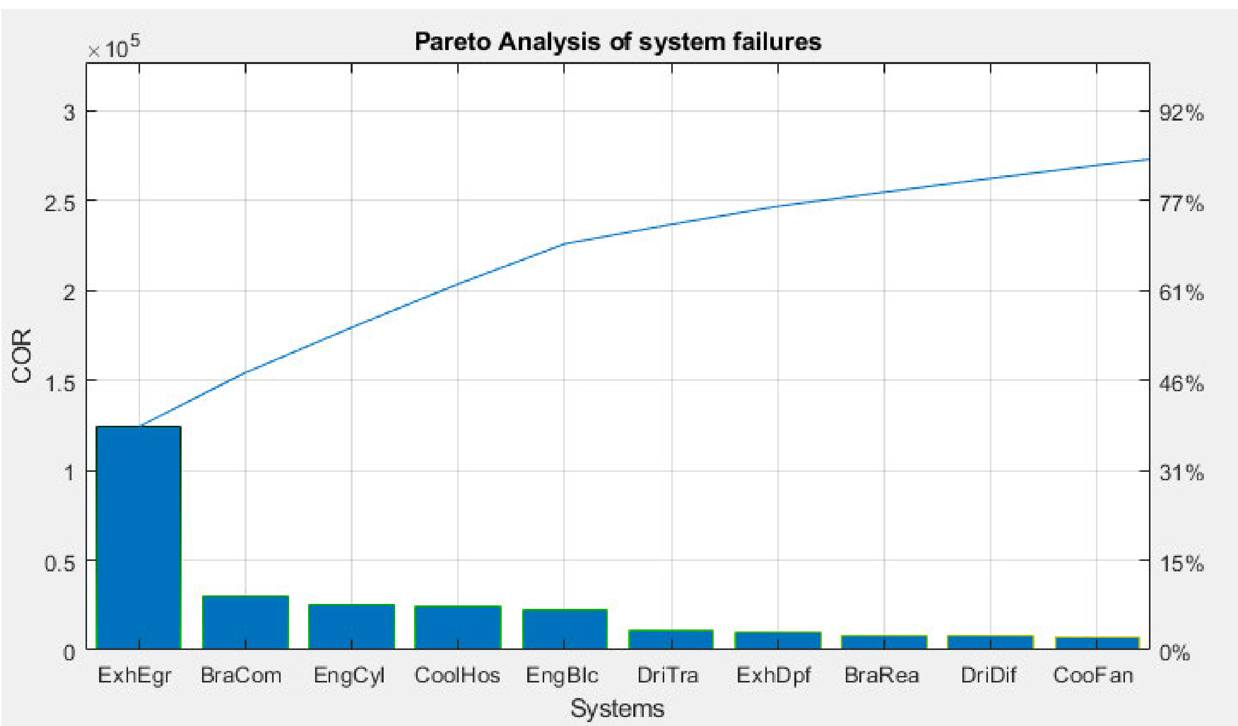

Figure 7: Pareto analysis of cost of repair

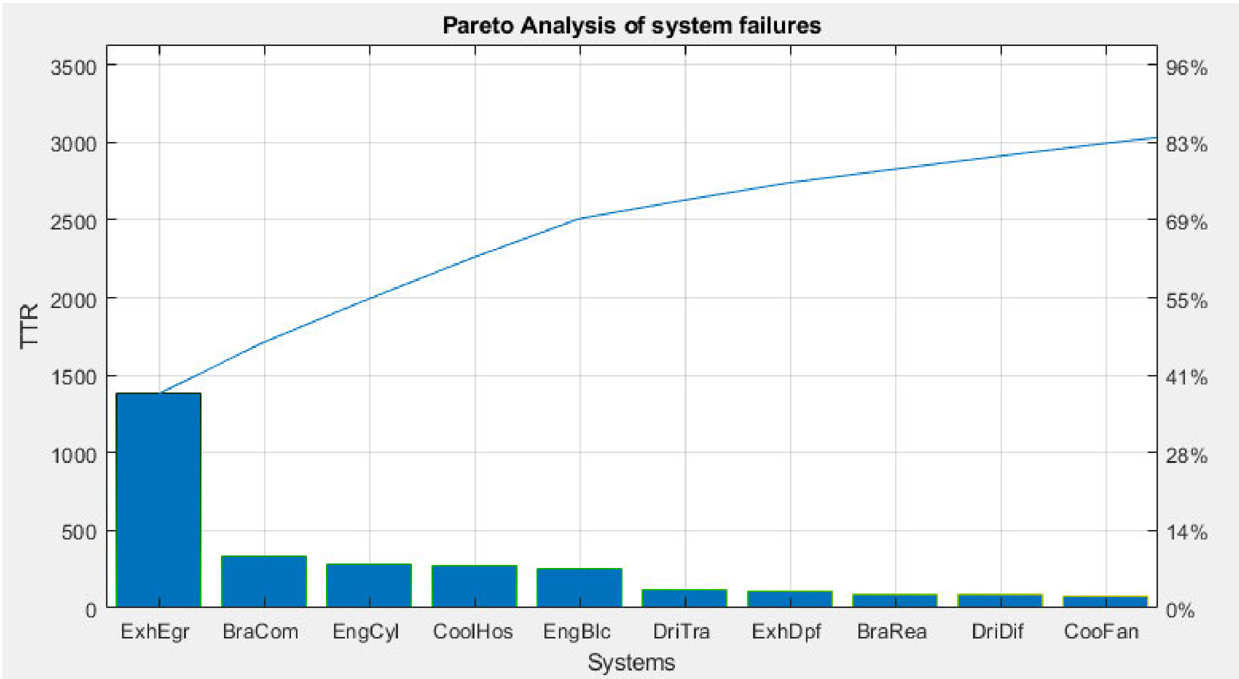

Figure 8: Pareto analysis of time to repair

Table 1 provides a summary of the maintenance data with respectful to failures, cost to repair and cost of repair labour. The greatest number of failures was associated with exhaust/emission systems and yielded the greatest cost of repair with respect to labour.

Table 1: Maintenance Data

System	Failure Count	Time to Repair	Cost of Repair Labour
Exhaust/Emissions	92	1380	124200
Cooling system	67	268	24120
Brakes (Air System)	38	76	6840
Engine (Cylinder head)	35	280	25200
Brakes (Rear)	29	87	7830
Exhaust (DPF)	28	112	10080
Brakes (Compressor)	37	333	29970
Brakes (Chamber)	31	62	5580
Engine Block	31	248	22320
Rear tyres	33	66	5940
Drivetrain	24	120	10800
Brakes (Lines/Fittings)	23	46	4140
Drivetrain (Diff)	17	85	7650
Cooling System (Fan)	27	81	7290
Fuel system (Fuel Lines)	19	76	6840
Fuel System (Management)	10	50	4500
Steering Box	10	40	3600
Brakes (Air valve)	18	36	3240
Fuel Pump	15	75	6750
Steering Lines	15	45	4050
Air Intake manifold	13	65	5850

3.3 Step 2: Study of Equipment and Work Environment

The equipment that is under study consists of a fleet of approximately 300 Class 7-9 International Workstar Series trucks that are operated by the power generation company. The typical environment these assets are operated in are on-road conditions with weather conditions being highly variable. Operation of the assets is typically undertaken by trained tradespeople who use these trucks as a tool to complete their main job function, operation of the assets is also highly variable.

The power generation and distribution business requirements for these assets are that they are able to safely and reliably operate in the conditions identified above, the assets must also be maintained within budget.

There are federal and provincial legislation requirements with respect to the maintenance of on-road heavy truck fleets, these are:

- Vehicles are required to be inspected once a year by an authorized inspector at an authorized facility
- The vehicle must be under a preventative maintenance program and the program be approved by the Commercial Vehicle Safety and Enforcement (CVSE) Authority

The importance of conducting a study of the operating environment falls under two categories.

1. RCM requires that the operating context be identified to determine an appropriate evaluation criterion of the assets under investigation
2. It allows the RCM facilitation team to understand and discover aspects of their operating environment that could have been unknown or misunderstood

The 'system' under assessment is taken to be the Class 7-9 truck, the truck consists of the manufacturers components, this being the chassis and the equipment components, this being the aerial lifting device used by the operators. The trucks are acquired to perform the primary function of lifting powerline working personnel into position to safely carry out their roles.

The chassis side of the asset consists of the power plant (engine), transmission, drivetrain, electrical system, and the chassis. The aerial device that is fitted to the equipment at the time of purchase consists of the hydraulic system, major structural assemblies, and electronic control system. These two major systems must work together, and therefore a failure with one major system will cause the entire asset to fail its primary function.

Due to the many systems that make up the entire asset it is important to methodically choose systems that are deemed to be underperforming and causing the majority of the delays in operation. The analysis of subsystems was carried out in step one with the Pareto analysis and consultation with SMEs. This allows the RCM team to identify the significant systems to focus the analysis on and further break down the systems into sub-systems and components.

Due to the time restraints associated with this project and the nature of a full RCM analysis, it was decided that choosing the engine sub-system for analysis was sufficient to demonstrate the effectiveness of the proposed methodology. The reasons for choosing the engine subsystem was due to:

- The sub-systems of the engine being the major contributors in the Pareto analysis
- After consultation with the SMEs it was agreed the engine sub-systems should be the focus

Three sub-systems have been identified for RCM analysis and modeling:

1. The Exhaust Gas Recirculation System
2. The Cooling System
3. The Diesel Particulate Filter/Exhaust System

These sub-systems are discussed in further detail below.

Sub-System 1: Exhaust Gas Recirculation System

The objective of the Exhaust Gas Recirculation (EGR) system is to dilute the intake air charge with "dead" gas in an effort to reduce the Oxides of Nitrogen emission by lowering combustion heat (Bennett 2013, p. 831). There are some EGR systems that are cooled using the engine's cooling system, these are sometimes referred to as C-EGR and are comprised of:

- A heat exchanger (engine coolant is used)
- Electronically controlled mixing (ECM) chamber
- Mass air flow sensor
- Plumbing to route engine coolant through the heat exchanger
- Piping to route exhaust gas to the mixing chamber

Sub-System 2: Cooling System

The cooling system on an automotive diesel engine is responsible for the dissipation of rejected heat energy from the engine. This is accomplished by way of a network of components that are both internally and externally located throughout the engine (Bennett 2013, p. 189).

The functions of the cooling system are to:

- Absorb heat from the engine components
- Absorb heat from engine support systems, such as the EGR system
- Transfer absorbed heat energy through coolant circulation
- Supply heat to heating elements
- Dissipate heat to the atmosphere through heat exchangers
- Maintain optimum operating temperatures

Sub-System 3: Diesel Particulate System

The diesel particulate filter (DPF) in an exhaust after treatment system is used to eliminate diesel particulate matter generated by the combustion process in diesel engines (Bennett 2013, p. 189). The DPF which is typically made of cordierite or silicon carbide substrate is housed in a compartment within the exhaust system. The DPF system's primary function is to capture particulate matter that is created during the combustion process and its secondary function is to regenerate once it is at a designated capacity.

3.4 Step 3: Functional Failure

The literature review found the definition of a functional failure to be *"the inability of any asset to fulfil a function to a standard of performance which is acceptable to the user"* (Moubray 2001, p. 47). The asset is required to fulfill a pre-defined function and as such if it can no longer perform that function then the asset has been deemed to have suffered a functional failure. Functional failures impact the operation of a company due to the fact that the work can no longer be carried out or is carried out at a reduced rate.

The functional failures for the three sub-systems of interest are identified in Tables 2-4 below.

Sub-System 1: EGR System

Table 2: EGR System Functional Failures

FUNCTION	FUNCTIONAL FAILURE
Dilute the intake charge air with cooled recirculated exhaust gas thus reducing the NOx emissions	A) Unable to supply cooled charge air to intake
Cool the exhaust gases that will be reintroduced back into intake charge	A) Unable to cool exhaust gases
Maintain separation between the engine coolant and the exhaust gases	A) Coolant enters exhaust gas side of EGR system B) Exhaust gas enters coolant side of EGR system

Sub-System 2: Cooling System

Table 3: Cooling System Functional Failures

FUNCTION	FUNCTIONAL FAILURE
Absorb heat from engine and supporting components and dissipate excess heat into environment	A) Unable to absorb and/or dissipate heat from engine or supporting components B) Unable to dissipate enough heat from engine
Regulate temperature of engine to the specified range	A) Temperature not being kept within the specified range
Provide heat to compartments that require heat	A) Components not being supplied heat from cooling system B) Components not releasing heat

Contain coolant without losing any during operation or whilst being stored both internally and externally	A) Loses coolant form cooling system during operation B) Loses coolant whilst being stored C) Loses coolant externally D) Loses coolant internally

Sub-System 3: DPF System

Table 4: DPF System Functional Failures

FUNCTION	FUNCTIONAL FAILURE
Capture particulate matter and store until regeneration is required	A) Unable to capture particulate matter B) Unable to store particulate matter
Does not restrict exhaust gas flow anytime during operation	A) Exhaust gas flow is restricted before and after regeneration is performed B) Contaminated and does not regenerate

3.5 Step 4: Failure Mode

A failure mode is any event which can cause a functional failure, there may be one or more failure modes for each functional failure. An example of a failure mode is a pump designed to deliver 200 liters per minute but was only producing 100 liters per minute. This reduced production is the functional failure and the failure mode could be a worn impeller.

The functional modes for the functional failures identified above are presented in Tables 5-7 below.

Sub-System 1: EGR System

Table 5: EGR System Failure Modes

FUNCTION	FUNCTIONAL FAILURE	FAILURE MODE
Dilute the intake charge air with cooled recirculated exhaust gas thus reducing the NOx emissions	A) Unable to supply cooled charge air to intake	1) Blockage in EGR system 2) EGR valve failed in closed position
Cool the exhaust gasses that will be reintroduced back into intake charge	A) Unable to cool exhaust gases	1) EGR cooler coolant system blocked 2) Carbon build up on internal heat exchanger
Maintain separation between the engine coolant and the exhaust gases	A) Coolant enters exhaust gas side of EGR system B) Exhaust gas enters coolant side of EGR system	1) EGR cooler heat exchanger leaking

Sub-System 2: Cooling System

Table 6: Cooling System Failure Modes

FUNCTION	FUNCTIONAL FAILURE	FAILURE MODE
Absorb heat from engine and supporting components and dissipate excess heat into environment	A) Unable to absorb and/or dissipate heat from engine or supporting components B) Unable to dissipate enough heat from engine	1) Water pump failure, no coolant circulation 2) No coolant in system 3) Radiator blocked internally or externally 4) Thermostat stuck in closed position

Regulate temperature of engine to the specified range	A) Temperature not being kept within the specified range	1) Thermostat defective 2) Radiator blocked
Provide heat to compartments that require heat	A) Compartments not being supplied heat from cooling system B) Components not releasing heat	1) Blockage in compartment heat exchangers 2) Coolant not circulating cooling system 3) Cab fan not operational
Contain coolant without losing any during operation or whilst being stored both internally and externally	A) Loses coolant form cooling system during operation B) Loses coolant whilst being stored C) Loses coolant externally D) Loses coolant internally	1) Cooling system hose fails 2) Cooling system joint fails 3) Radiator cap not holding specified pressure 4) Coolant being ingested by engine 5) Leaking component

Sub-System 3: DPF System

Table 7: DPF System Failure Modes

FUNCTION	FUNCTIONAL FAILURE	FAILURE MODE
Capture particulate matter and store until regeneration is required	A) Unable to capture particulate matter B) Unable to store particulate matter	1) DPF substrate damaged 2) DPF has been intentionally removed
Does not restrict exhaust gas flow anytime during operation	A) Exhaust gas flow is restricted before and after regeneration is performed B) Contaminated and does not regenerate	1) DPF substrate damaged 2) DPF blocked by soot or contaminates that are not able to be cleared during regeneration 3) Full of ash and requires manual cleaning 4) Engine producing excessive smoke or passing oil

3.6 Chapter Summary

The first four steps of the modified RCM process were presented in Chapter 3. The steps include:

1. Preliminary analysis system selection: This includes establishing an RCM working group, the group plan and rules as well as the system selection which is determined by the level of analysis required.
2. Study of equipment and work environment: The equipment type was presented as a fleet of approximately 300 Class 7-9 International Workstar Series trucks that are operated by the power generation company and the work environment and context of operation of this equipment was used with a Pareto analysis to determine the sub-systems of interest. The sub-systems identified for RCM analysis and modeling were:

- The Exhaust Gas Recirculation System
- The Cooling System
- The Diesel Particulate Filter/Exhaust System

3. Functional failure: An asset is deemed to have suffered a functional failure if it is unable to perform or fulfill a pre-defined function. Functional failures were presented for the three sub-systems identified above.
4. Failure mode: Any event which can cause a functional failure is considered a failure mode. This step was used to identify the failure modes of the functional failures identified in the previous step.

The next chapter discusses failures and the consequences in further detail.

Chapter 4

Reliability-Centered Maintenance Data Collection and Analysis

4.1 Chapter Overview

Chapter 4 provides a simulation of the data obtained from test subject. This includes the following steps adapted from the RCM methodology:

1. Failure detection
2. Failure consequences
3. Modelling of components
4. Simulate models against maintenance plan

4.2 Step 5: Failure Detection

Failure detection is the point at which the failure becomes detectable through some method of inspection. There are a number of methods of inspection and each method will detect the failure at different times. It is critical to understand which method of inspection is being used to ensure that the P-F interval, as defined in Chapter 2, will be a useful tool in assisting with the maintenance interval.

Methods used for inspection of the EGR system:

- Pressure testing of the cooling system to identify internal or external leaks
- Vacuum testing the cooling system to inspect for an internal leak at the cooler
- Visual inspection of the system
- Checking for fault codes relating to the EGR system operation
- Carrying out a functional test via scanning equipment

Methods used for inspection of the cooling system:

- Pressure testing of the cooling system to identify internal or external leaks

- Vacuum testing to inspect for internal or external leaks
- Pressure testing the cooling system pressure cap
- Visual inspection of all components
- Temperature inspection
- Fault code inspection to see if coolant level has previously dropped and been topped up

Methods used for inspecting the DPF system:

- Visual inspection
- DPF differential pressure test
- Soot and ash levels accessed via scan tool
- Fault code inspection
- Temperature inspection to see blockages

4.3 Step 6: Failure Consequences

In the literature review it was found that the consequence of failure determines the priority of the maintenance activities or design improvement required to prevent its occurrence.

The chosen subsystems and components will be evaluated against the following criteria:

- Safety Consequences: the potential harm likely, including injury or death, to occur due to a particular failure
- Environmental Consequences: the extent of damage likely to occur to the environment, consequences that could breach any corporate, regional, or national environmental standards
- Operational Consequences: the cost incurred from failure, direct and indirect, that affect production or operation such as product quality, operating costs in addition to direct costs, production
- Non-Operational Consequences: failures that cause non-operational and trivial failure, those that involve only the direct cost of repair as they do not affect safety or production

These assessments together with SME input contribute to the selection of MSIs.

Sub-System 1: EGR System

The EGR systems objective is to dilute the intake charge air with "dead" gas that has been recycled from the exhaust systems and cooled via the heat exchanger or "cooler".

Safety Consequences: The operation of the EGR system in its intended state has been evaluated and it has been concluded that there is no risk of injuring an operator.

The reasons for the EGR system being class as a non-safety item is due to:

- The EGR system is located in the engine compartment and away from personnel
- If the EGR system fails, the failure does not release any uncontrolled energy
- If the EGR system fails, failure is not catastrophic and in most cases the engine continues running

Environmental Consequences: EGR system has been assessed as a subsystem that can cause environmental breaches.

The reasons for the EGR system being classed as an environmental hazard are:

- The intended purpose of the EGR system is to dilute the intake charge air and thus lower output emissions, therefore a failure would impede this purpose
- Internal EGR cooler failure allows coolant (ethylene glycol) to enter the exhaust system and escape to atmosphere
- External EGR cooling system failure allows the coolant to escape to the ground in liquid form

Operational Consequences: Costs incurred from failure of the EGR system resulting in operational consequences have been identified.

The reasons for the EGR system being classed as an operational consequence are:

- Failure of the EGR system will lead to the engine becoming non-operational, this will stall any work scheduled for the asset and in turn affect operating costs

- Often there are work crews consisting of a number of personnel ranging from 2 – 10 people using the asset to complete work, an unscheduled repaired would lead to this becoming an unplanned cost
- Failure at a time when work is interrupting production would have an impact financially and would impact the customers

Non-operational Consequences: An assessment of the non-operational consequences was conducted and determined the EGR system does not contain such consequences.

The reasons the EGR system is not classed as non-operational consequences are:

- Failure of the EGR does have an adverse effect on the non-direct cost of operation
- Failure of the EGR affects productions output

Sub-System 2: Cooling System

The cooling systems objective is to dissipate rejected heat energy from the engine, the engine support systems, and to provide heating to the operator cabin.

Safety Consequences: The operation of the cooling system in its intended state has been evaluated and it has been concluded that there is no risk of injuring an operator.

The reasons for the cooling system being classed as a non-safety item is due to:

- The majority cooling system is located in the engine compartment and away from personnel
- If the cooling system fails, the failure does not release any uncontrolled energy and any coolant spills would not be in the area of the operator
- If the cooling system fails, failure is not catastrophic as the engine can sense a failure and can shut the engine down gradually in most circumstances

Environmental Consequences: The cooling system has been assessed as a sub-system that can cause environmental breaches.

The reasons for the cooling system being classed as an environmental hazard are:

- The coolant (Ethylene glycol) is toxic to the environment and any living creature
- If coolant were to escape uncontained it has potential to spread quickly due to being a liquid, this could be into storm drains, waterways, unsealed surfaces

Operational Consequences: Operational consequences have been identified in the cooling system.

The reasons for the cooling system being classed as an operational consequence are:

- Failure of the cooling system will lead to the engine becoming non-operational, this will stall any work scheduled for the asset and in turn affect operating costs
- Often there are work crews consisting of a number of personnel ranging from 2 – 10 people using the asset to complete work, an unscheduled repaired would lead to this becoming an unplanned cost
- Failure at a time when work is interrupting production would have an impact financially and would impact the customers

Non-operational Consequences: The cooling system was assessed, and no non-operational consequences were identified.

The reasons the cooling system is not classed as non-operational consequences are:

- Failure of the cooling system does have an adverse effect on the non-direct cost of operation
- Failure of the cooling system affects productions output

Sub-System 3: DPF System

The DPF systems objective is to capture particulate matter that is generated during the combustion process and to allow exhaust gasses to pass through unrestricted.

Safety Consequences: The operation of the DPF system in its intended state has been evaluated and it has been concluded that there is no risk of injuring an operator.

The reasons for the DPF system being class as a non-safety item is due to:

- The DPF system is located under the vehicle and away from personnel

- If the DPF fails, the failure does not release any uncontrolled energy
- If the DPF system fails, failure is not catastrophic as the engine can sense a failure and shut engine down gradually in most circumstances

Environmental Consequences: The DPF system has been assessed as a subsystem that can cause environmental breaches.

The reasons for the DPF system being classed as an environmental hazard are:

- Damage to the substrate could potentially allow diesel particulates through and escape to the environment
- During regeneration, the temperature of the DPF system can reach up to 1000 degrees Celsius which has the potential to cause fires

Operational Consequences: Operational consequences have been identified for the DPF system.

The reasons for the DPF system being classed as an operational consequence are:

- Failure of the DPF system will lead to the engine becoming non-operational, this will stall any work scheduled for the asset and in turn affect operating costs
- Often there are work crews consisting of a number of personnel ranging from 2 – 10 people using the asset to complete work, an unscheduled repaired would lead to this becoming an unplanned cost
- Failure at a time when work is interrupting production would have an impact financially and would impact the customers

Non-operational Consequences: The DPF system does not have any assessed non-operational consequences.

The reasons the DPF system is not classed as non-operational consequences are:

- Failure of the DPF system does have an adverse effect on the non-direct cost of operation
- Failure of the DPF system affects productions output

4.4 Step 7: Modelling of Component

4.4.1 Collection of Reliable Failure Data

The identification and selection of the problematic systems has been carried out through a Pareto analysis and the historical failure data relating to the chosen systems was acquired for modelling. The data obtains the following parameters:

- Hours at failure (emergency replacement)
- Hours at schedule replacement
- Waiting time before repairs begin
- Number of failures
- Total operating hours
- Service time
- Emergency repair time

4.4.2 Statistical Analysis

The statistical analysis is described in the following steps:

1. **Classification of the data into either complete data or censored data**

   The data obtained requires classification into the correct category, which is either complete data or censored data. Complete data in this situation refers to knowing when all failures occurred with the assets and censored data refers to knowing only that data about failures which had occurred at the time measurement taken. The three sub-systems chosen for further analysis in this project fall under the censored data category, which is the most common.

2. **We conduct data ranking using the appropriate formula**

   Following the classification of data, it is then important to rank the data, data ranking is carried out using methods such as linear regression or maximum likelihood estimate. The choice depends on the input data, for example complete data or censored data. It is suggested for this projects data, which is censored data, to use the maximum likelihood method.

3. **Carry out the fitting of the data to the candidate models in their linear form with the criteria for precision**
   The ranked data is now converted into their linear form for ease of assessment.

4. **Model is chosen using engineering knowledge and from consultation with SME**
   The data model is now to be decided, this typically would fall under the responsibility of the SME or analyst. Data models for reliability engineering often follow the Weibull model however, it is important to consider other models such as Normal, Lognormal, and Exponential. For this project, the Weibull model was chosen for the analysis of the failure data and the Lognormal model was chosen for the analysis of the labour times.

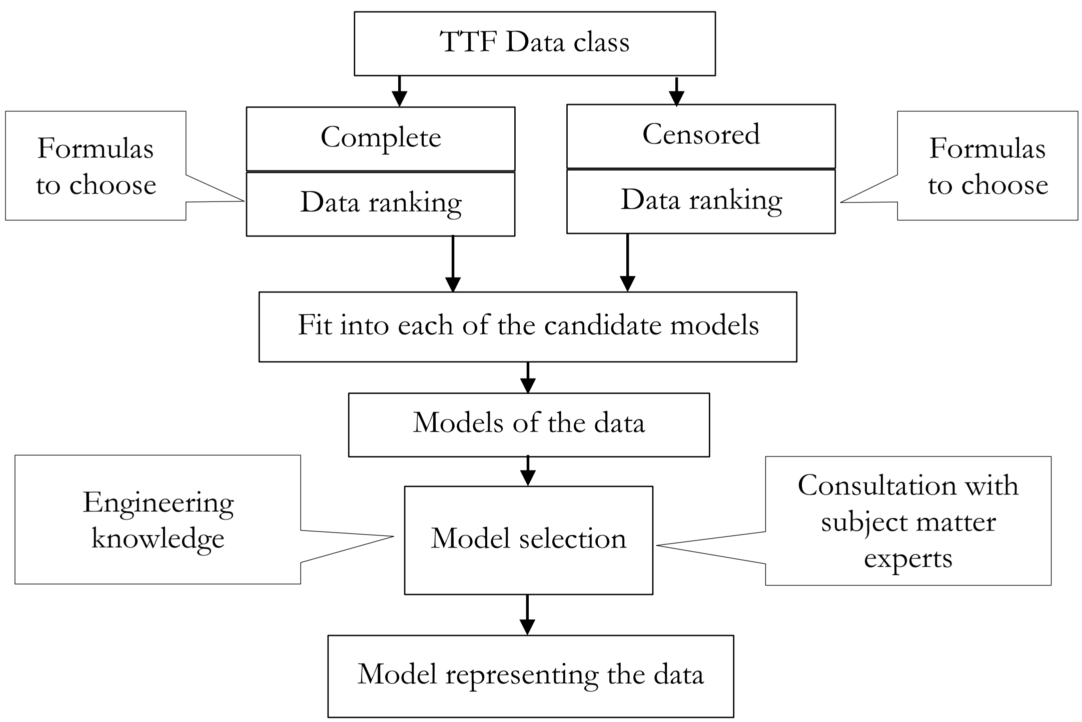

Figure 9: Statistical Analysis Flow Chart

The SME is required to input the selection of the model, for example, Weibull, Normal, Lognormal or Exponential. The MATLAB program then produces an output. Provided is an example of the MATLAB program output of the above steps.

```
WEIBULL MODEL FOR TTF
--------------------------------
Scale parameter a = 2196.198
Confidence interval for a
ans =
   1.0e+03

    2.1041
    2.2923
Shape parameter b =  8.143
Confidence interval for b
ans =
    6.1932
   10.7060
```

Figure 10: Weibull Model

In this example 95% confidence interval was selected

$$f(t) = \frac{b}{a}\left(\frac{t}{a}\right)^{b-1} e^{\left[-\left(\frac{t}{a}\right)^{b}\right]}, t \geq 0$$

In the probability density function for the Weibull model with 2 parameters the character alpha = scale parameter. The scale parameter is the time in which 63.2% of the units fail.

By 95% confidence level the program captures the scale parameter $2104 < a < 2291$ and the shape parameter is $6.1932 < b < 10.7060$.

4.5 Step 8: Simulate Models Against Maintenance Plan

Once the RCM analysis has been completed the decision maker can input the variables of the specific organisation into the MATLAB program. The variables for this project largely revolve around operational costs, operational hours of the asset and the system components, repair and service time in hours and downtime of asset in hours. From an Excel spreadsheet the simulation program then takes the acquired data and applies the Monte Carlo method to simulate the randomness of reality. In this project, forty lifecycles were applied to a single simulation and then twenty simulations on each system were run. The results can be inspected Appendix C.

The following steps were performed:

1. **Build the objective function by consultation with decision makers and SME**

   The objective function is derived through consultation with a number of individuals responsible for decision making, consultation with SMEs are also carried out to ensure the objective function is technically sound.

   Within this project the objectives were set as costs per operating hour and availability of the unit in terms of percentage.

$$TC = srCost + erCost + srDownCost + erDownCost$$

TC is the total cost in dollar per operating hour, srCost is schedule replacement cost in dollar per operating hour, erCost emergency replacement cost is in dollar per operating hour, srDownCost is cost of downtime due to schedule replacement in dollar per operating hour, erDownCost is cost of downtime due to emergency replacement in dollar per operating hour.

$$srDownCost = DownCostS \times \frac{TST}{TOT}$$

$$erDownCost = DownCostE \times \frac{TET}{TOT}$$

DownCostS is the downtime cost in dollar per hour due to schedule replacement, DownCostE is the downtime cost in dollar per hour due to emergency replacement, TST is total schedule replacement time, TET is total emergency replacement time, TOT is the total operating time of the machine in hours.

$$srCost = \frac{\left(TST \times laborS + NS \times (headS + matCost - \ scrap\_value)\right)}{TOT}$$

$$erCost = \frac{\left(TST \times laborE + NE \times (headE + matCost)\right)}{TOT}$$

LaborS is the labor cost in dollar per hour for schedule replacement, NS is the number of scheduled replacements in one simulation, headS is the overhead cost for each schedule replacement, matCost is material cost, scrap value the salvage value.

LaborE is the labor cost in dollar per hour for emergency replacement, NE is the number of emergency replacements in a simulation, headE is the overhead cost in dollars for each emergency replacement.

The availability objective is calculated as follows

$$Availability = \frac{TOT}{TT} \times 100\%$$

$$TT = TOT + TST + TET$$

TST is the total schedule replacement time in hour including the waiting time for one simulation, TET is the total emergency replacement time in hour including the waiting time. Modelling for the time required to complete the replacement jobs using data collected from the company history records is carried out using the lognormal model.

For waiting times only minimum and maximum hours were available for future simulations the waiting times are predicted as uniformly distributed random numbers between minimum and maximum values.

Each lifecycle represents the time to failure or the time to schedule replacement, whichever comes first. The number of lifecycles for any simulation should not be too big or too small, the reason for this is if number of lifecycles is too many then it's projecting too far into the future which can be beyond the validity of the situations that occurred in the past. For example, there may be changes in technology, suppliers, and standards. If the number of lifecycles is too few, then the situation could arise where the simulation suggests that change may be required too often which could lead to unrest within an organisation.

This project chose to run forty lifecycle simulations within the simulation modelling.

2. Run simulation on each system, failure pair against each maintenance plan

The simulation model is built using MATLAB analysis software. MATLAB allows flexible programming to ensure objectives can be met using the owner's specific requirements. The MATLAB program constructed for this project incorporates statistical data analysis and Monte Carlo (probabilistic) modeling that allows for multiple scenarios and any number of trial runs desired. The advantage of the probabilistic modelling is that it allows the asset owner or decision maker to 'test run' their plan without the risks of having to complete it before seeing the possible results.

The input data from the Excel spreadsheet may be found in Appendix B. The variables are defined as follows: H = time to failure and time to schedule replacement, C = censoring vector failure or no failure, H1 = emergency replacement time from the past records, H2 = schedule replacement time for the past, headS = overhead cost for each schedule replacement in dollar amount, overhead E = overhead cost for each emergency replacement, LaborS = labor cost per hour for schedule replacement, Labor E = labor cost for emergency replacement.

The input data placed directly into MATLAB is as follows: the confidence level was set at 95%, the number of lifecycles to simulate, the minimum and maximum waiting hours for emergency replacement, the minimum and maximum waiting hours for schedule replacement, the downtime cost per hour for schedule replacement, and the downtime cost per hour for emergency replacement. The maintenance plan hours is input into MATLAB in three numbers, minimum, increment and maximum.

Below is an example of the output graphs of the simulations. Output graphs for each simulation may be found in Appendix C.

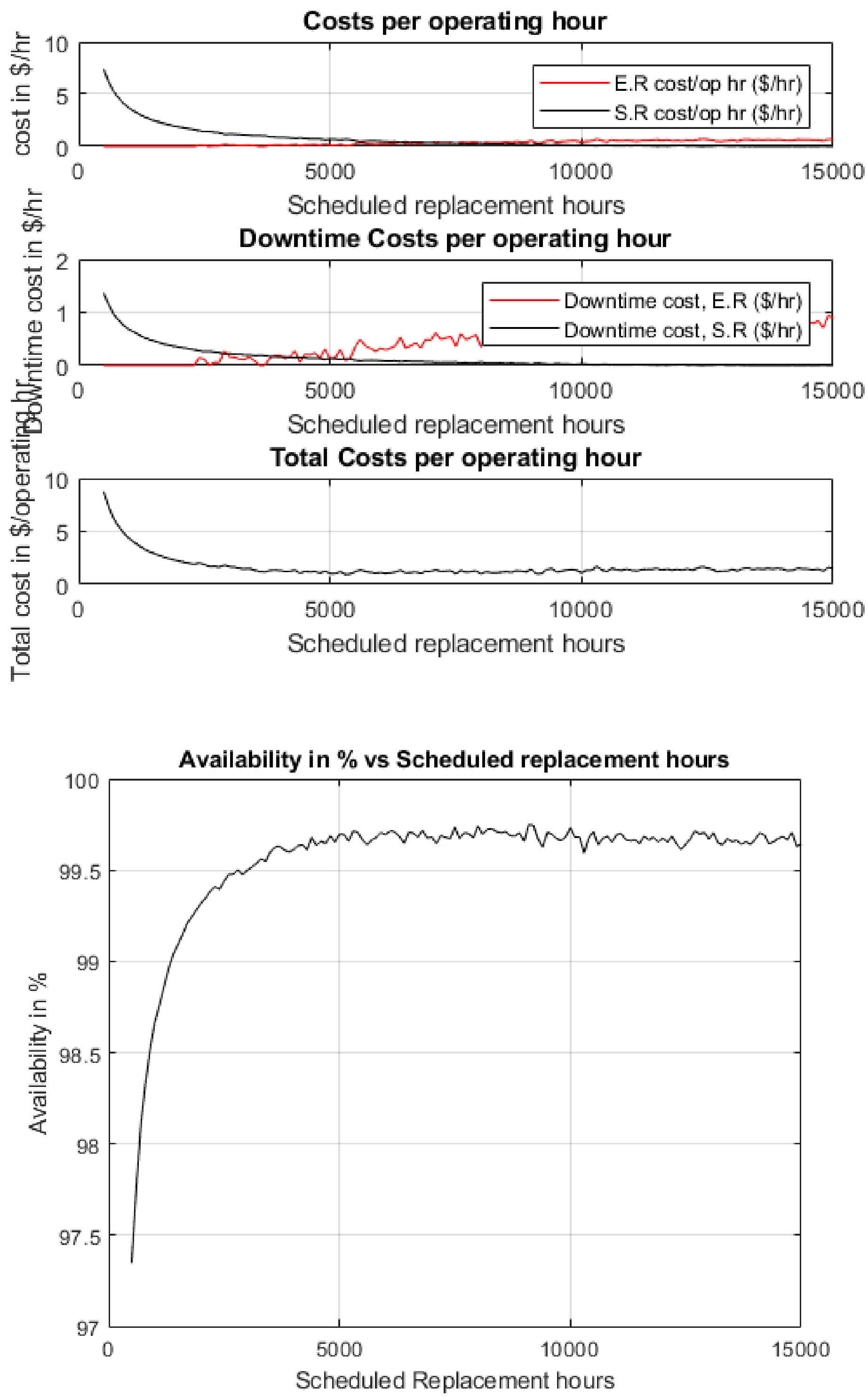

Figure 11: Sub-System 1: Example of EGR System Output Graph

3. **Organize the data**

   The output data that is produced from multiple runs of the program is produced directly into an Excel spreadsheet to allow ease of viewing and further analysis can then be carried out if so desired.

4. **Decision maker takes output of the objective function values with respect to each maintenance plan**

   The decision maker takes the output from multiple runs and multiple variables and can then get a numerical description and a visual description of the output. The information gained from the modeling can supplement the knowledge of the SMEs and decision makers. The output information can also be used to assist in building a larger or longer-term picture of the maintenance plan and potential outcomes. This is in contrast to an RCM analysis which alone relies heavily on qualitative descriptions and group recommendations.

4.6 Chapter Summary

Chapter 4 detailed Steps 5 through 8 which progresses through from failure detection to consequences followed by modelling and analysis. A summary of the steps is detailed below.

1. Failure detection: The point at which the failure becomes detectable through some method of inspection. The methods of inspection for each sub-system were presented.
2. Failure consequences: The chosen sub-systems and its components were evaluated against four criteria; safety consequences, environmental consequences, operational consequences and non-operation consequences. The evaluation of consequences of failure assists in determining maintenance activity priorities as well as preventative measures through design improvement.
3. Modelling of components: A Pareto analysis was used in the identification and selection of the problematic systems and historical failure data for each sub-system was acquired for modelling. The four steps involved in the statistical analysis process was explained and an example of the Weibull model is presented.
4. Simulate models against maintenance: MATLAB programming is used implement the Monte Carlo method to simulate the randomness of reality. The four steps involved in the simulation and modelling against maintenance plans are detailed.

Chapter 5

Reliability-Centered Maintenance Discussion of Results

5.1. Chapter Overview

Chapter 5 provides a discussion and implementation of the results obtained in Chapter 4. This includes the following adapted from the RCM methodology:

1. Key findings
2. Implementation
3. Assumptions, Limitations and Deviations

5.2. Step 9: Key Findings - Summary and Discussion

The ability to simulate future possibilities repeatedly with relatively low cost that provides increased confidence in the result of the simulation if the results follow the same patterns.

The outcome of applying probabilistic modelling to the RCM analysis allows for the ability to simulate future possibilities repeatedly with relatively low cost and the simulations provide increased confidence if the results follow similar patterns.

Sub-System 1: EGR System

The hybrid analysis of the EGR system produced an output that may indicate, according to total cost and availability that run to failure looks like a viable option. During the RCM analysis however the EGR system was found to be an environmental and operational consequence, this would suggest that using a run to failure plan would not be a viable option. In accordance with RCM rules after analysis, if it is found that the system carries environmental and operational consequences and there is no effective preventative maintenance that can be administered then a redesign may be an option. Given the complexities of the EGR system it is recommended that the organisation consider other engine manufacturers going forward that use a different method for emissions reduction.

Sub-System 2: Cooling System

The hybrid RCM analysis of the cooling system produces a definitive result in terms of the total cost. It can be observed that it is likely the cooling system should have a preventative maintenance program that focuses on detailed inspections around the 1000 hour mark. The 1000 hour mark is also when availability is generally at its highest. Given these two features of the probabilistic analysis and combined with the RCM analysis of the system being an operational and environmental consequence system, then this would likely help to defend the SMEs decision to implement such a plan. An alternative simulation was run with adjusted parameters on the cooling system and it was observed that the downtime costs at 1000 hours starts to climb sharply. In reality, a company's overheads cannot be changed as easily as changing a number in a program however these simulations can give the decision maker and insight into changing other processes such as the waiting time for parts. Depending on the circumstances, the organisation may not be able to do anything about the maintainability of a given system, instead they can offset the costs of these failure by improving the processes surrounding the operation.

Sub-System 3: DPF System

The hybrid RCM analysis of the DPF system shows that generally, availability is at its highest around the 1500 hour mark on average with total cost around it lowest at the 1500 hour mark also. It can be observed that the total cost is increasing after the 1500 hour mark and that availability drops off significantly. Together with the RCM analysis and DPF system being defined as having operational and environmental consequences, the probabilistic outputs on the future scenarios would indicate that constructing a scheduled replacement maintenance program may be beneficial.

The construction of a maintenance plan is often complicated and requires the consideration of many variables, this can sometimes produce a cautious approach which in turn could lead to high costs and could make the organisation uncompetitive. The methodology constructed for this project allows for 'trial runs' of an organisations assumptions and input variables, the incorporation of probabilistic modelling into the RCM process will simulate the probabilities of the outcomes to a desired amount of trial runs.

Although the Pareto analysis at the start of the RCM analysis identifies which systems or components are the cause around 80 percent of the issues, which is where the analysis ends. When conducting the probabilistic modelling on those chosen systems that are causing issues, the user has the ability to further analyse these systems in greater detail and with different input variable that once again allows variations on outcomes.

When the results of each output are graphed for example the total costs per operating hour there is more to be read from that graph besides the obvious values. A total costs per operating hour graph plot that has somewhat of a 'Bathtub' shape can be observed to start off at a higher value then come to some minimum amount and then curve back up at the end. The key takeaway from this graph is that when costs are the main concern as opposed to reliability or another factor then the decision maker can see when the maintenance plan costs are at its lowest, this can also be seen numerically in the Excel sheet print out.

When the results of the total costs per operating hours graph starts out higher then transitions into a constant or straight line, the takeaway from this shape of graph is that once the curve flattens out it does not matter when you conduct maintenance or repair and a run to failure mode may be acceptable. It should be noted that this example is a simplified view, of course the SME decision maker would need to consider the RCM objectives such as whether the system is a safety, environmental, operational or non-operation concern. If the system alone was a non-operational concern then a likely logical choice would to be a run-to-failure strategy.

5.3. Step 10: Implementation

For this project, the author focused firstly on the power plant system with its attached sub-systems, after accessing the failure data and carrying out the analysis on the most problematic systems, the new methodology was applied. In reality, the creation of a comprehensive maintenance plan must take into consideration many factors and the asset as a whole. Some literature claims that while carrying out an original RCM study many organisations can take a number of months just on completing a few steps of the seven step process. The fact that it can take RCM working groups a substantial amount of time to complete the RCM study and then put forward their plan that can then be largely qualitative and based on a select few experts often causes frustrations at the administrative level. RCM was created in the airline industry only after they realised their approach to maintenance needed to change after suffering too many reliability issues and it became a major concern. With examples like the airline industry or large complex assets such as in the mining industry, RCM is an easier "sell" to administrators and provides them a systematic process that is defendable under scrutiny. However, in industries where the assets don't have the same acquisition price tag as a Boeing 747 or a mining dump truck, RCM seems like a large upfront cost that the organisation will never see returned. RCM is proven to be beneficial in many industries, regardless of asset type, the goal of the author's hybrid methodology is to create a way in which organisations can see probable outcomes of their assumptions without having to wait years before seeing if their assumptions and analysis are correct. It should be noted that we live in an environment where change is unavoidable, therefore a maintenance plan needs to be dynamic and always under scrutiny. The probabilistic method allows the user to input these changing variables at any time and assess what the outcomes may be.

5.4. Step 11: Assumptions, Limitations and Deviations

Statistical Modelling

The modelling of component data can only produce beneficial results if the data is accurate, while all due care was taken to acquire quality data there may be some inadequacies. This was acknowledged by the SME at the organisation and under further work I have sighted this as a potential topic for further study.

RCM Working Group

RCM literature states that the analysis benefits from having an RCM working group comprised of participants from key areas in the organisation. This was explored however due to time restraints and then the restrictions placed on personnel due to the Covid-19 global pandemic a working group was not possible. To mitigate this the author did consult with several SME with respect to the project, and through this a good outcome was achieved.

Time Restraints

A full RCM analysis can take a considerable amount of time to complete, with the restrictions place on time for this project a full RCM analysis was not possible.

5.5. Chapter Summary

Chapter 5 provided a discussion of the key findings for each sub-system investigated in this project and the implementation of hybrid methodology approach to RCM and PM planning. Finally, assumptions and limitations identified in the course of the project are presented.

Chapter 6

Conclusions and Further Work

6.1. Chapter Overview

Chapter 6 reviews the project objectives presented in Chapter 1 and discusses the achievement of these objectives based on the project works. As a result of the findings, further works regarding the implementation of a hybrid RCM methodology are discussed. Finally, a reflection on the project and the process is provided.

6.2. Achievement of Project Objective

The project aimed to establish a modified maintenance assessment and optimization program for on-road vehicle fleets by incorporating probabilistic methods of analysis into traditional and existing Reliability Centered Maintenance (RCM) methodology.

The research objectives as discussed in Section 1.2 and in the Project Specification in Appendix A are addressed and concluded below:

1. **To conduct a review of the literature relevant to RCM, probabilistic modelling and optimization**
   The project was an opportunity for the author to understand reliability centered maintenance at a deeper level, RCM is widely used in many industries and it was a strategic choice by the author to use this opportunity to gain this knowledge. Learning about probabilistic modelling and optimization and then combining these with RCM into a hybrid methodology was successfully achieved.

2. **To develop and identify a method of identifying changing maintenance requirements**
   An RCM analysis can be undertaken at any point in the assets lifecycle and from the RCM analysis a maintenance plan is usually formed. The hybrid methodology combines RCM with probabilistic modelling and has the ability to forecast the probable outcomes of any maintenance plan. This was observed with the outcome of the three systems that were assessed within this project.

3. **Identify whether the data from the companies maintenance system is adequate and identify areas of weaknesses and opportunities**

   During the course of the project and the literature review it was discovered that within the maintenance industry there is an issue with data acquisition, accuracy, storage and the ability to process it. While conducting literature reviews on many similar papers, most authors discussed the problems with accessing useful data. Textbooks on the subject often warned about the challenges of understanding any data that may be available if there was any available. This project was no different, the data used in this project was painstakingly acquired and at times difficult to access. This is an area in which many organisations have many opportunities for improvement.

4. **To identify the system and or sub-systems for study, the failure modes and their consequences, data collection and choosing models in cooperation with subject matter experts**

   The project was successful in identifying the systems for study, this came after acquiring failure data, performing a Pareto analysis to identify problematic systems and conducting the RCM analysis. While there was consultation with SMEs it was limited due to significant changes within the organisation due to the Covid-19 pandemic.

5. **To identify the maintenance plans with high probability of producing best reliability in the future, based on the past data and using optimization tools and acceptable models**

   This objective was achieved and can be observed in the appendix section

6. **To translate, present and discuss the results and benefits of such RCM**

   This objective was achieved through the presentation in PP2 ENG4903 and throughout this dissertation.

7. **To present technical details encountered in design, set up and the operation of a Hybrid RCM Program in a large public utility company**

   Reliability Centered Maintenance program in a large public utility company.

8. **To translate, present and discuss the results and benefits of such a RCM**
   The reality of setting up a full RCM program within an organisation was not possible given the time restraints of this project, however, it was possible to select a few critical systems to test the hybrid methodology on and confirm the output could potentially be of use to an organisation.

9. **Present technical details encountered in design, setting up and the running of a Hybrid**
   This objective is covered throughout the dissertation and the author believes an understanding of how this could be achieved would be gained from reading the dissertation. The construction of the MATLAB program in appendix C is also part of the technical aspect of the methodology.

6.3. Further Work

During the data collection phase of the project it was realised that there are many challenges in this area of maintenance, this is an industry wide problem as was discovered during the literature review. Many organisations have substantial investments in data collection software systems however in this circumstance it does not appear that it is being used to its potential. Further investigation about data collection and utilisation would be a worthwhile endeavor, it would also be beneficial to investigate the potential of automating the process of carrying out data analysis such as Pareto and perhaps linking it to the MATLAB program directly.

6.4. Project Reflection

The project began with the idea of gaining a better understanding of what RCM entails, the advantages and disadvantages, how it is conducted and why organisations use it. The author, before undertaking this project had a limited understanding of RCM and thus upon reflection feels like new knowledge has been acquired. The idea of combining RCM with probabilistic modelling came from the author's experience where they observed the difficulties in trying to get 'buy in' or support from those that oversee the organisation and perhaps do not have the necessary background to fully appreciate maintenance. It was also observed that RCM has the added challenge of being largely qualitative thus compounding the issues of gaining support from those that oversee. The addition of probabilistic modeling into RCM allows everyone involved to gain a better quantitative aspect of the whole process and in turn it is likely to more enthusiastically endorsed.

6.5. Chapter Summary

Chapter 6 revisits the project objectives and identifies the achievement of each objective from the project works. Based on the project findings and process, a discussion is provided as a guide for future investigation. The chapter is concluded with a reflection on the project process.

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Appendix A

Project Specification

ENG 4111/4112 Research Project

Project Specification

For: Cliff Mylrea

Title: A Reliability Centred Maintenance program incorporating probabilistic based simulation

Major: Mechanical Engineering

Supervisor: Dr Steven Goh

Sponsorship: N/A

Enrolment: ENG4111 – EXT S1, 2020 ENG4112 – EXT S2, 2020

Project Aim: Using a hybrid version of RCM, identify the maintenance plans with high probability of producing best reliability in the future, based on the past data and using optimization tools and acceptable models.

Programme: Version 2, September 1, 2020

Objectives/Stages:

1. Review literature relevant to RCM, probabilistic modelling and optimization.
2. Develop/identify a method of identifying changing maintenance requirements
3. Identify whether the data from the companies maintenance system is adequate and identify areas of weaknesses and opportunities.
4. Identify the system and or sub-systems for study, the failure modes and their consequences, data collection and choosing models in cooperation with subject matter experts.
5. Identify the maintenance plans with high probability of producing best reliability in the future, based on the past data and using optimization tools and acceptable models.
6. To translate, present and discuss the results and benefits of such a RCM.
7. Present technical details encountered in design, setting up and the running of a Hybrid Reliability Centered Maintenance program in a large public utility company.

Appendix B

Input Data

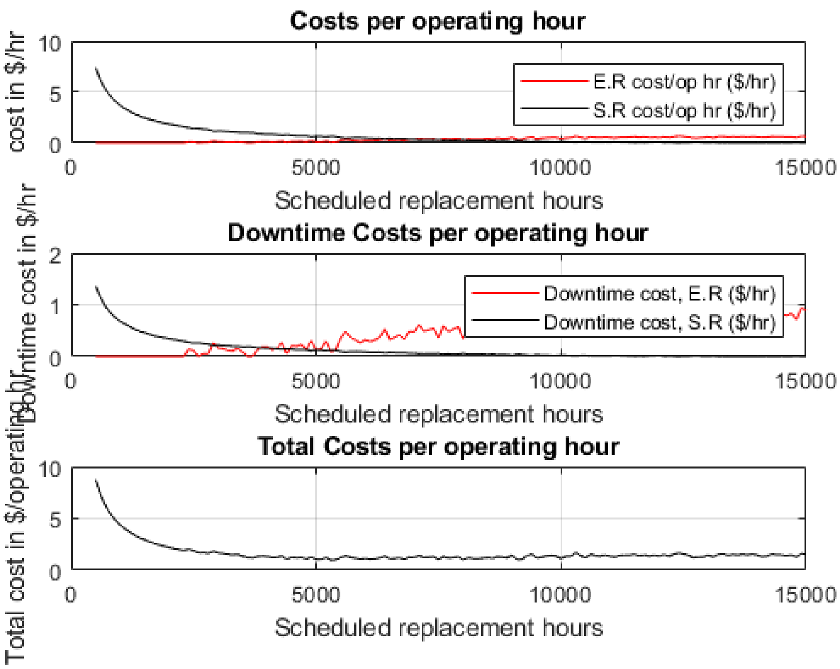
Sub-System 2: Cooling System Input Data

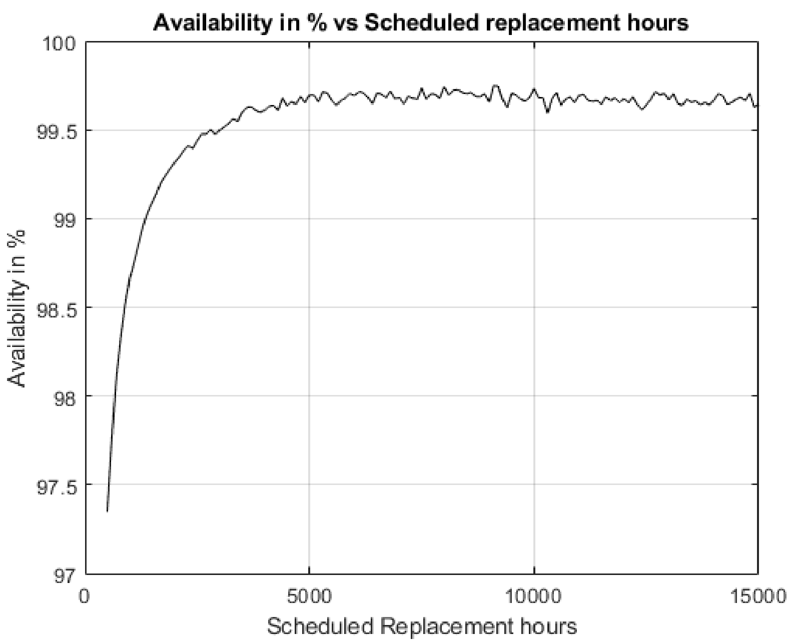
H	C	H1	H2	Overhead S	Labour S	Overhead E	Labour E	Mat Cost
1452	0	6.9		100	80	200	80	200
1063	1		1.8					
1456	0	8.9						
1316	0	5.9						
1048	1		1.6					
1139	0	7.4						
1273	0	8.2						
1478	0	8.5						
1482	0	8.7						
1078	1		1.5					
1485	0	6.3						
1478	0	8.2						
1242	0	5.8						
1400	0	5.6						
1070	0	7.5						
1210	1		1.9					
1457	0	6.7						
1396	0	7.9						
1469	0	6.1						
1327	0	8.7						
1017	1		1.3					
1424	0	7.5						
1467	0	8.5						
1394	0	9.4						
1378	0	9.7						
1371	0	7.7						
1196	0	5.7						
1327	0	6.2						
1085	0	9.2						
1353	0	9						
1015	0	6.2						
1138	0	9.6						
1032	0	5.9						
1048	0	8.2						
1411	0	7.4						
1347	1		1.9					
1158	0	7.4						
1475	0	5.9						
1017	0	6.7						
1219	0	7.5						

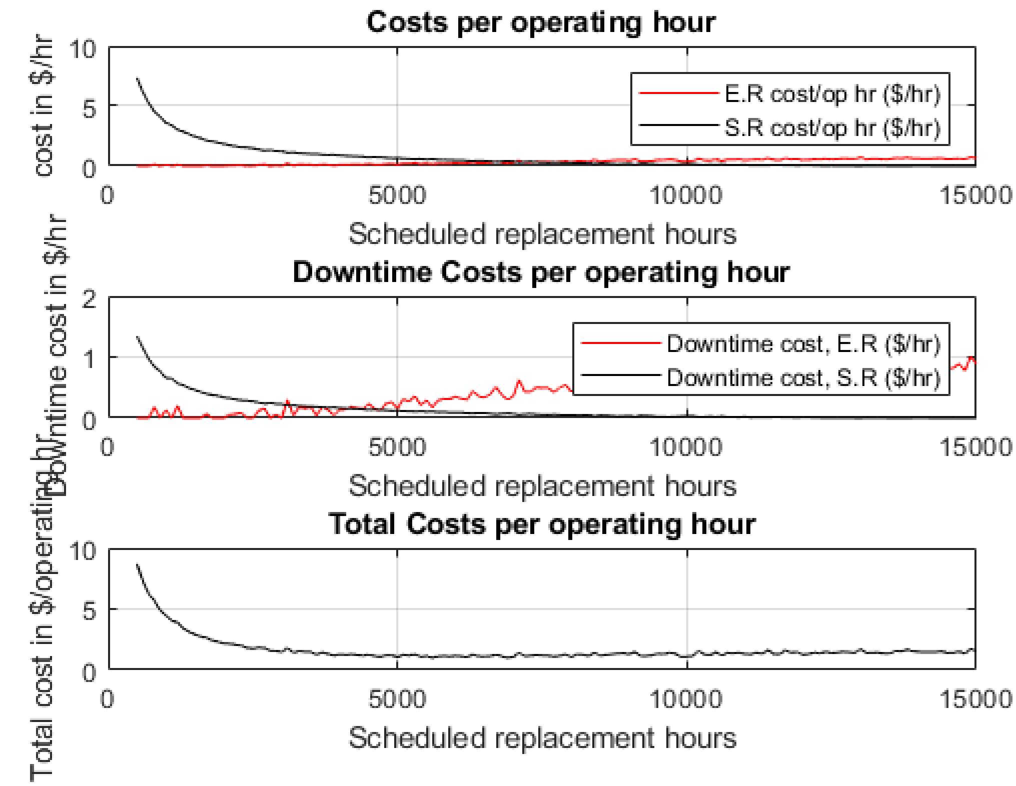
Appendix C

Output Graphs & Data

Sub-System 1: EGR System Output Graphs







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S.R cost/op hr ($/hr)
Scheduled replacement hours
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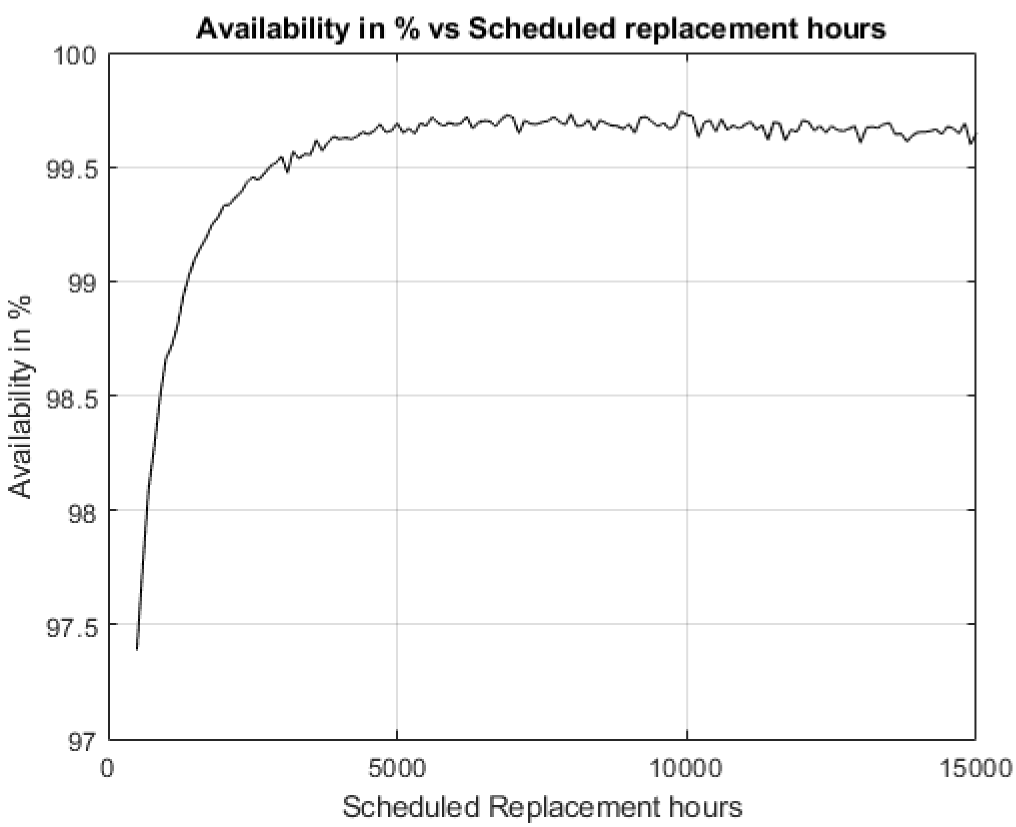
Downtime cost, S.R ($/hr)
Scheduled replacement hours
Total Costs per operating hour
Total cost in $/operating hr
Scheduled replacement hours



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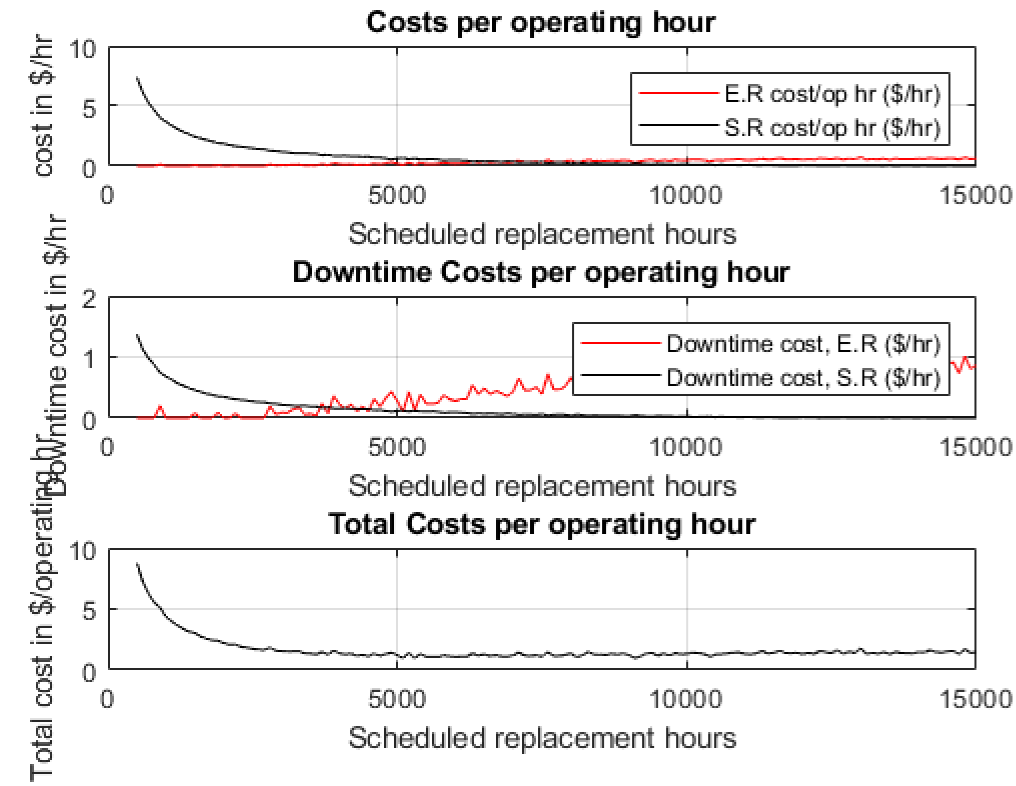
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Scheduled replacement hours
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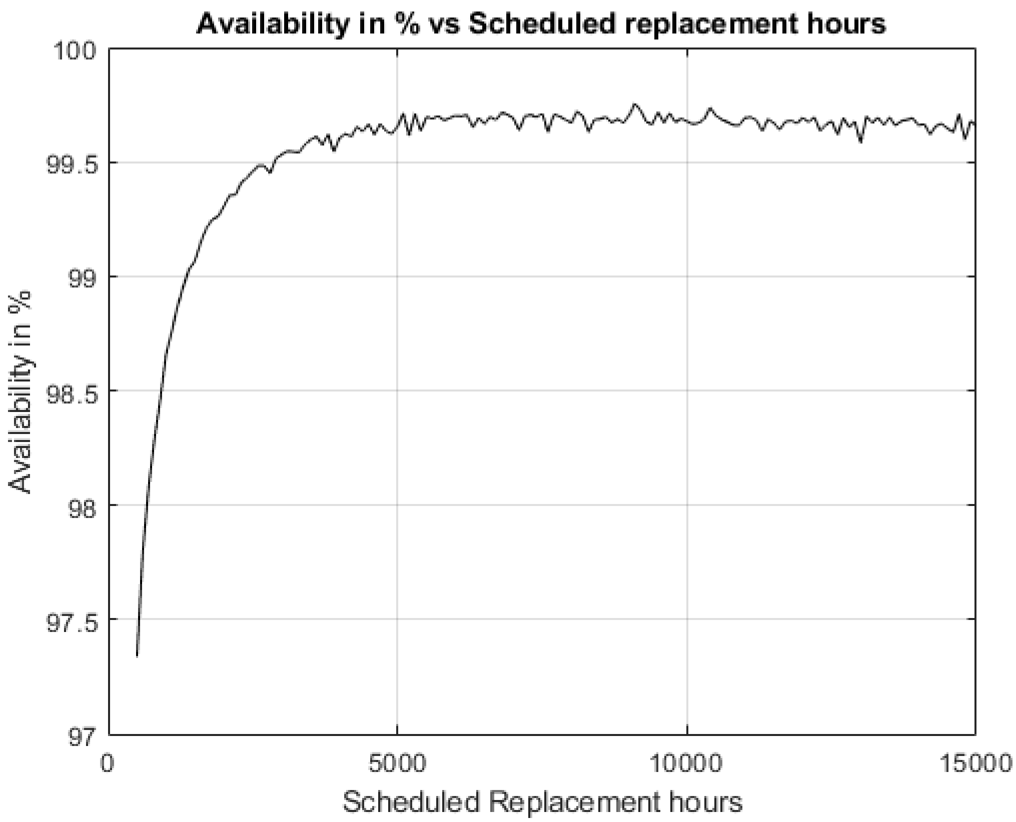
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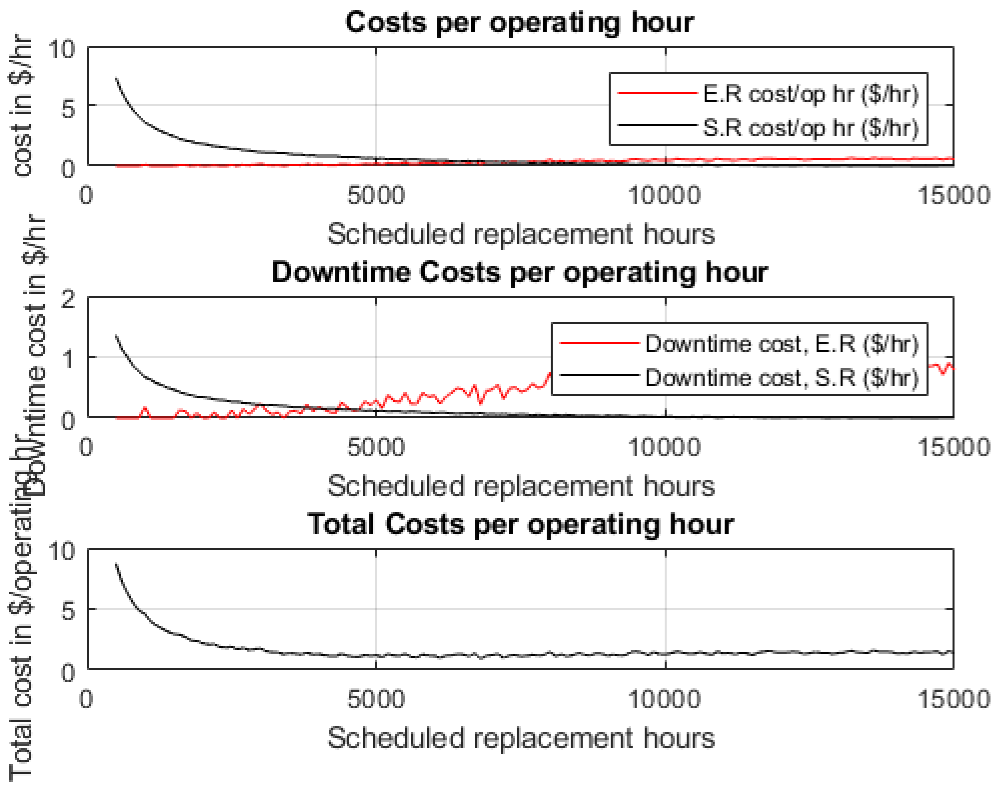

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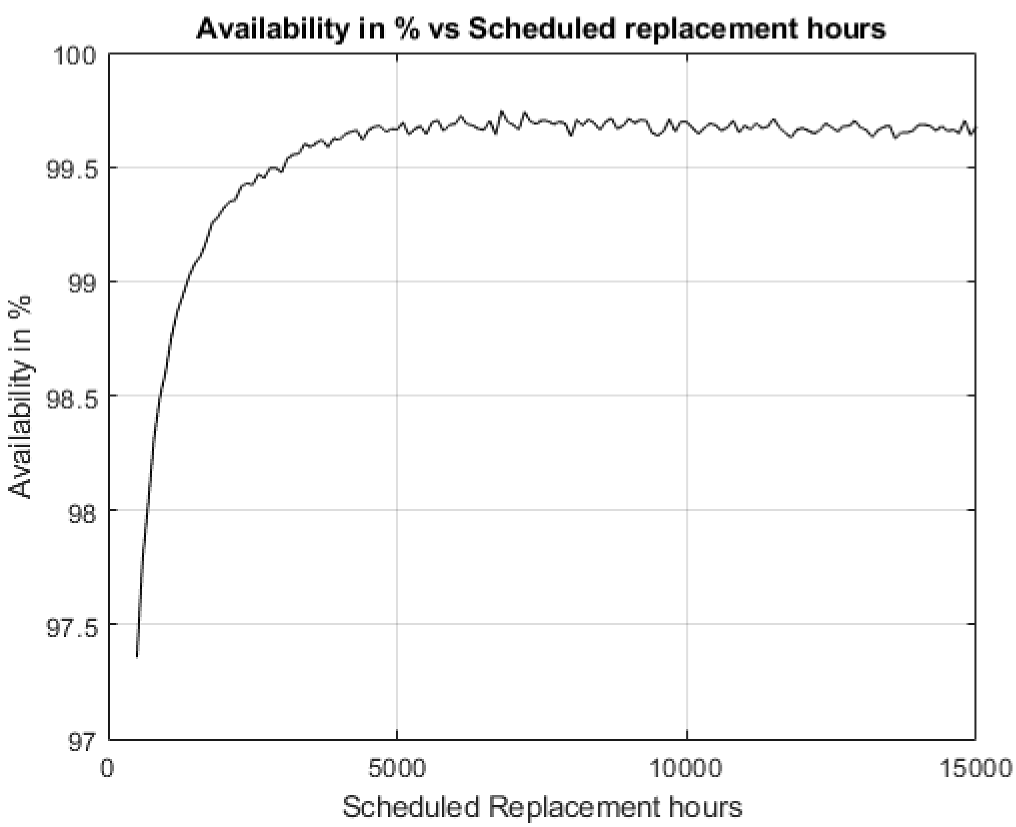

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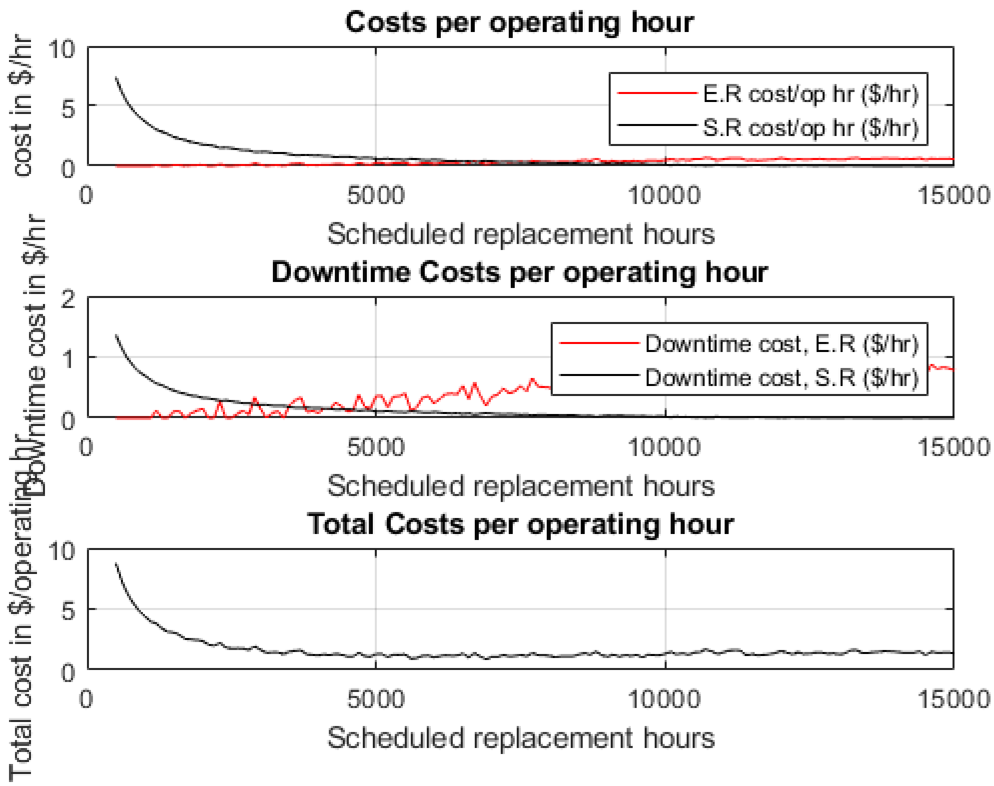
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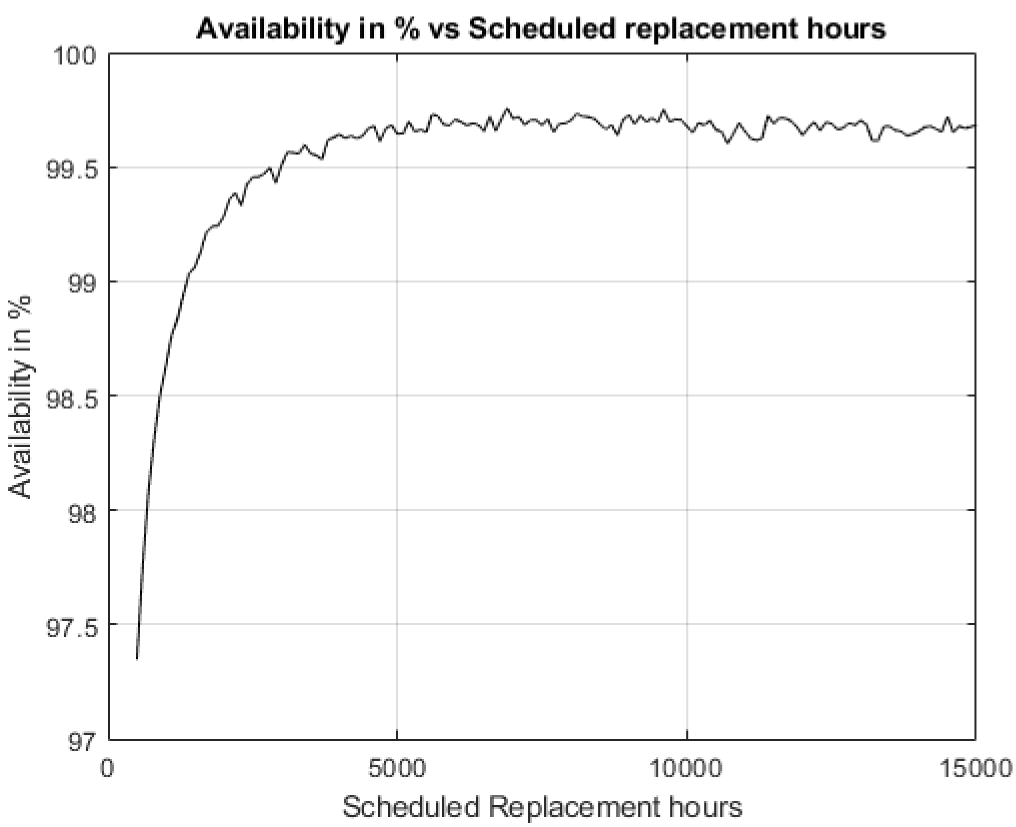
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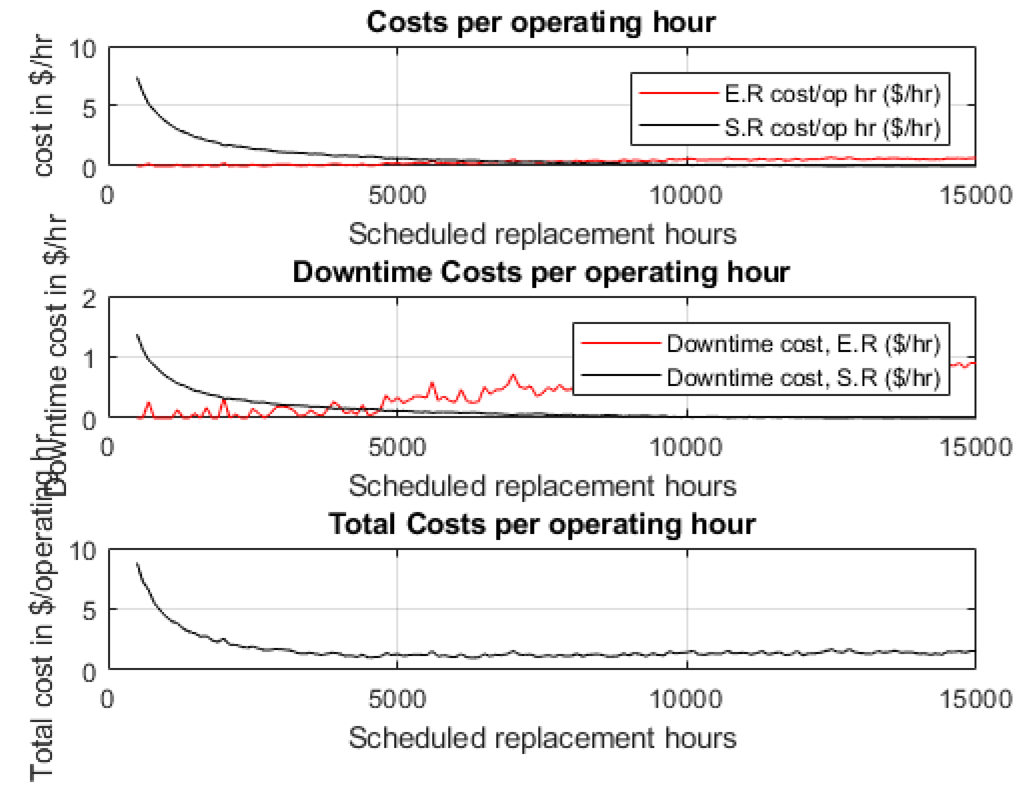

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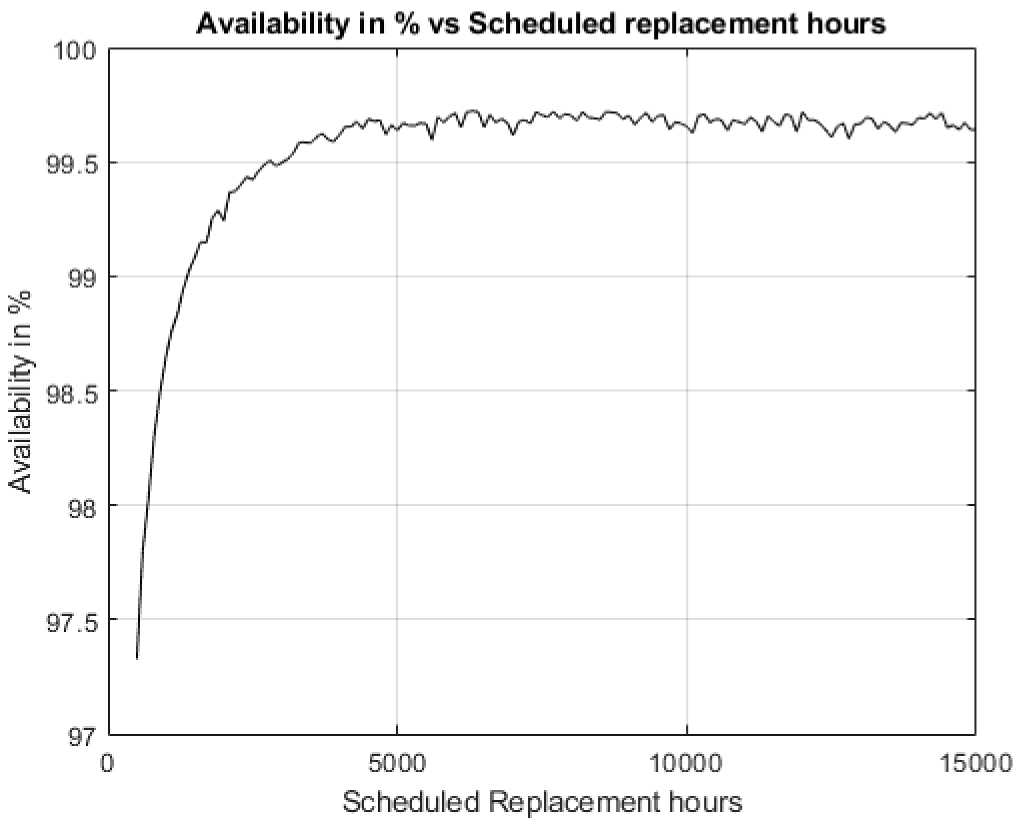

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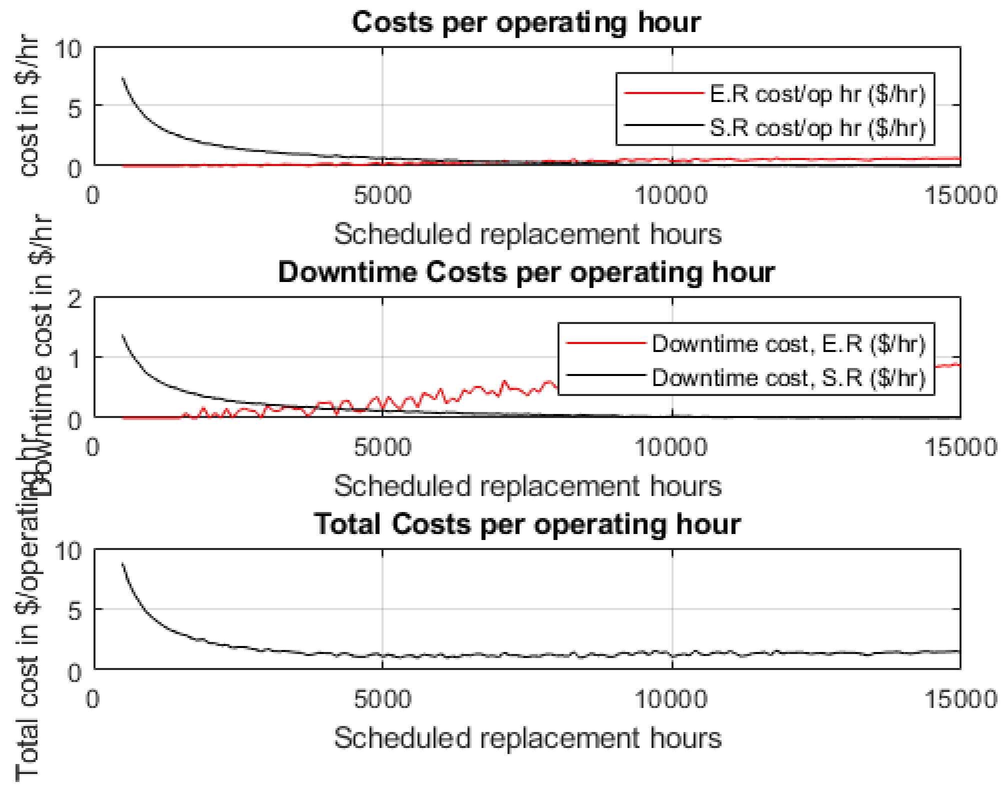
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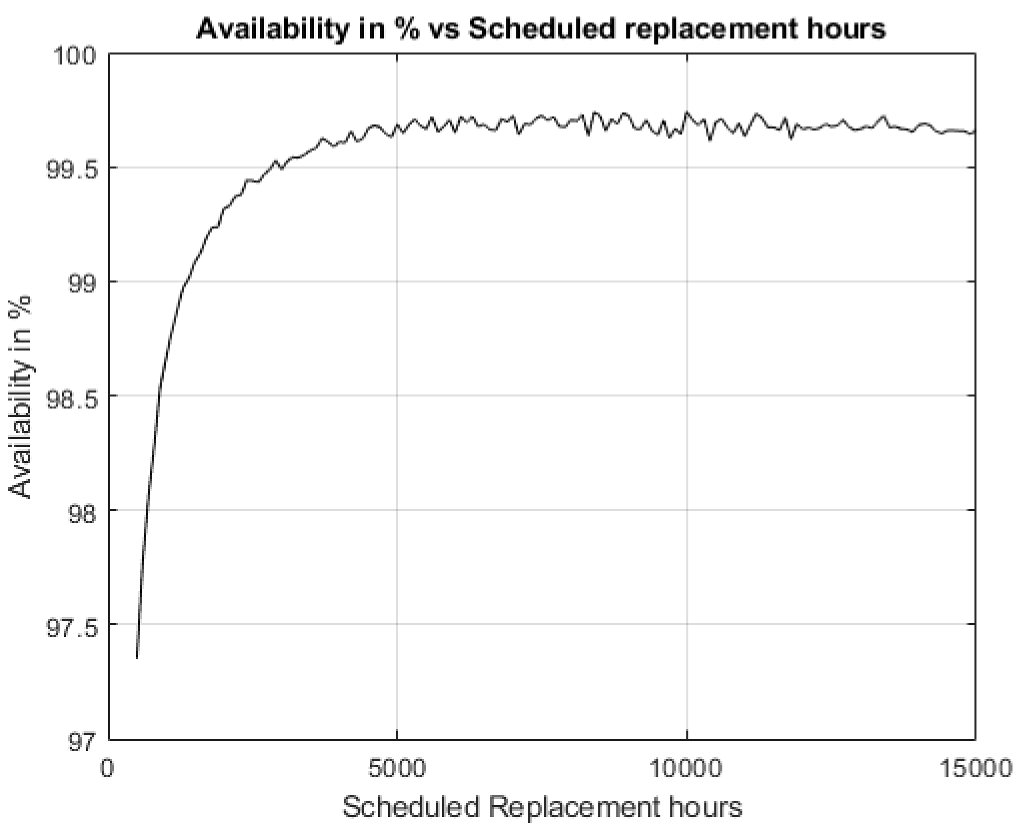
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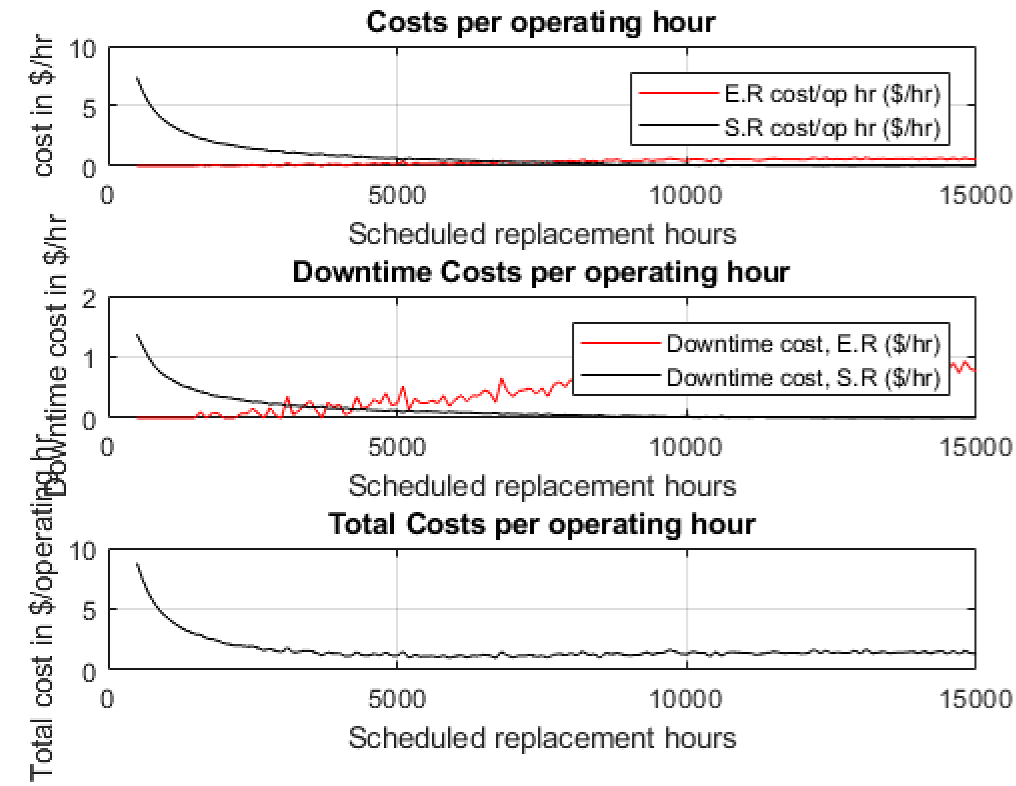
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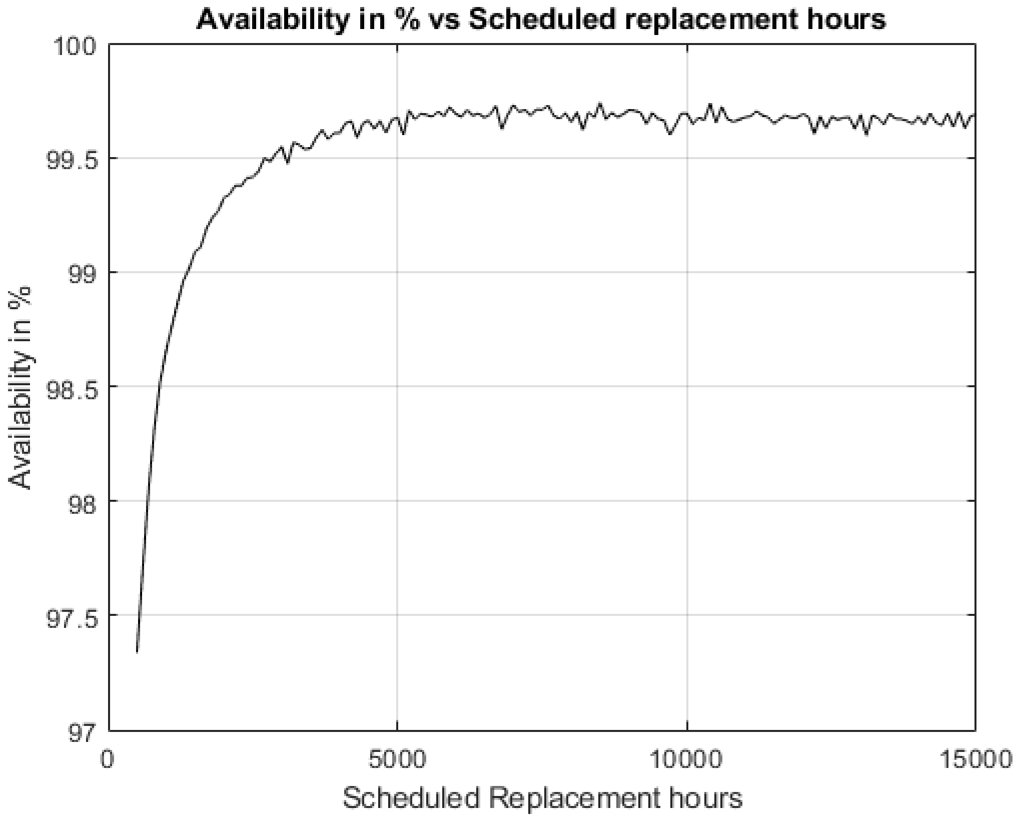
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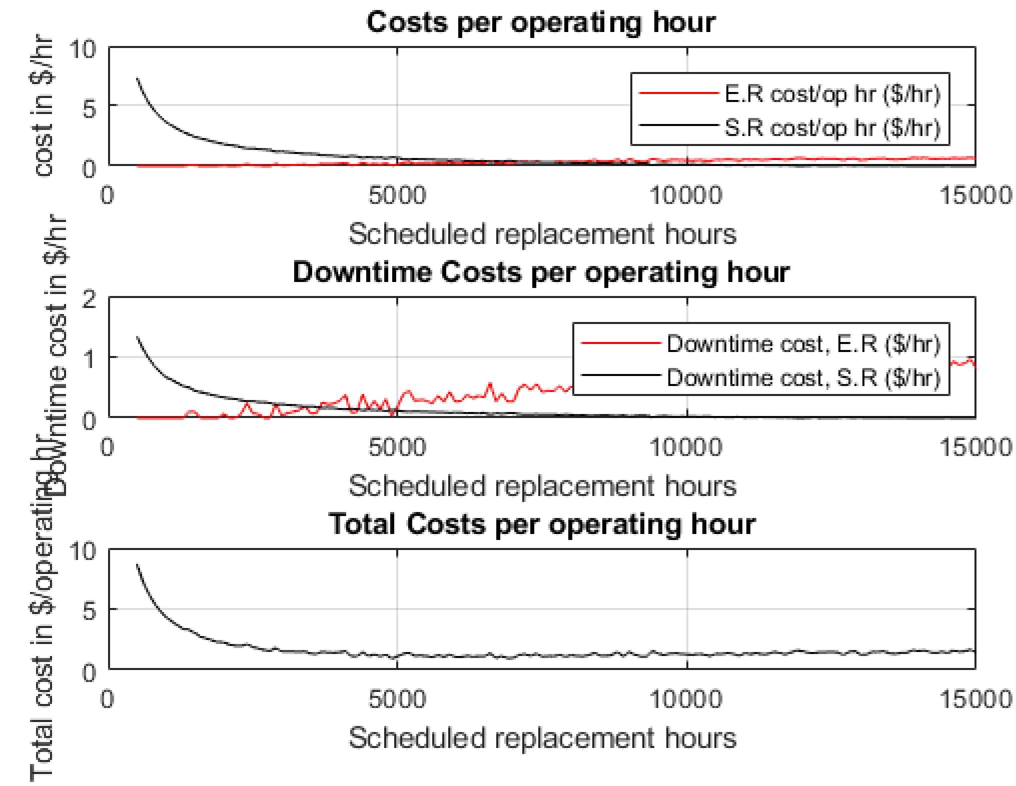
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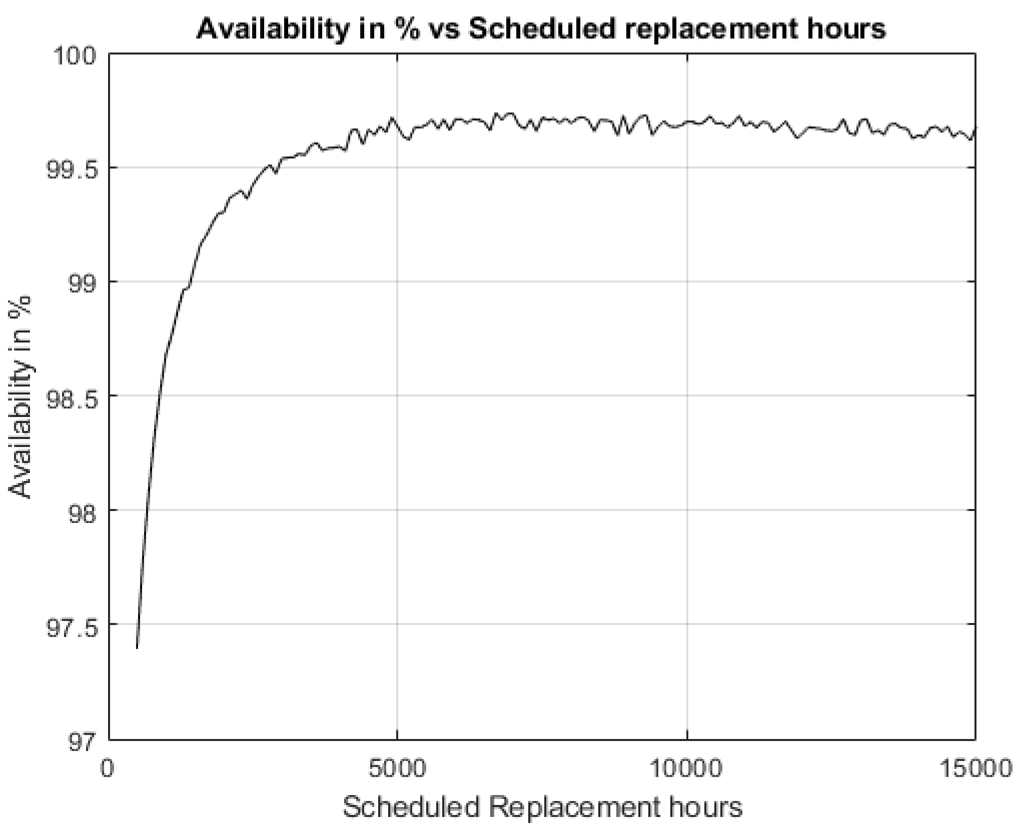
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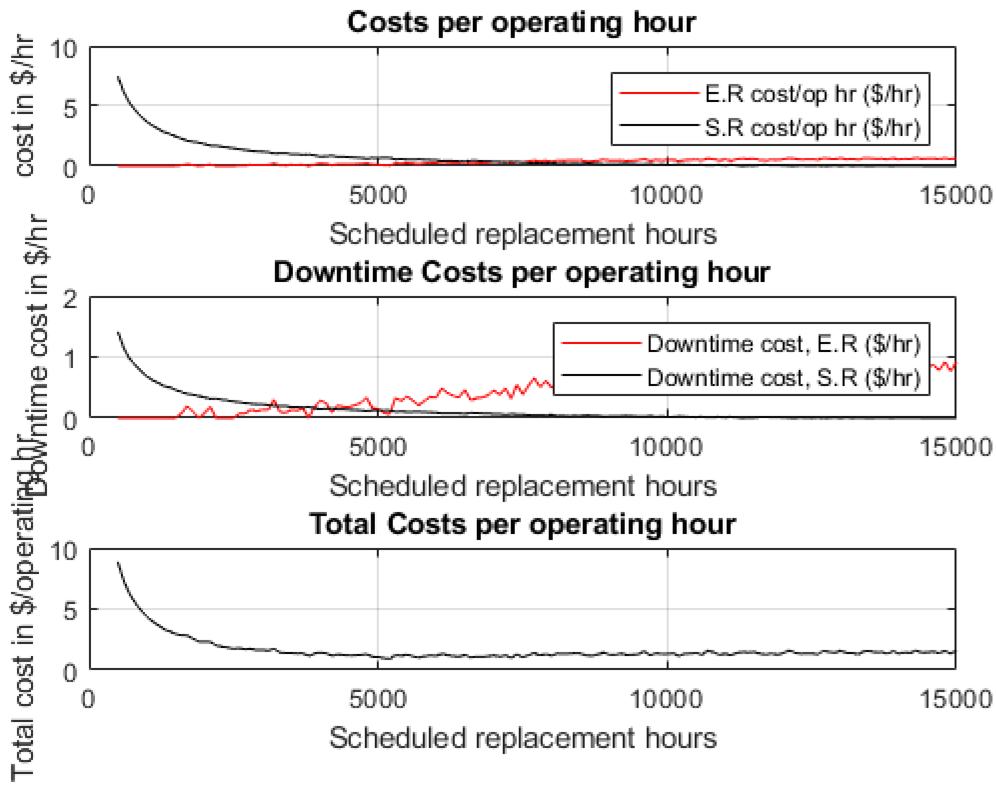
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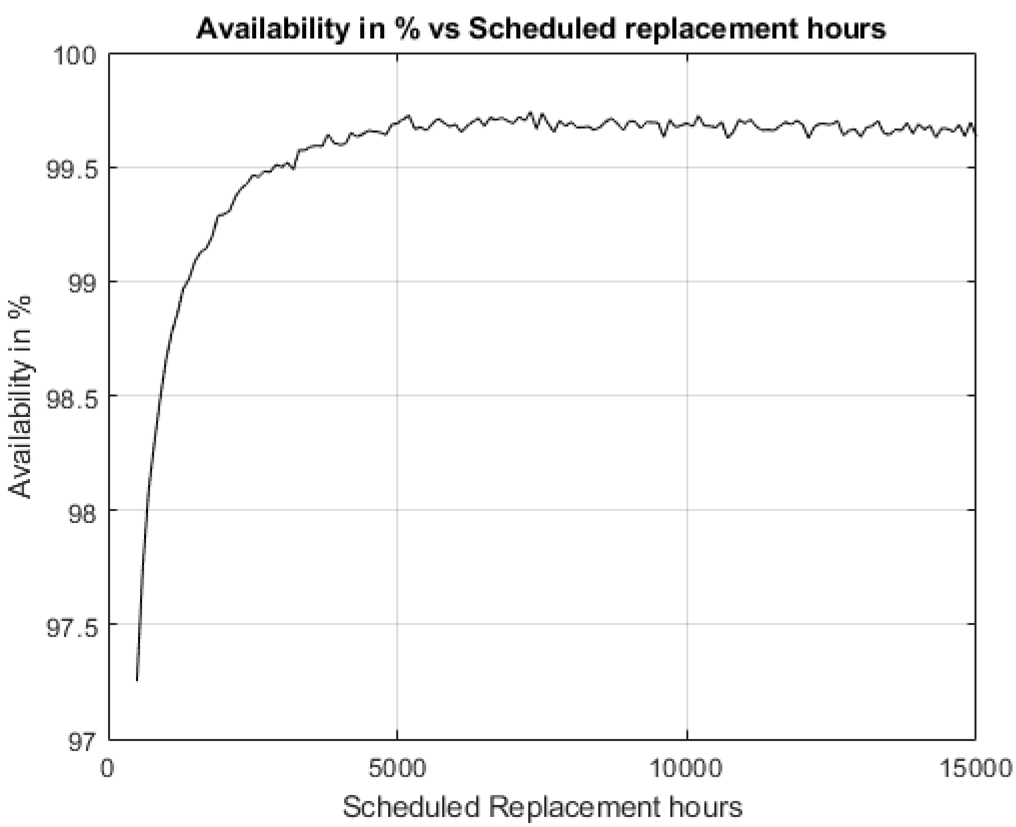
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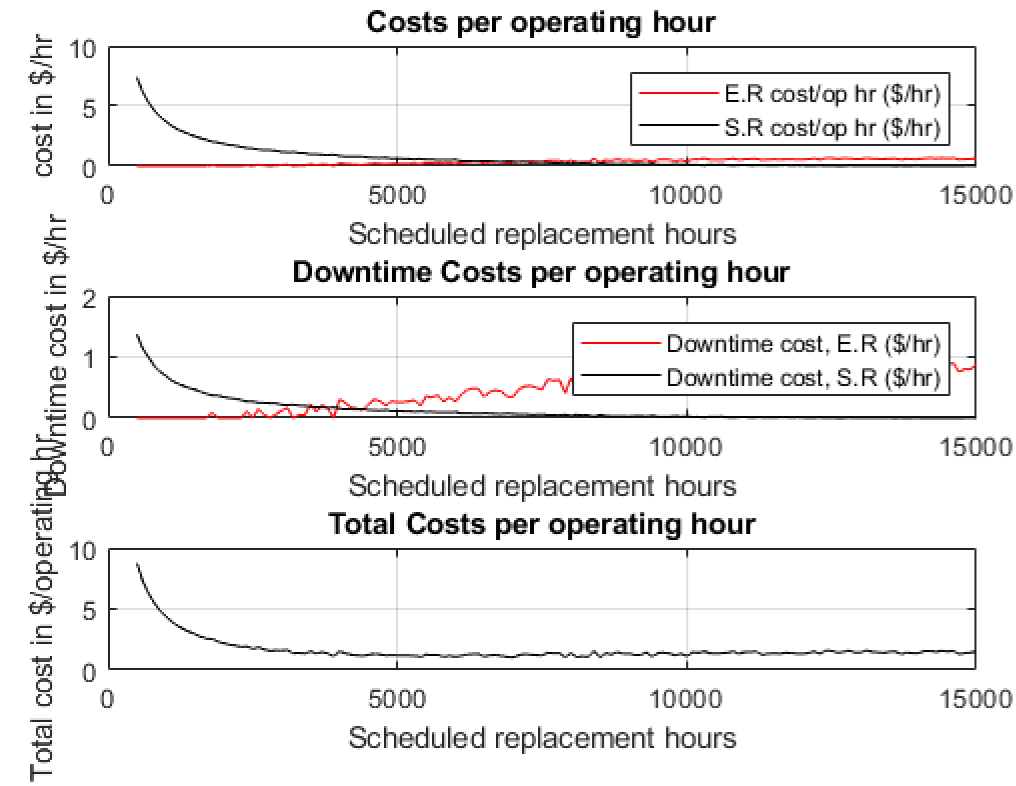
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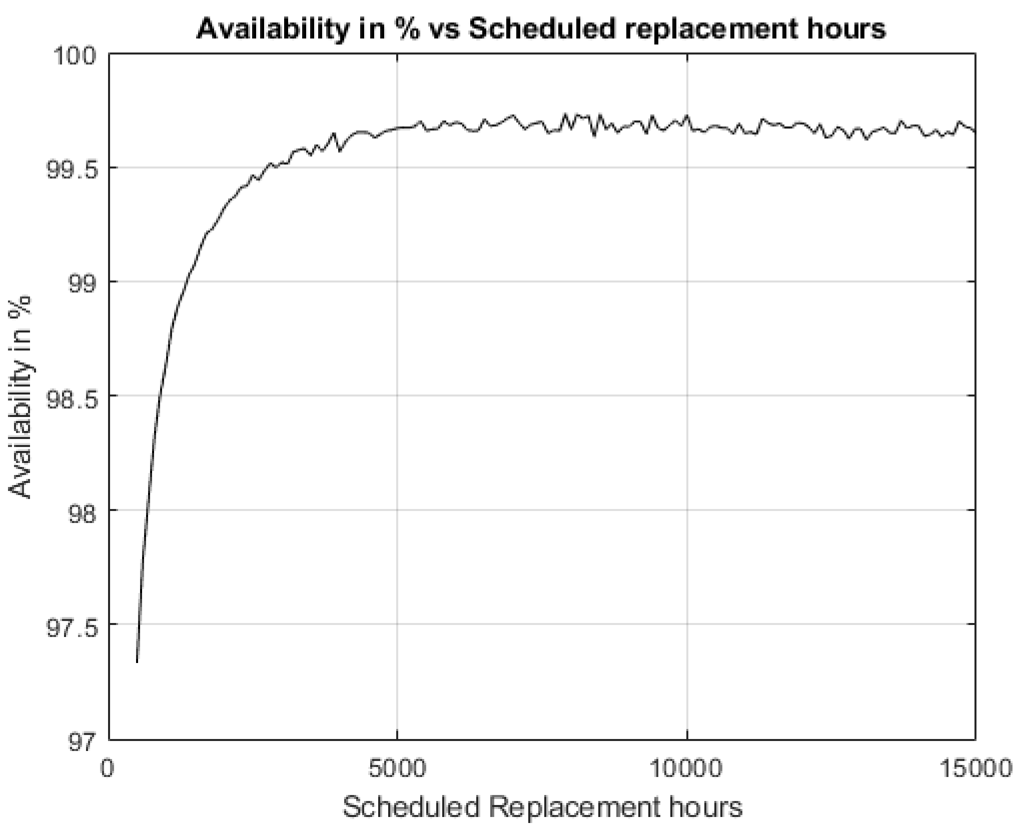
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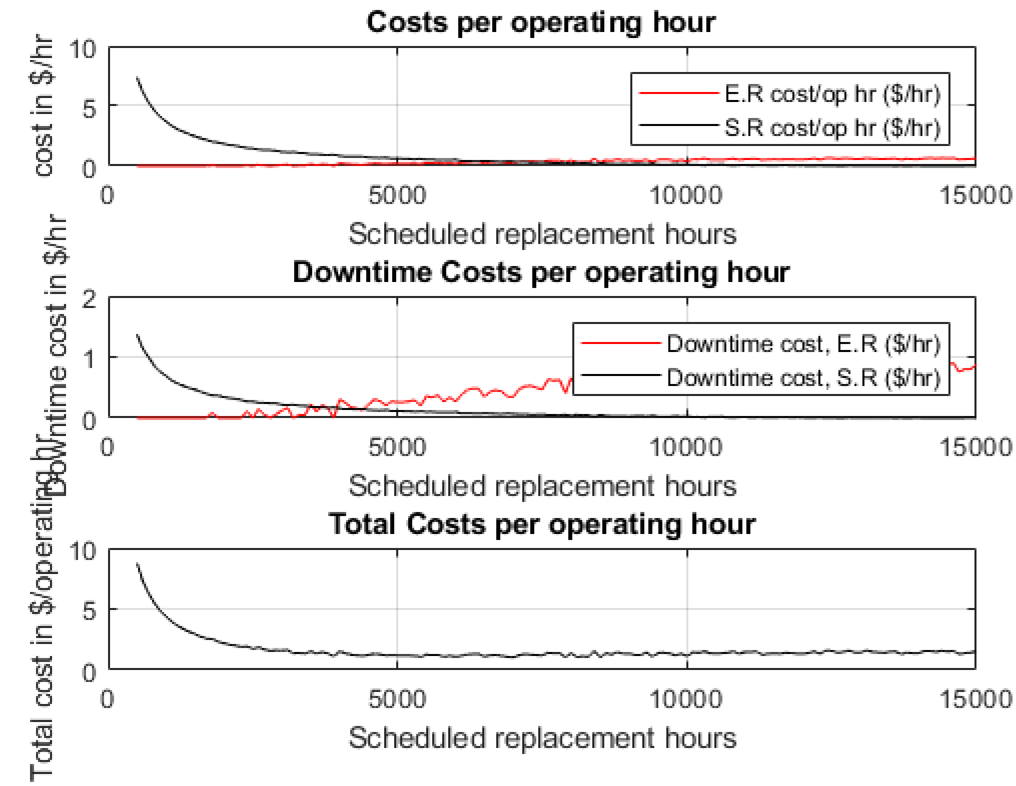
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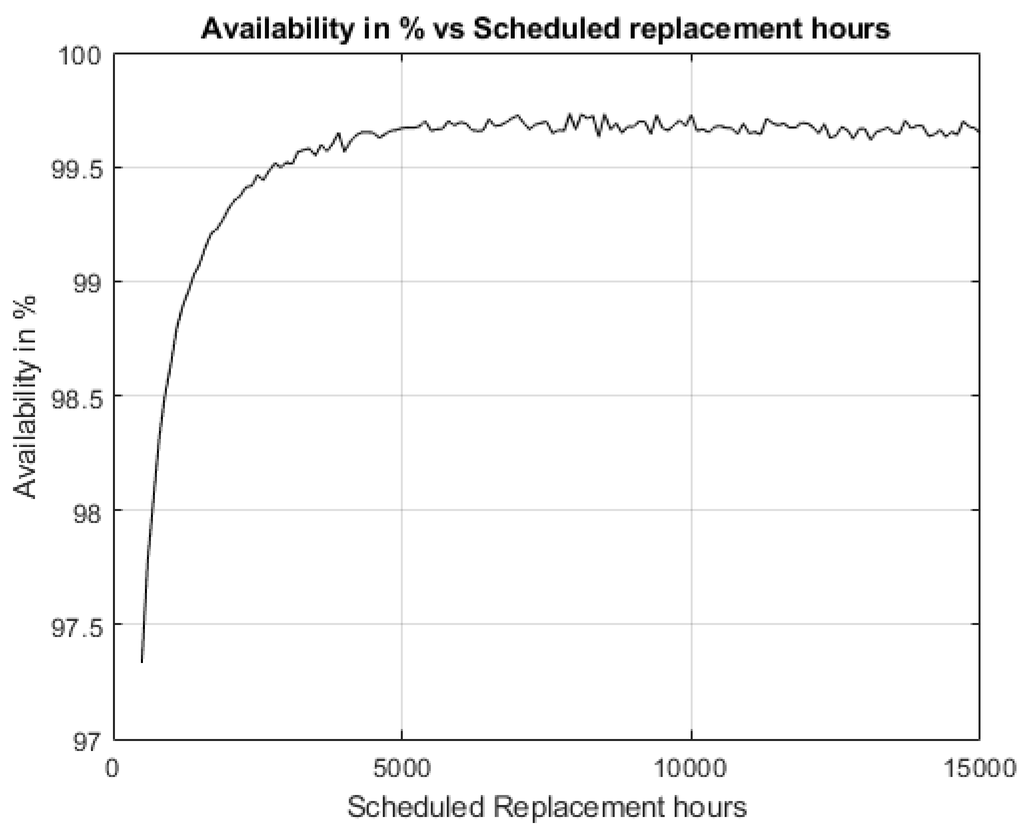
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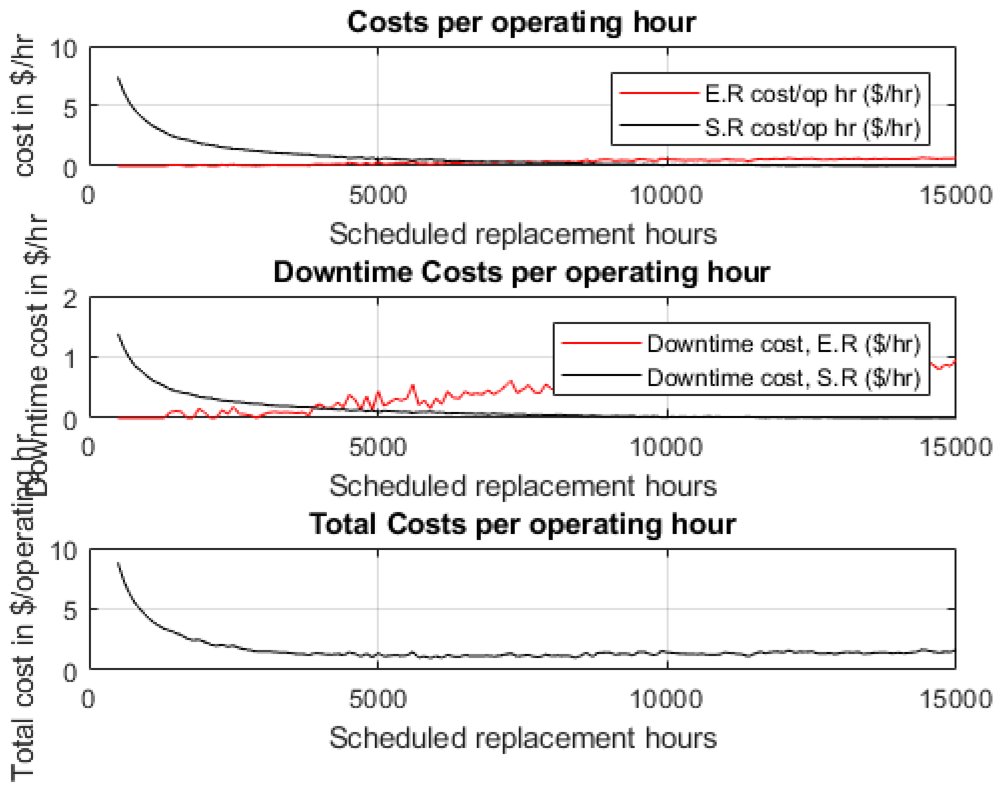
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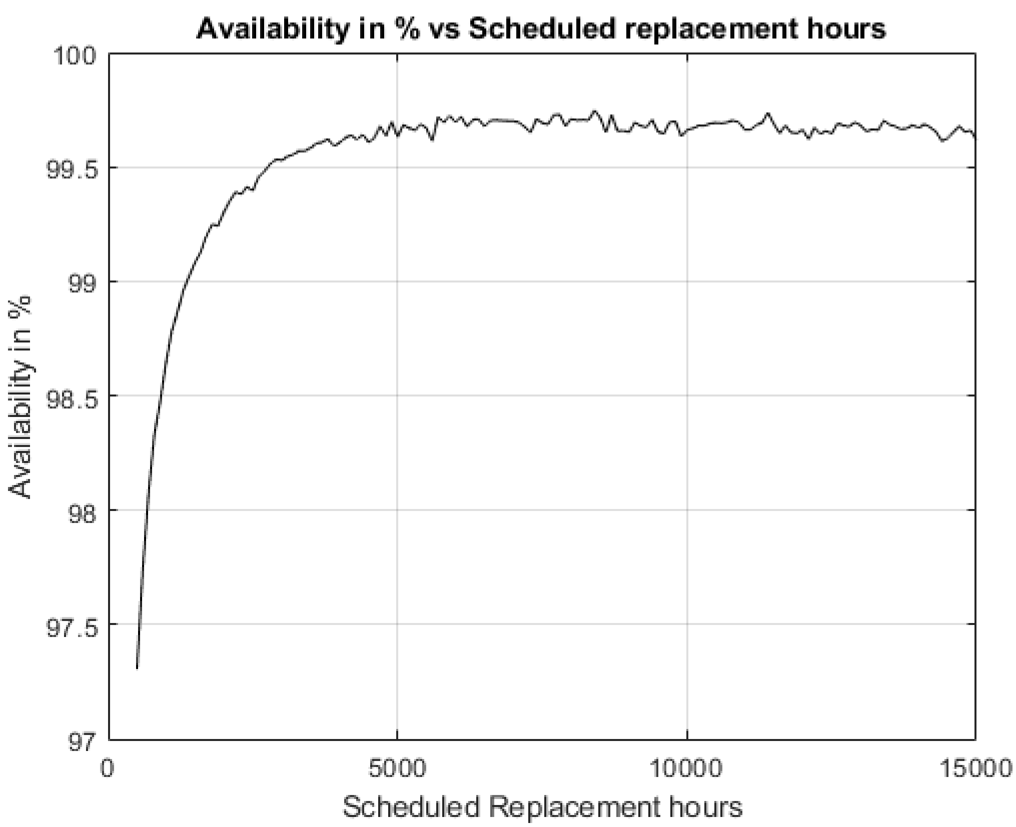
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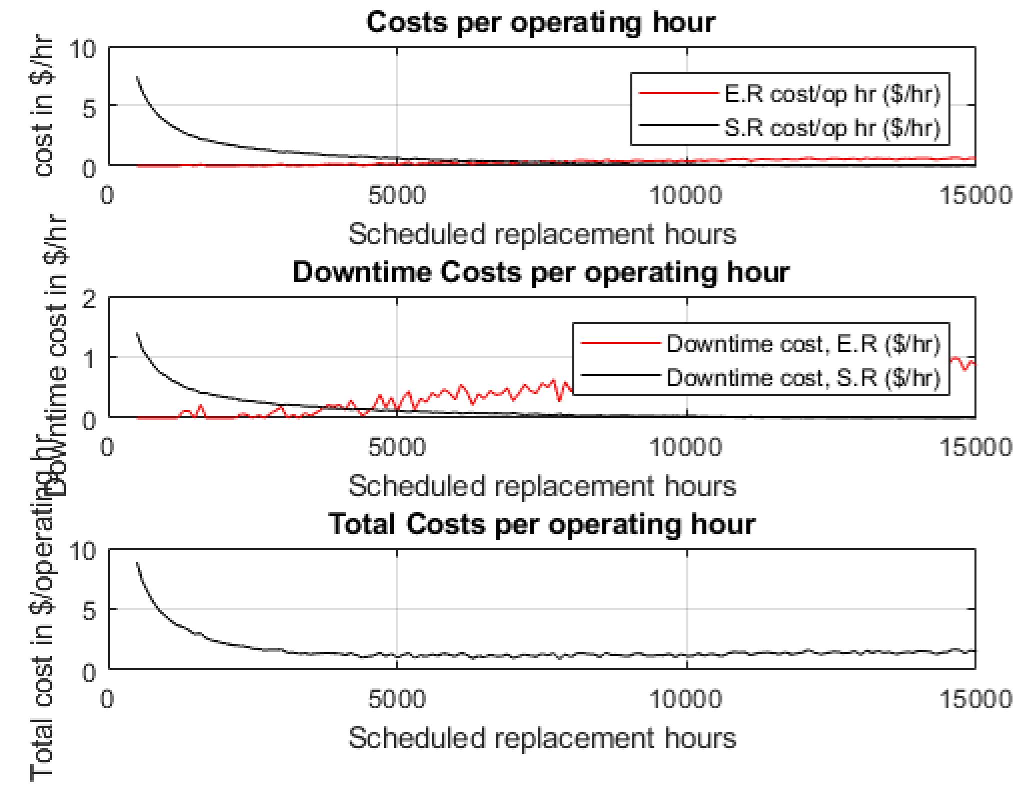
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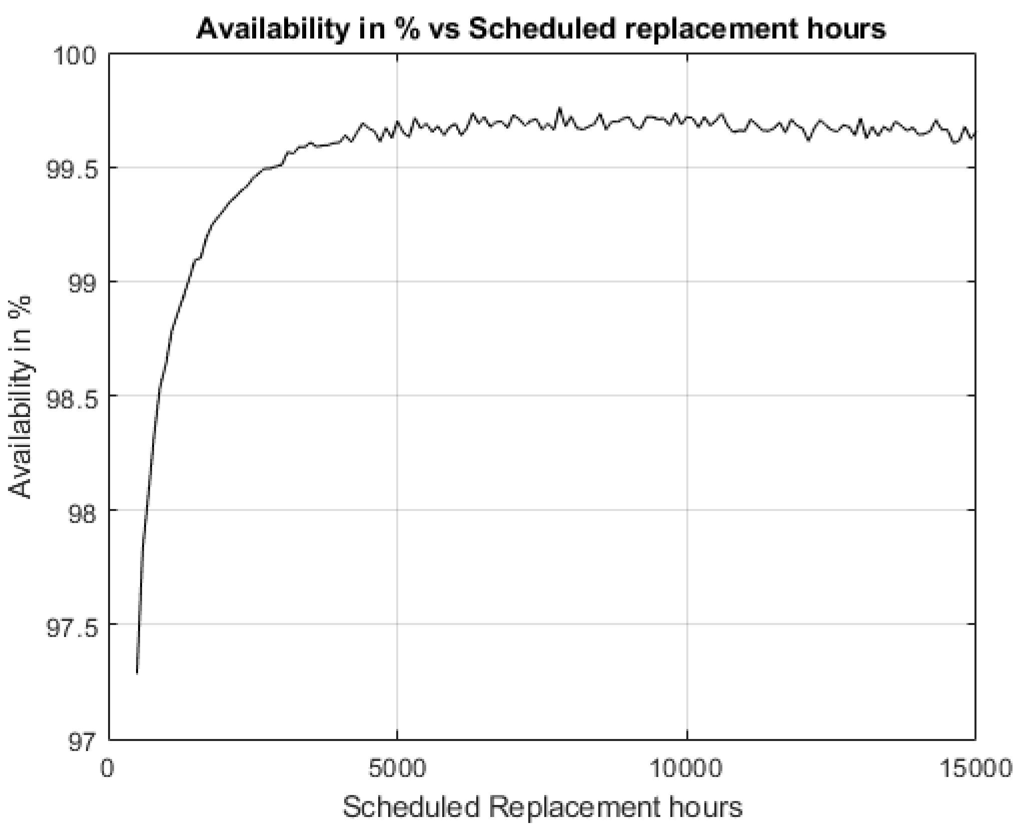
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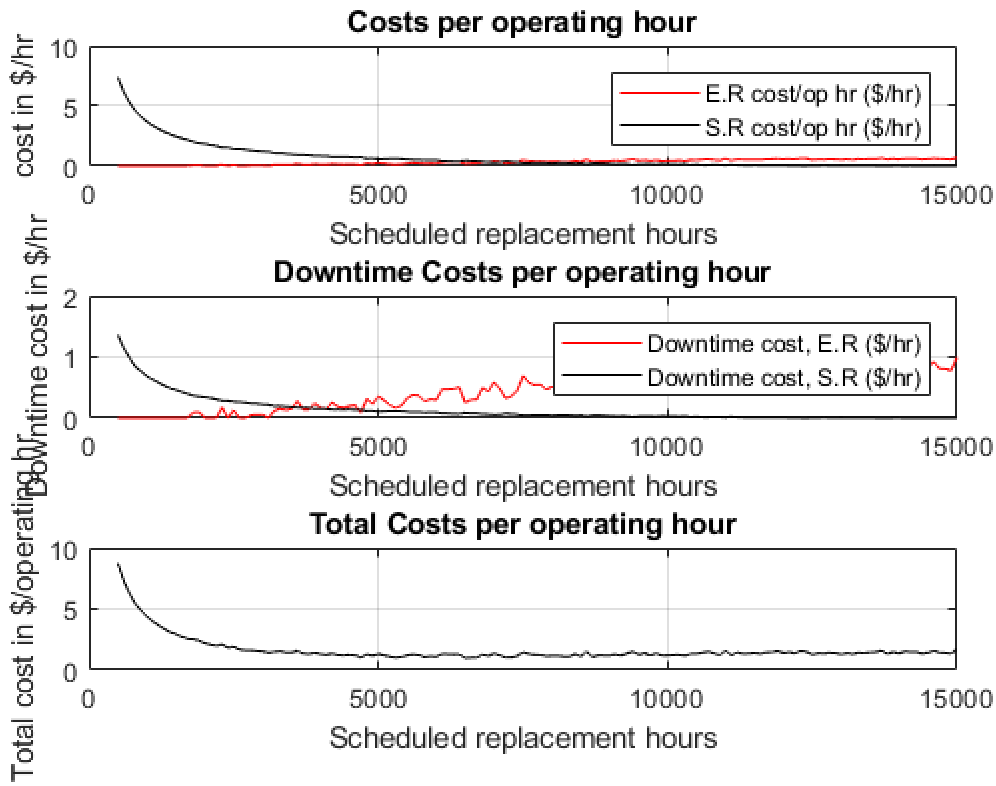
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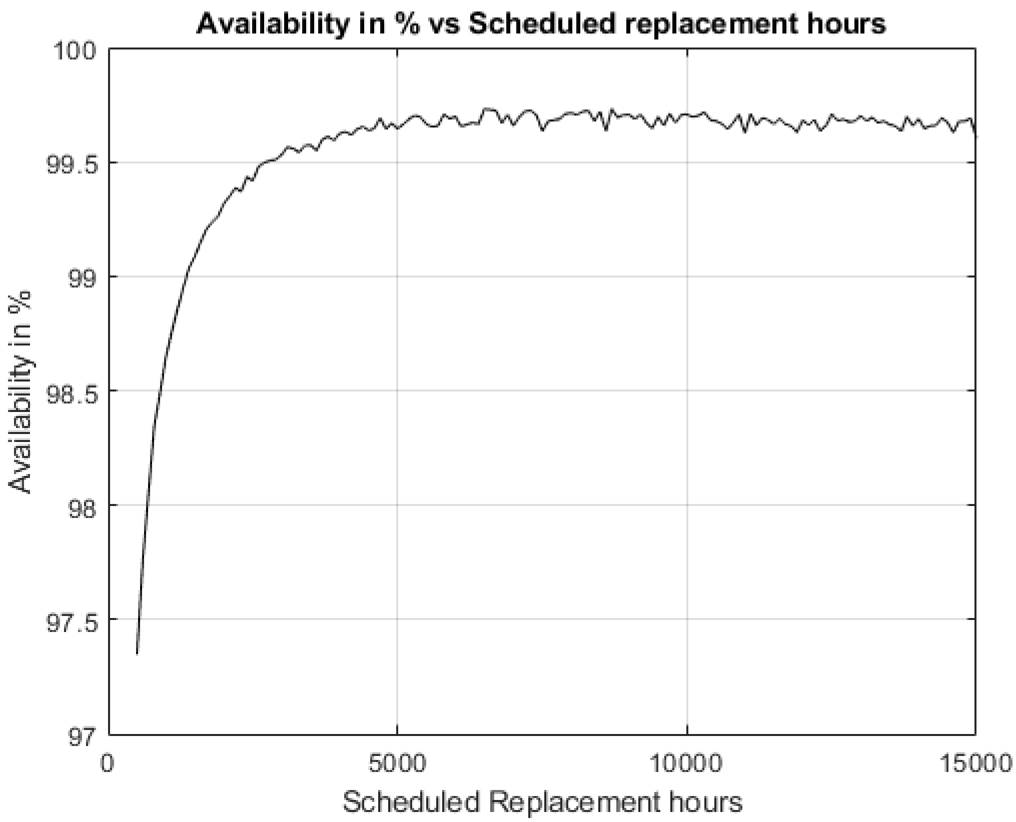
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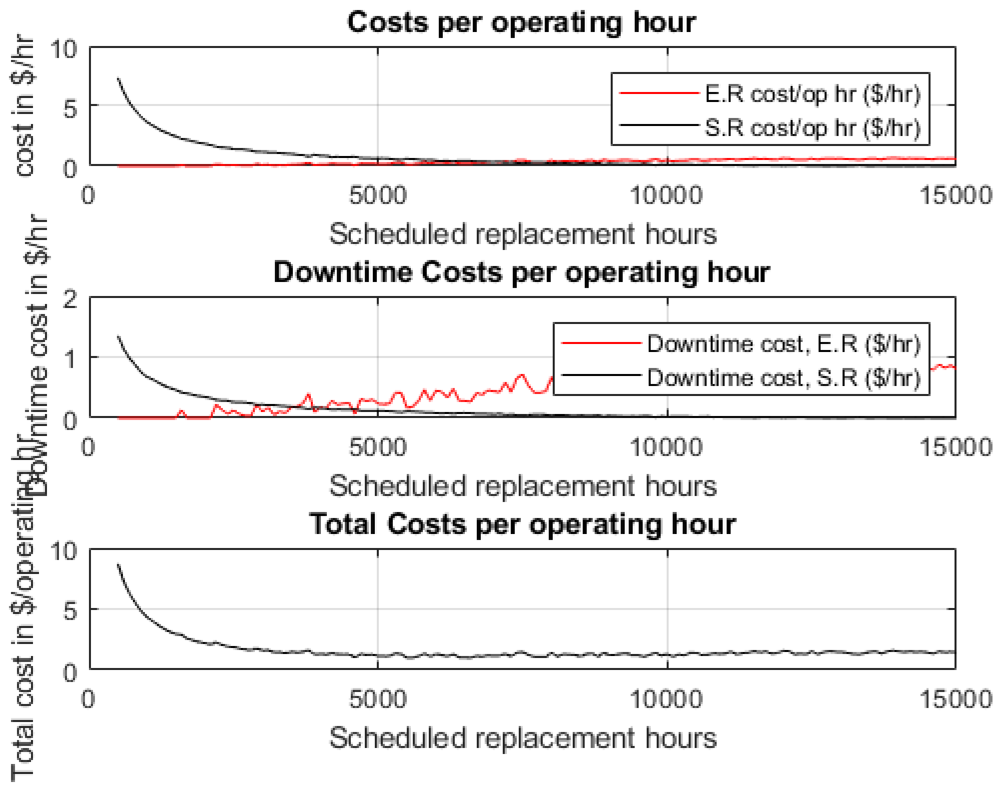
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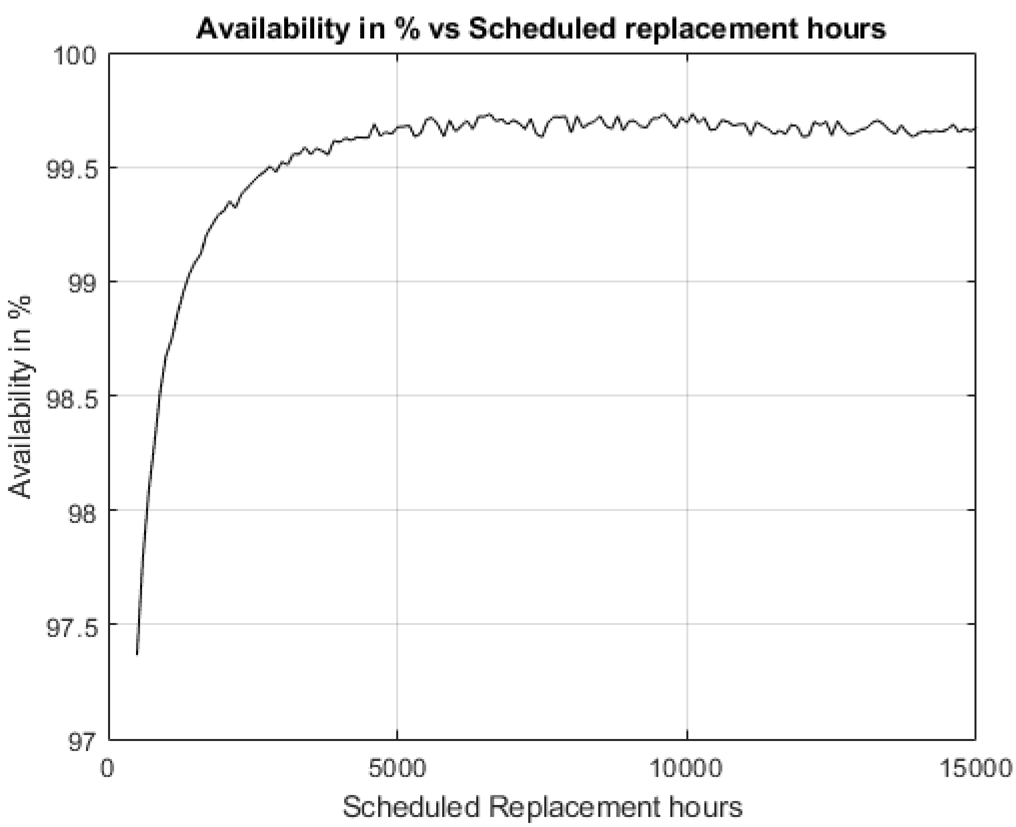
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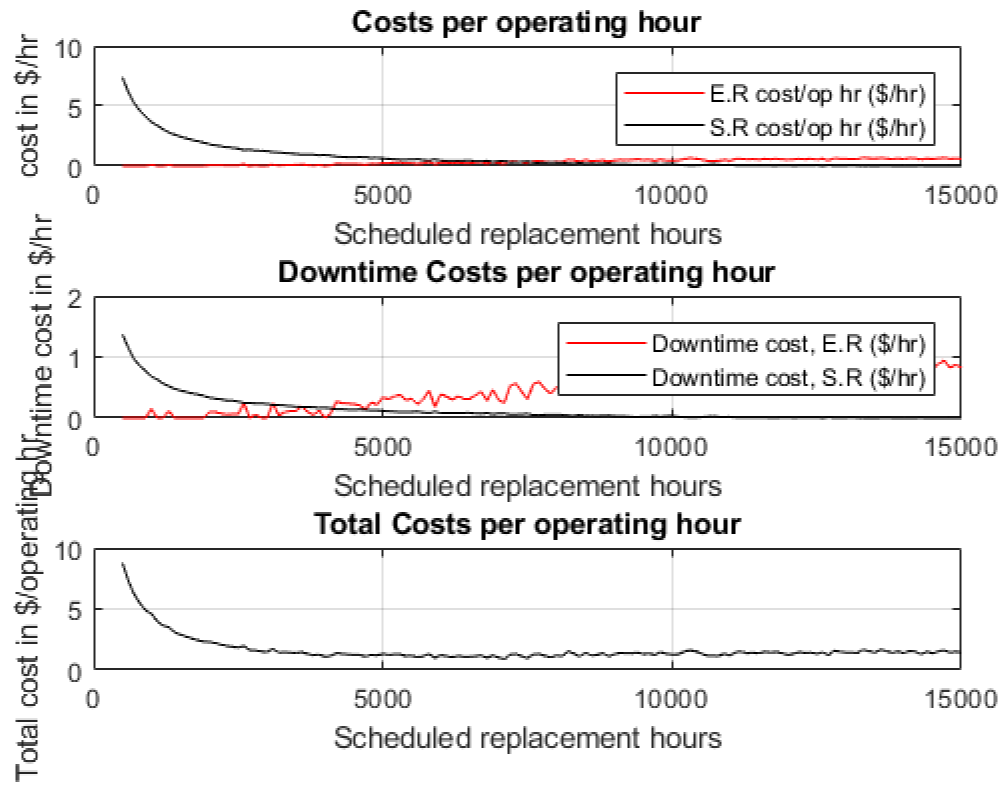
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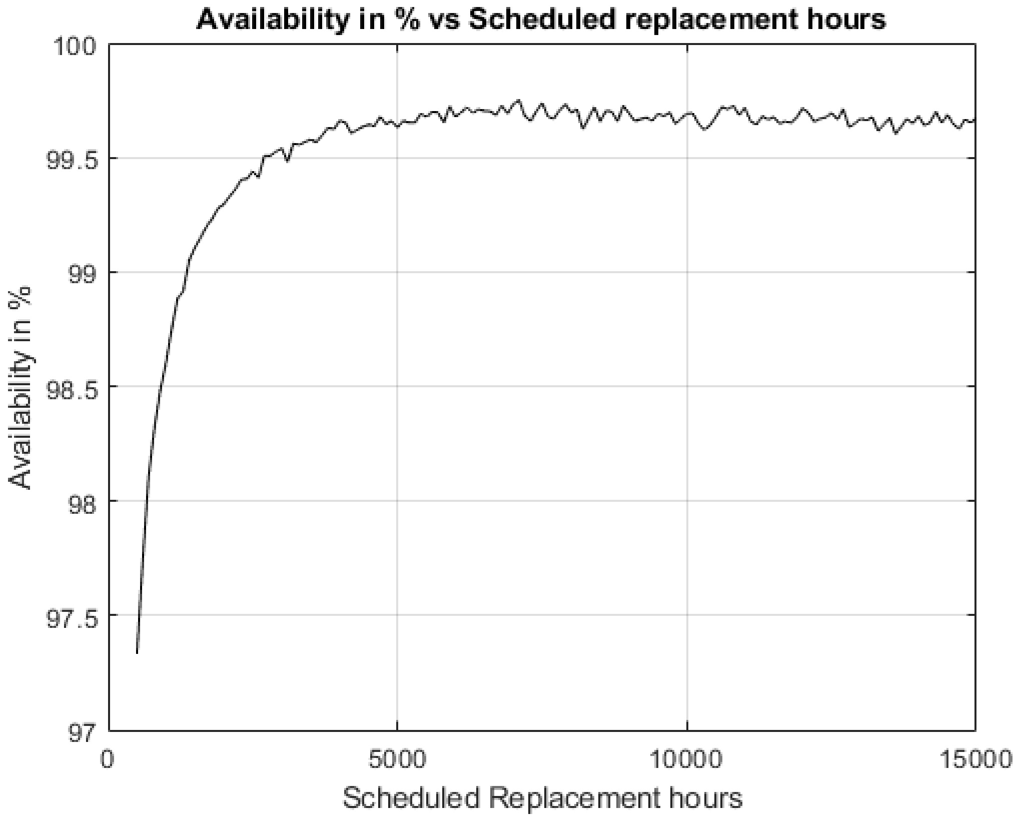
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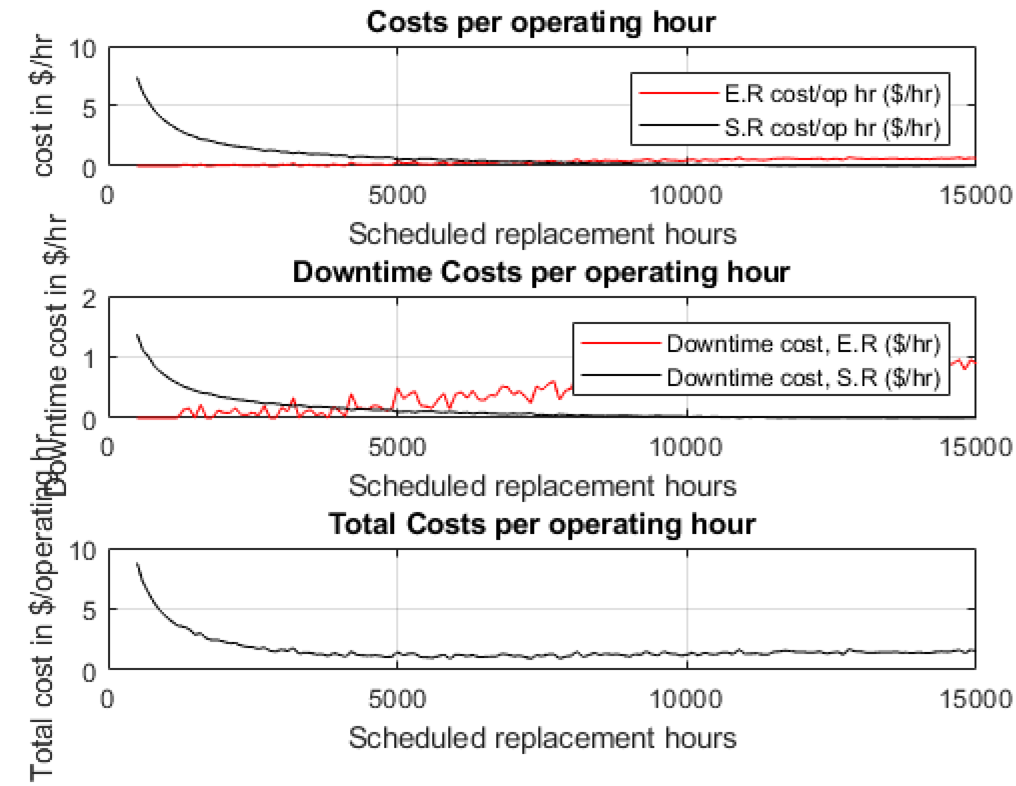

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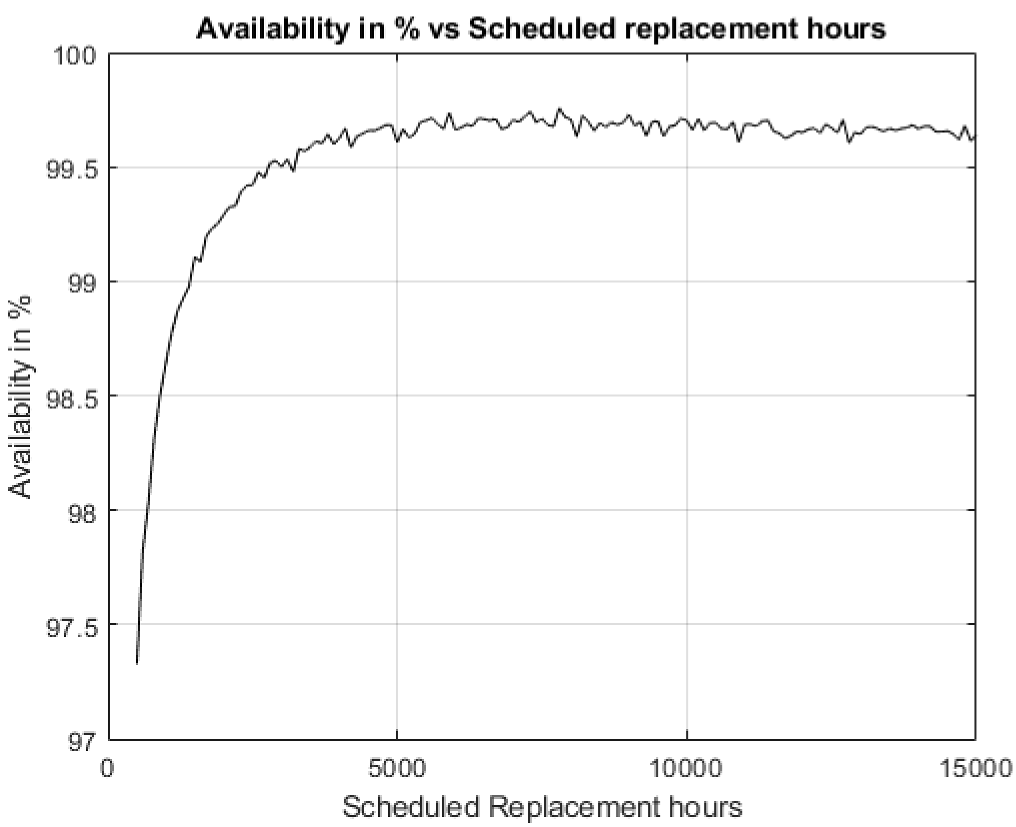
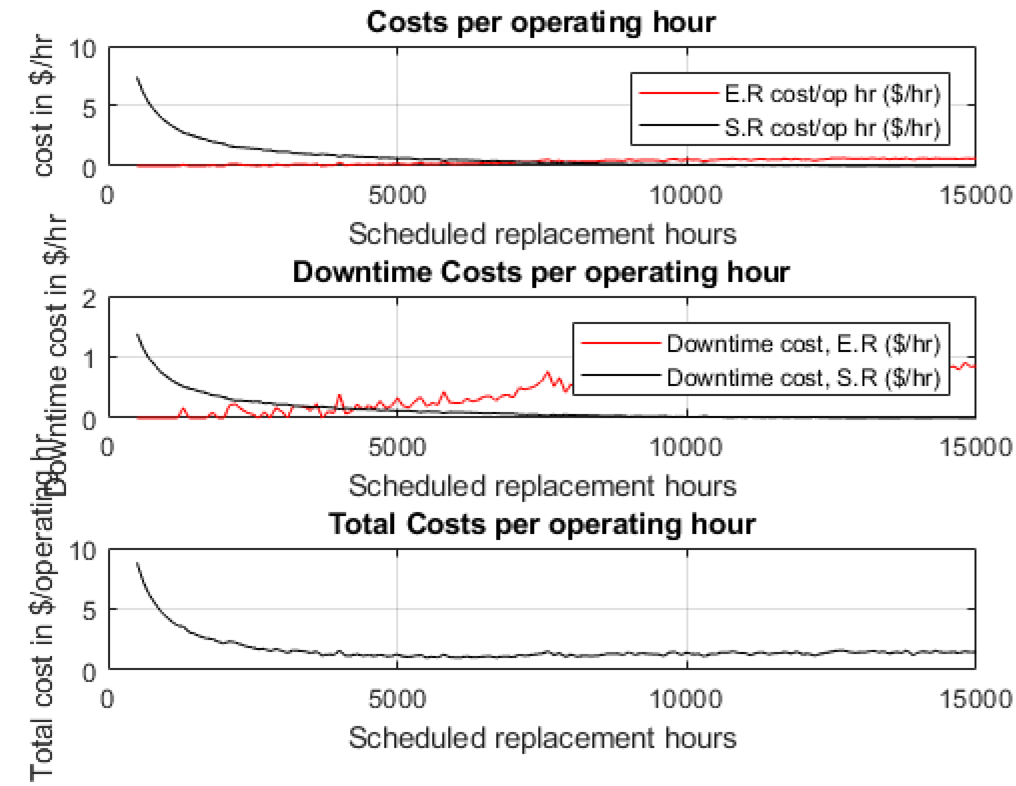
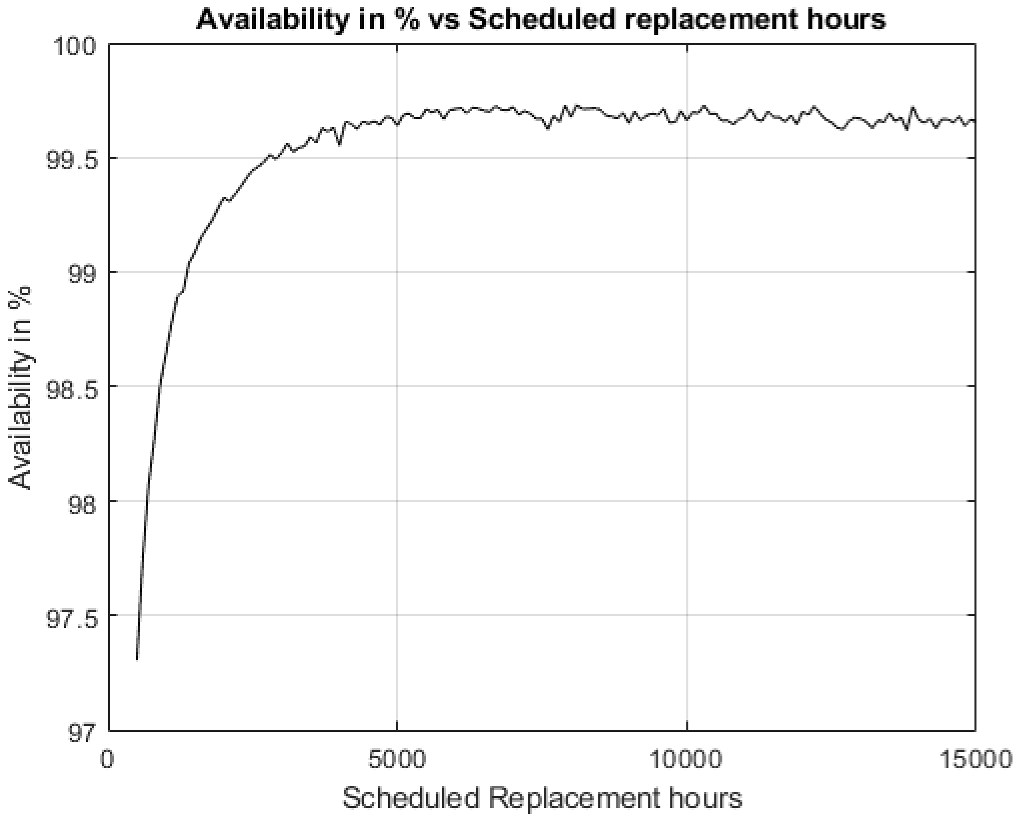
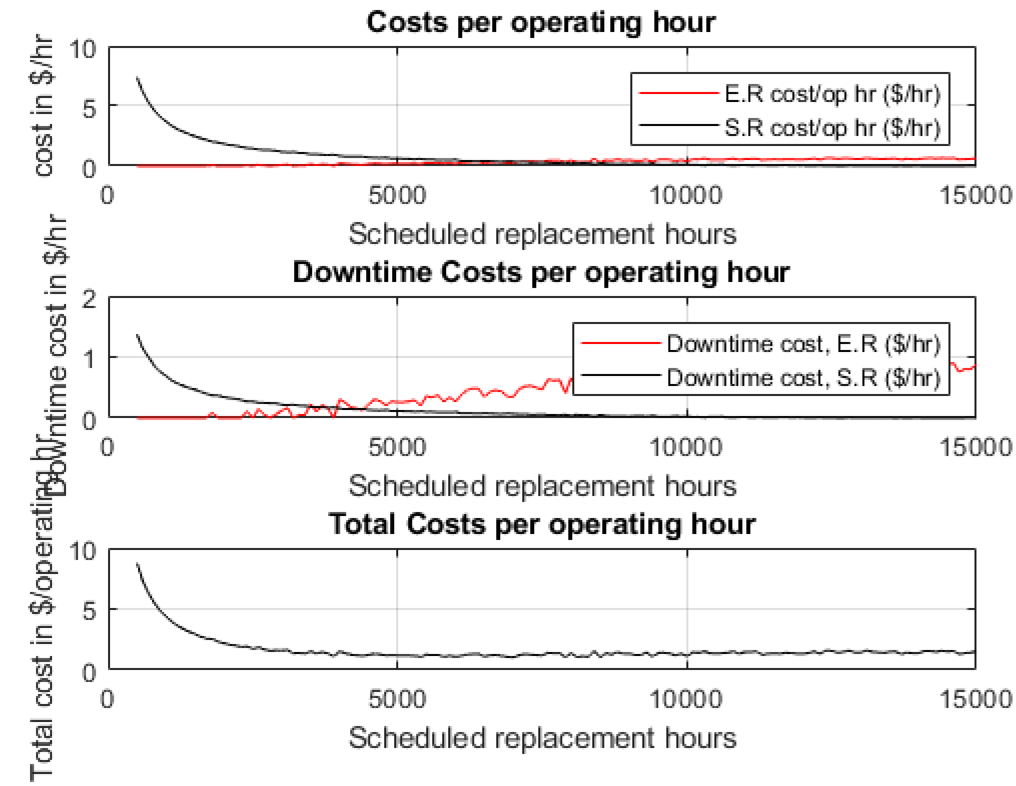
Downtime Costs per operating hour
Downtime cost in $/hr
Downtime cost, E.R ($/hr)
Downtime cost, S.R ($/hr)
Scheduled replacement hours
Total Costs per operating hour
Total cost in $/operating hr
Scheduled replacement hours

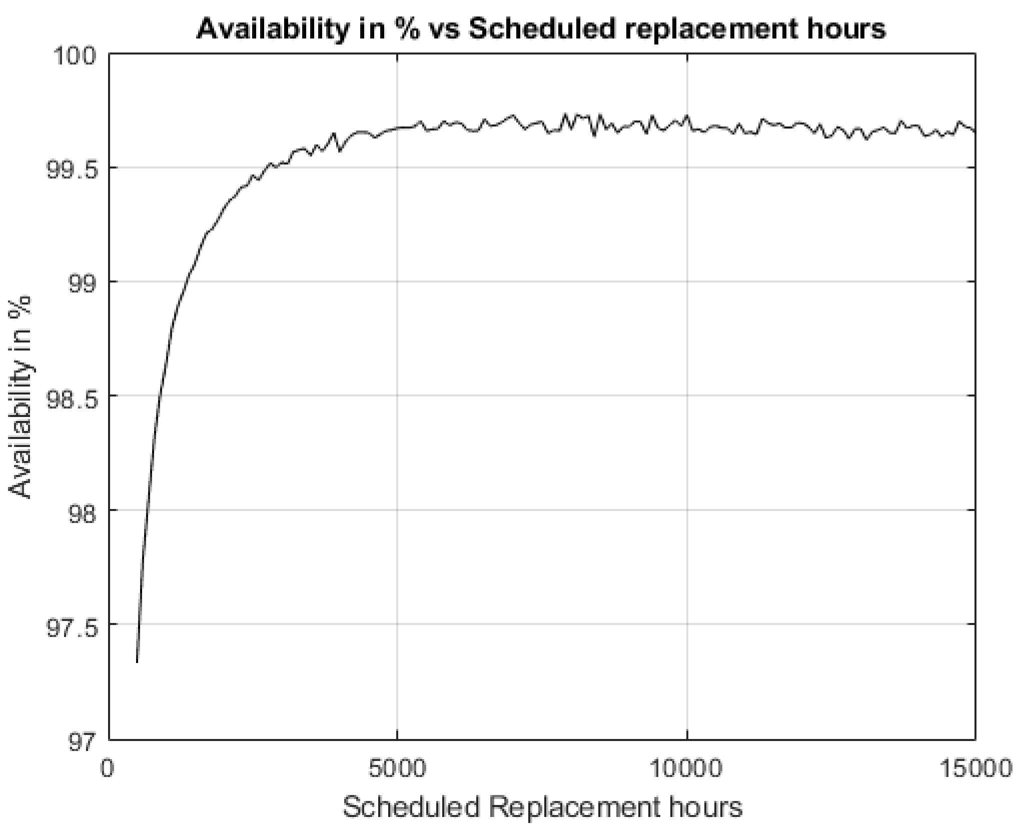


Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours


Costs per operating hour
cost in $/hr
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
Scheduled replacement hours
Downtime Costs per operating hour
Downtime cost in $/hr
Downtime cost, E.R ($/hr)
Downtime cost, S.R ($/hr)
Scheduled replacement hours
Total Costs per operating hour
Total cost in $/operating hr
Scheduled replacement hours


Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours


Costs per operating hour
cost in $/hr
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
Scheduled replacement hours
Downtime Costs per operating hour
Downtime cost in $/hr
Downtime cost, E.R ($/hr)
Downtime cost, S.R ($/hr)
Scheduled replacement hours
Total Costs per operating hour
Total cost in $/operating hr
Scheduled replacement hours


Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours

Sub-System 1: EGR System Output Data

Time	Description
500	Operation
14	Scheduled Replacement
500	Operation
13	Scheduled Replacement
500	Operation
13	Scheduled Replacement
500	Operation
12	Scheduled Replacement
500	Operation
12	Scheduled Replacement
500	Operation
13	Scheduled Replacement
500	Operation
13	Scheduled Replacement
500	Operation
14	Scheduled Replacement
500	Operation
14	Scheduled Replacement
500	Operation
13	Scheduled Replacement
500	Operation
13	Scheduled Replacement
500	Operation
17	Scheduled Replacement
500	Operation
14	Scheduled Replacement
500	Operation
13	Scheduled Replacement
500	Operation
12	Scheduled Replacement
500	Operation
14	Scheduled Replacement
500	Operation
13	Scheduled Replacement
500	Operation
13	Scheduled Replacement
500	Operation
14	Scheduled Replacement
500	Operation
14	Scheduled Replacement
500	Operation
14	Scheduled Replacement
500	Operation
15	Scheduled Replacement

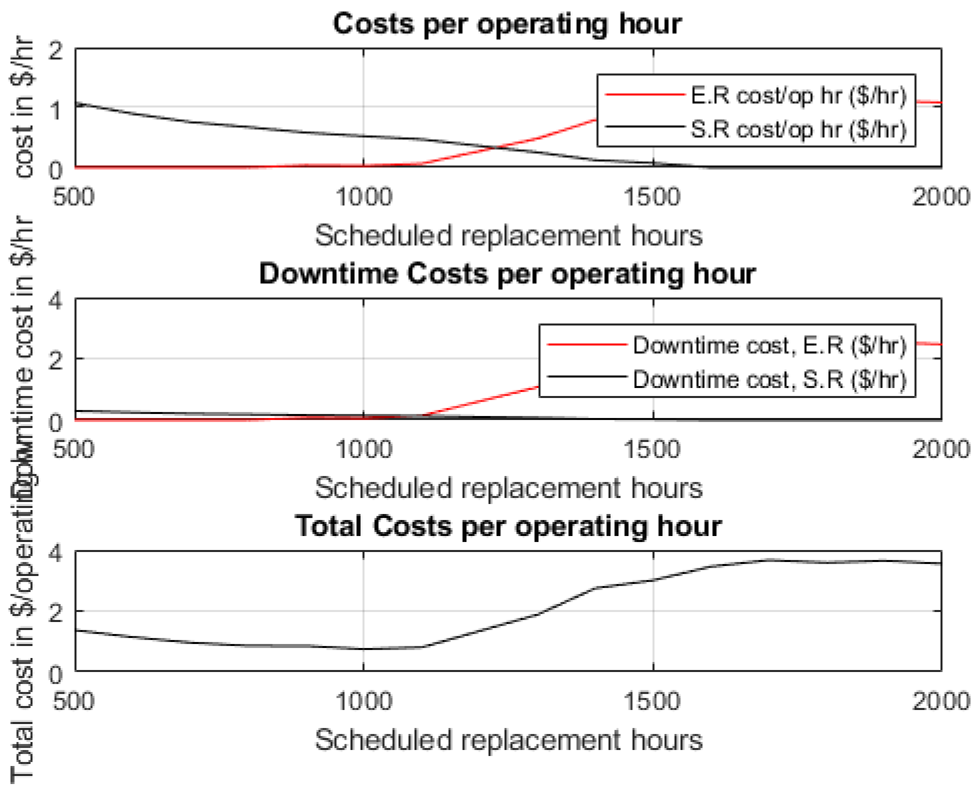
Parameters	Counts
TOT (hr)	20000
TST (hr)	544
TET (hr)	0
TT (hr)	20544
Availability (%)	97.35
NS	40
NE	0

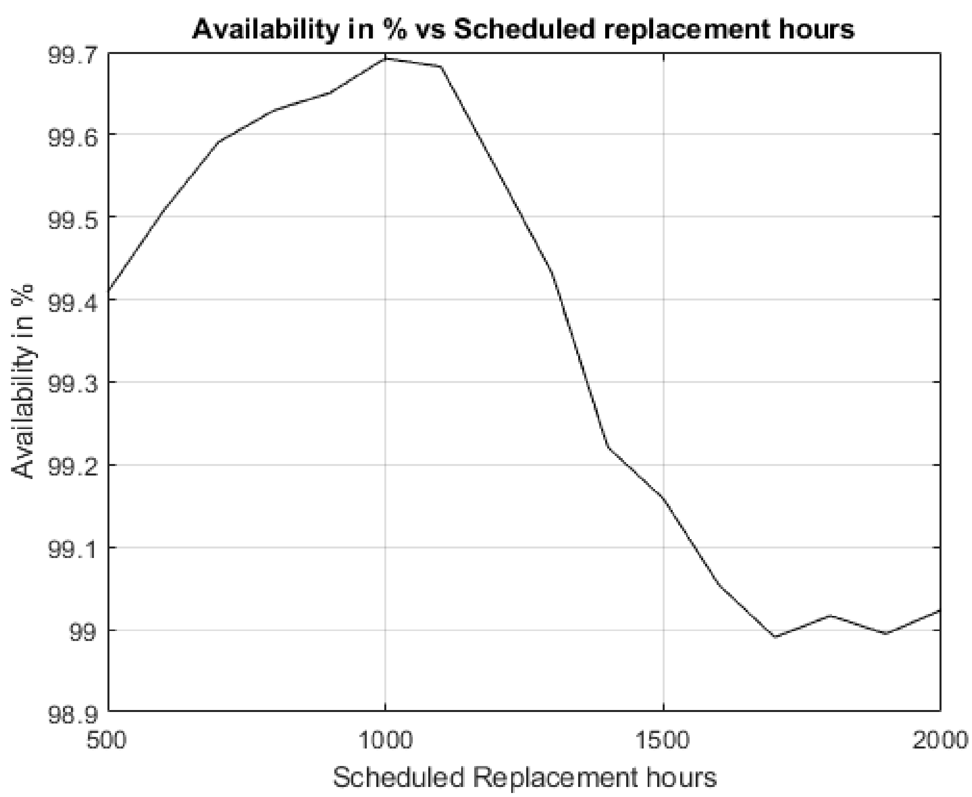
Jobs	Costs
Scheduled replacement cost per operating hr	7.376
Emergency replacement cost per operating hr	0
Downtime Cost (For Schedule replacement) per operating hr	1.36
Downtime Cost (emergency replacment) per operating hr	0
Sum	8.736

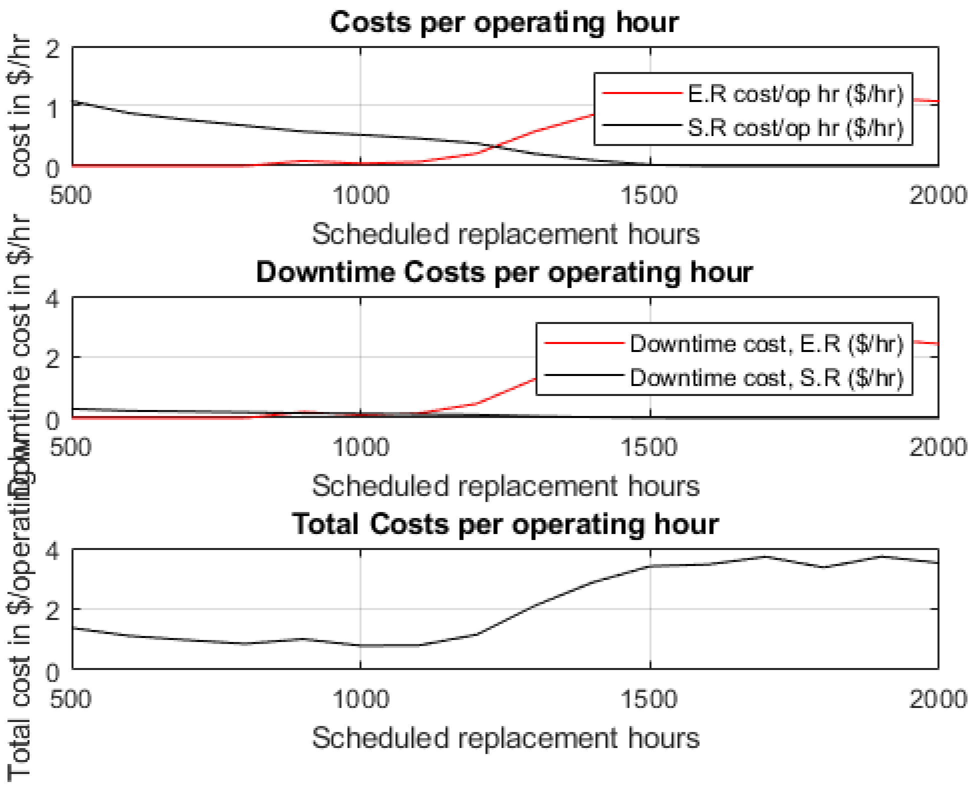
Others	Value
Alpha level in model	0.05
Schedule hr	500
Min Wait time in hr (emergency)	10
Max wait time in hr (emergency)	20
Min wait time in hr (Schedule)	10
Max wait time in hr (Schedule)	12
Downtime cost (scheduled replacement) $/hr	50
Downtime cost (emergency replacement) $/hr	250
Scrap value	0

500	Operation
13	Scheduled Replacement
500	Operation
14	Scheduled Replacement
500	Operation
14	Scheduled Replacement
500	Operation
14	Scheduled Replacement
500	Operation
17	Scheduled Replacement
500	Operation
16	Scheduled Replacement
500	Operation
14	Scheduled Replacement
500	Operation
13	Scheduled Replacement
500	Operation
13	Scheduled Replacement
500	Operation
13	Scheduled Replacement
500	Operation
13	Scheduled Replacement
500	Operation
12	Scheduled Replacement
500	Operation
13	Scheduled Replacement
500	Operation
14	Scheduled Replacement
500	Operation
14	Scheduled Replacement
500	Operation
14	Scheduled Replacement
500	Operation
13	Scheduled Replacement
500	Operation
13	Scheduled Replacement

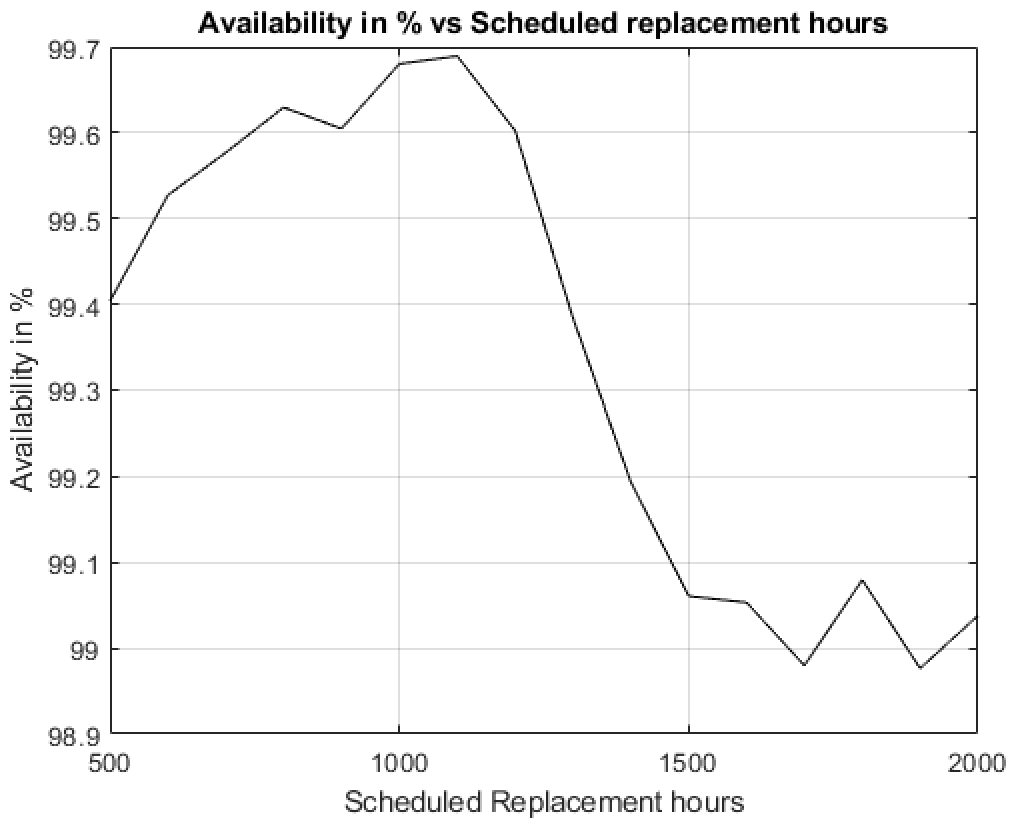
Sub-System 2: Cooling System Output Graphs



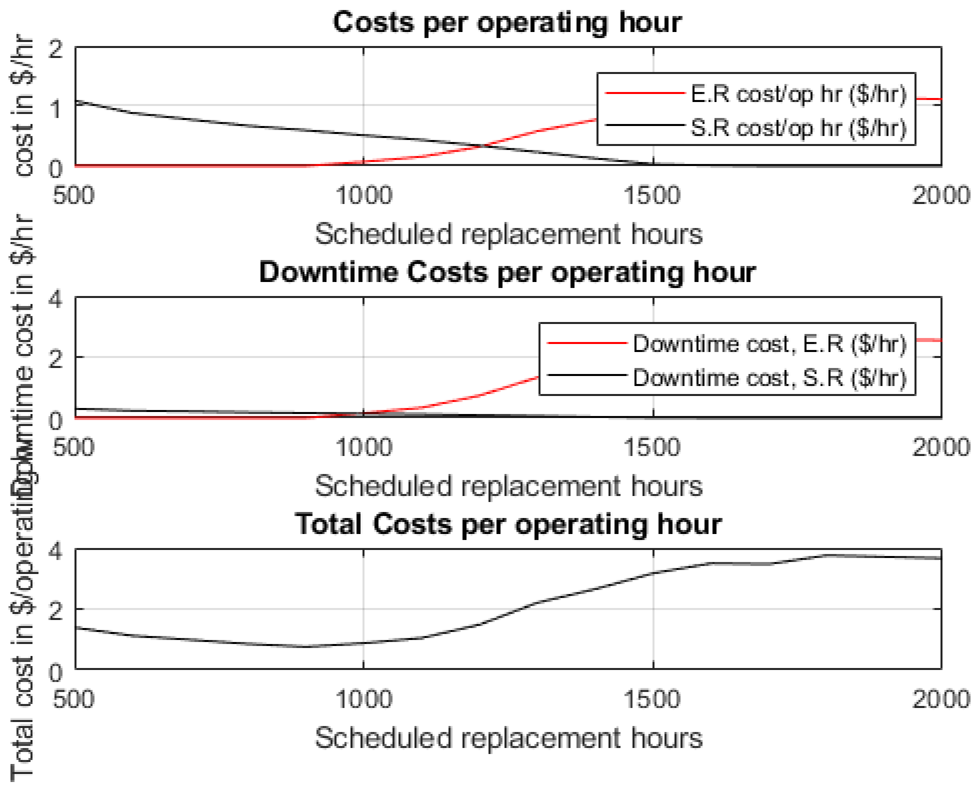


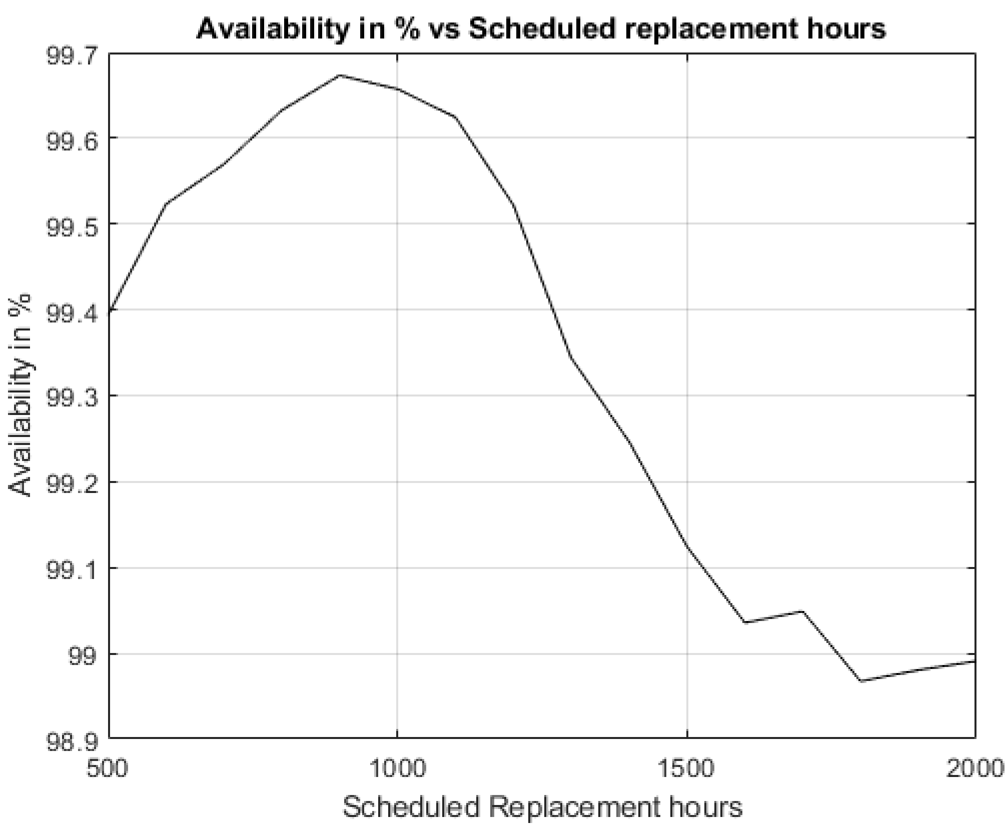


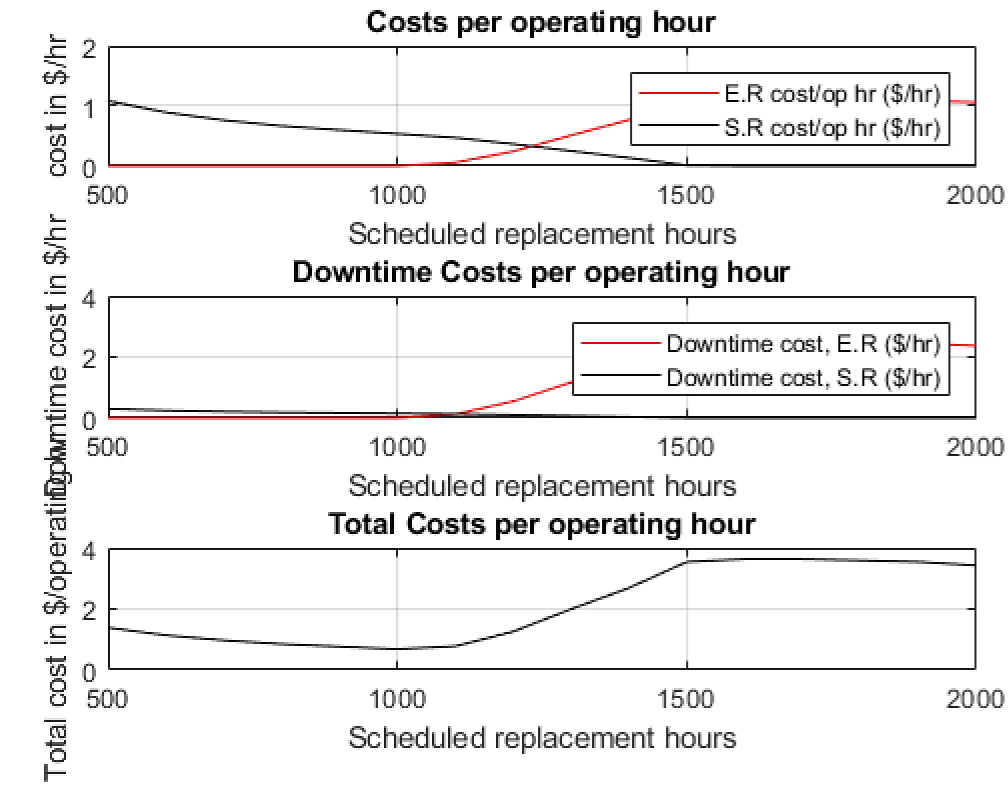
Costs per operating hour
cost in $/hr
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
Scheduled replacement hours
Downtime Costs per operating hour
Downtime cost in $/hr
Downtime cost, E.R ($/hr)
Downtime cost, S.R ($/hr)
Scheduled replacement hours
Total Costs per operating hour
Scheduled replacement hours

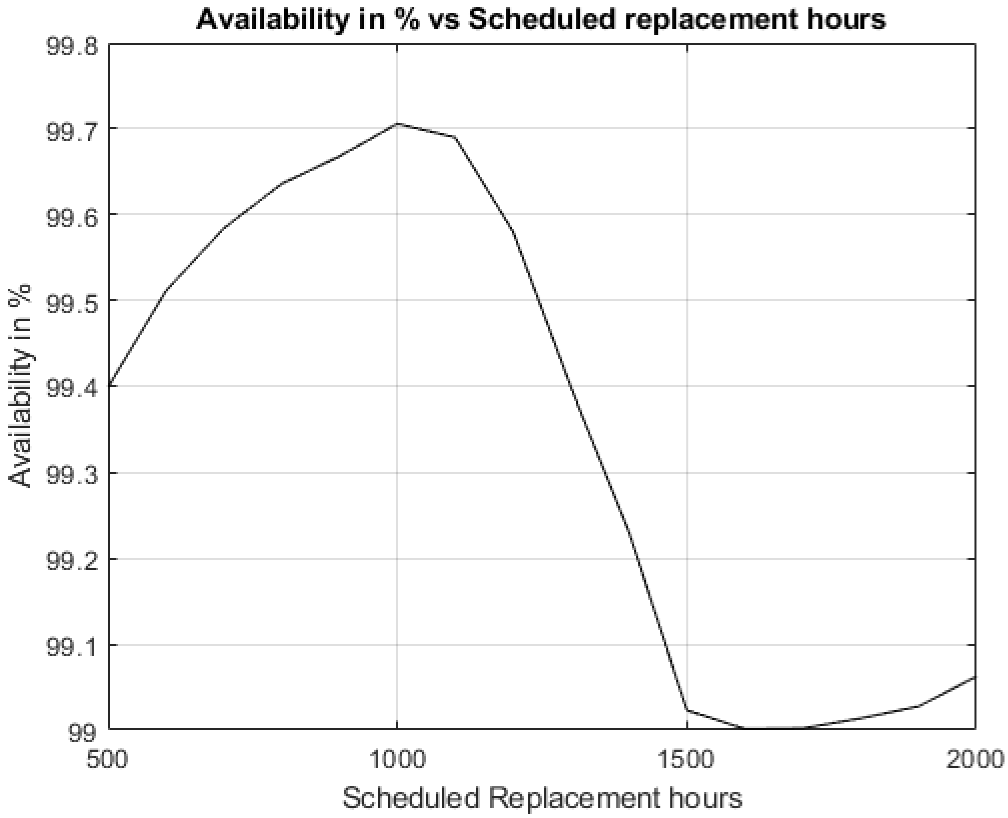


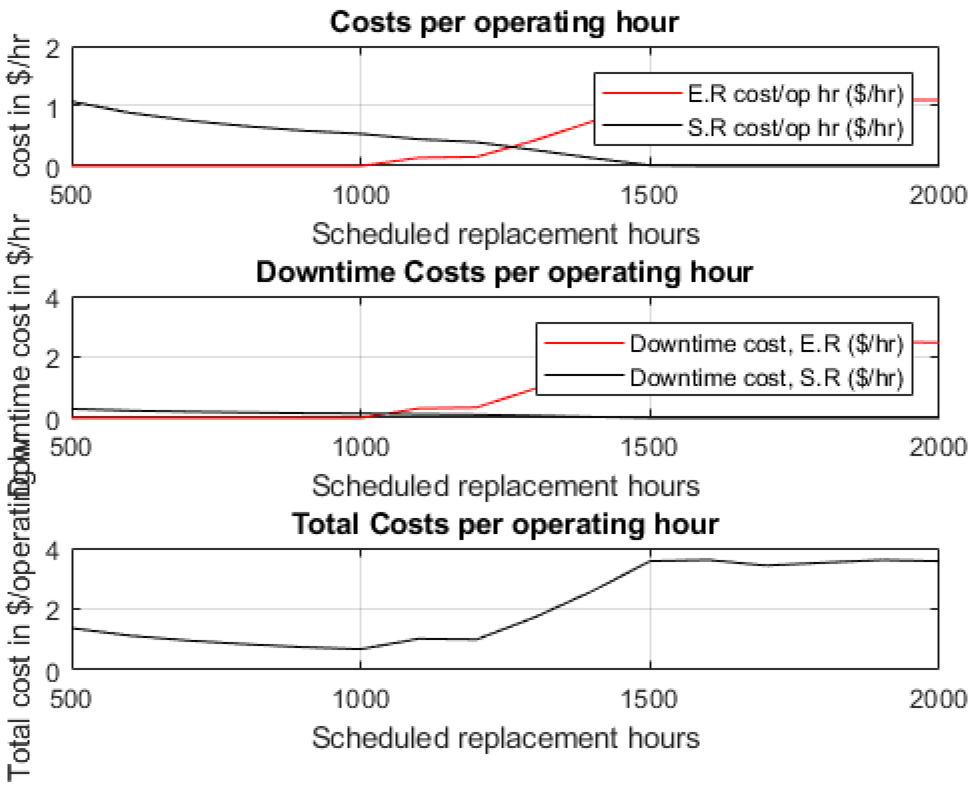
Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours

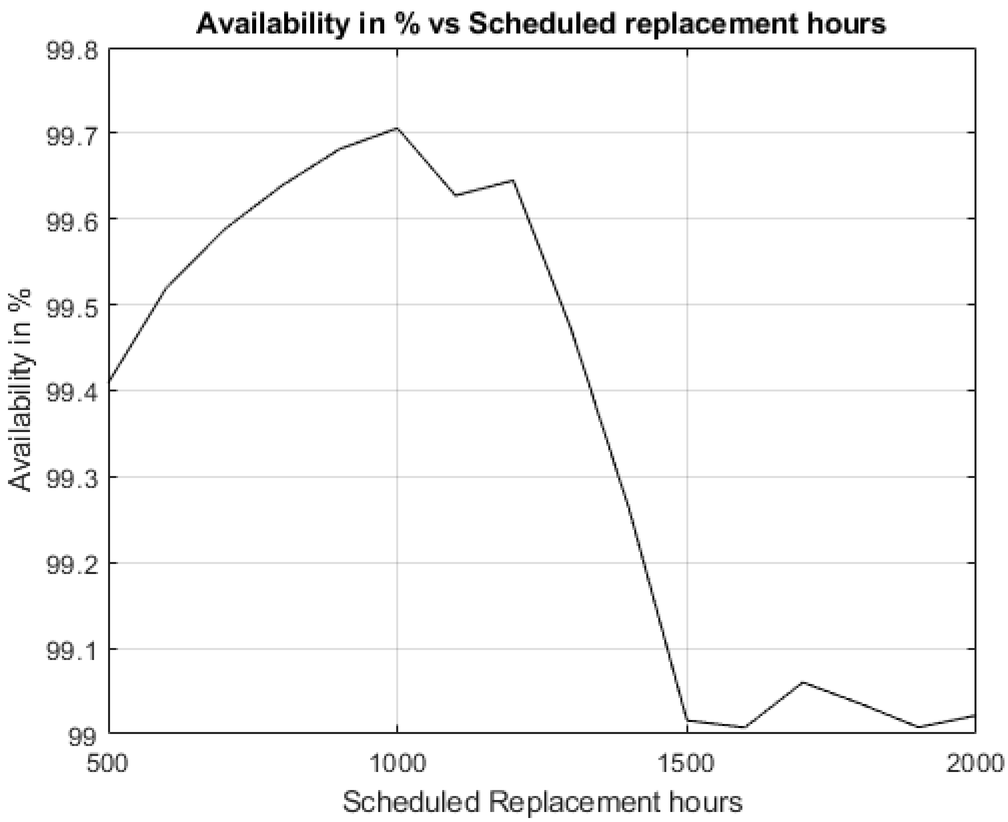

Costs per operating hour
cost in $/hr
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
Scheduled replacement hours
Downtime Costs per operating hour
Downtime cost in $/hr
Downtime cost, E.R ($/hr)
Downtime cost, S.R ($/hr)
Scheduled replacement hours
Total Costs per operating hour
Total cost in $/operating hr
Scheduled replacement hours

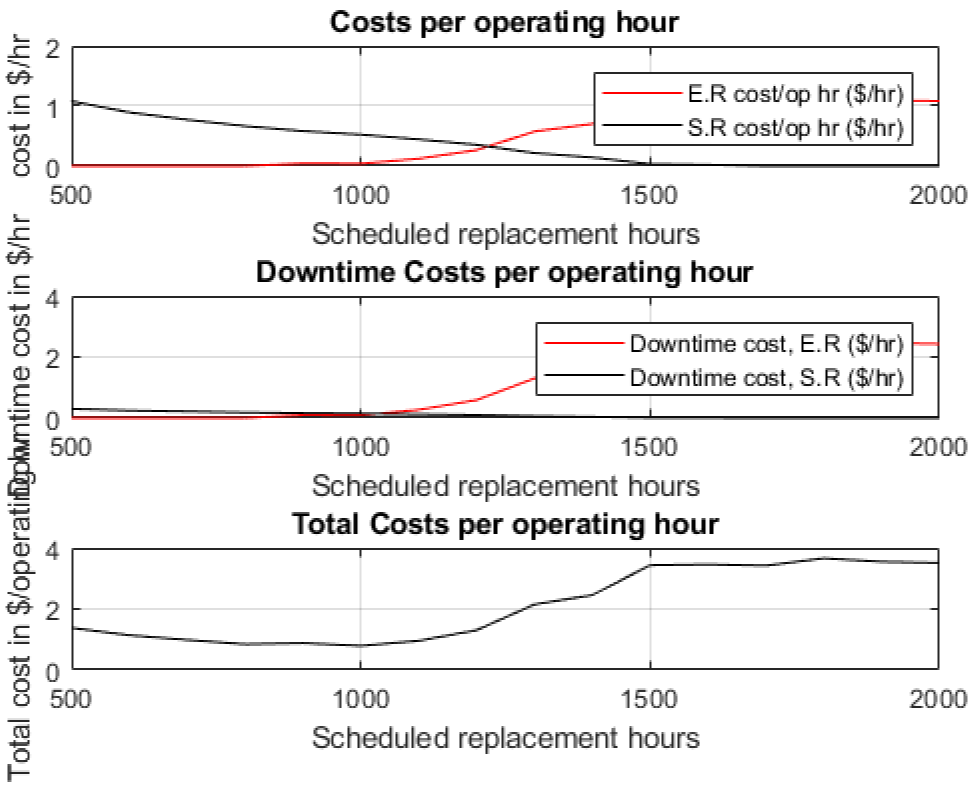

Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours

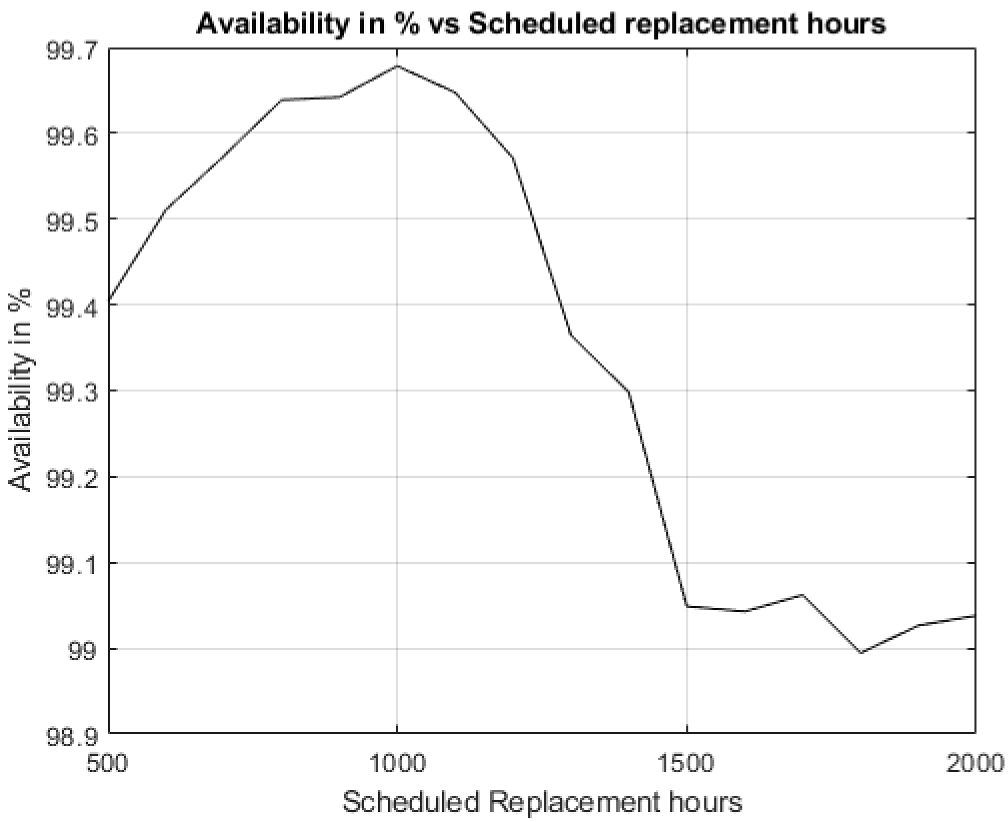

Costs per operating hour
cost in $/hr
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
Scheduled replacement hours
Downtime Costs per operating hour
Downtime cost, E.R ($/hr)
Downtime cost, S.R ($/hr)
Scheduled replacement hours
Total Costs per operating hour
Scheduled replacement hours

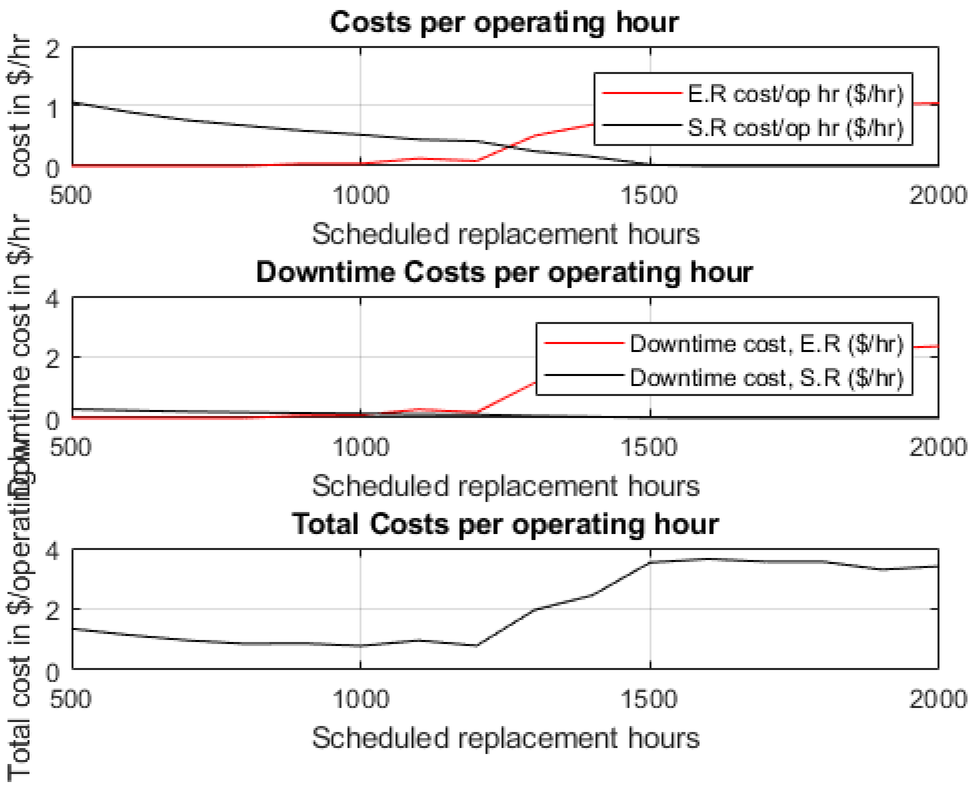

Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours

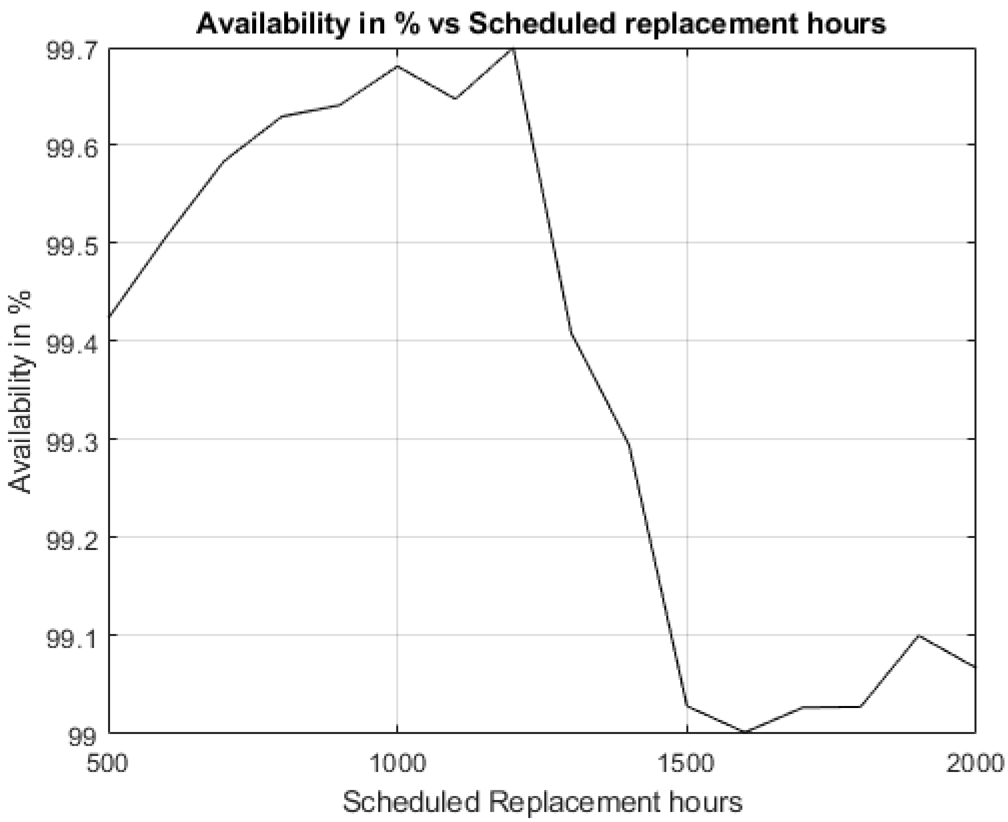

Costs per operating hour
cost in $/hr
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
Scheduled replacement hours
Downtime Costs per operating hour
Downtime cost in $/hr
Downtime cost, E.R ($/hr)
Downtime cost, S.R ($/hr)
Scheduled replacement hours
Total Costs per operating hour
Total cost in $/operating hr
Scheduled replacement hours

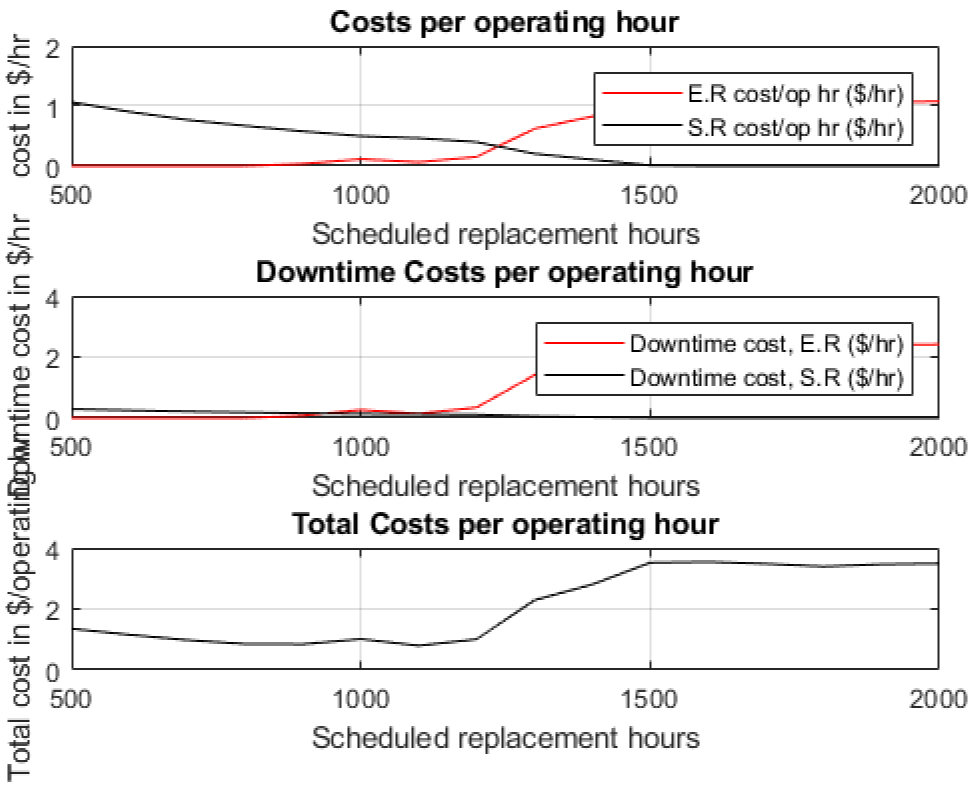

Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours

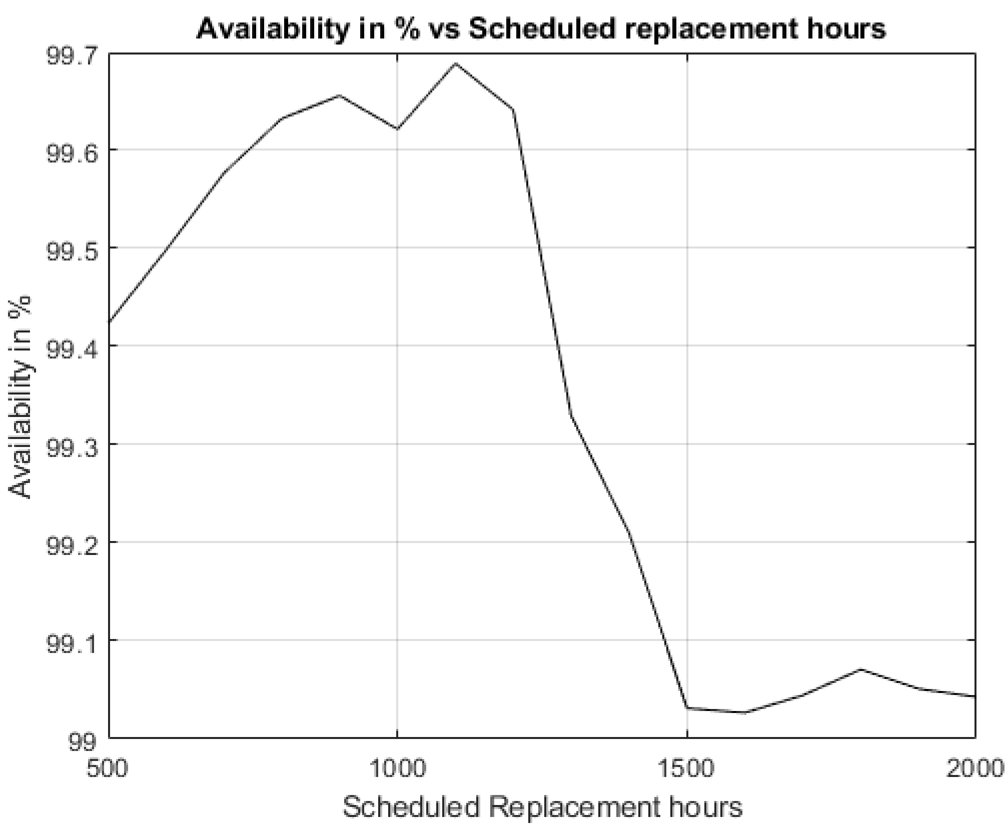

Costs per operating hour
cost in $/hr
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
Scheduled replacement hours
Downtime Costs per operating hour
Downtime cost in $/hr
Downtime cost, E.R ($/hr)
Downtime cost, S.R ($/hr)
Scheduled replacement hours
Total Costs per operating hour
Total cost in $/operating hr
Scheduled replacement hours

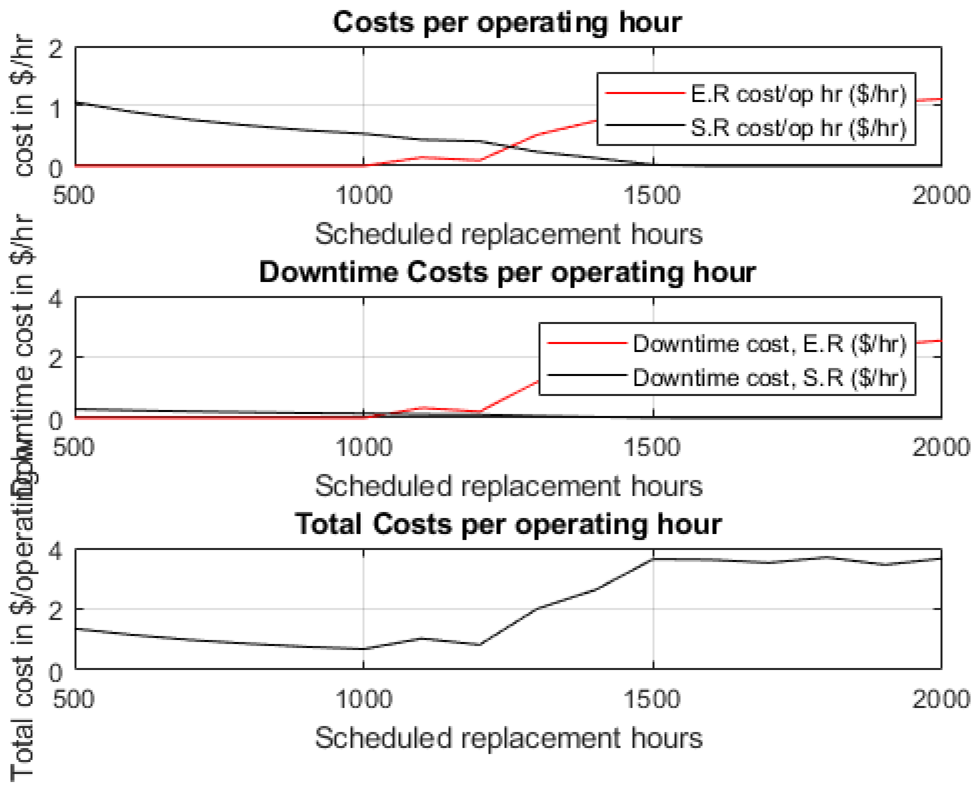

Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours


Costs per operating hour
cost in $/hr
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
Scheduled replacement hours
Downtime Costs per operating hour
Downtime cost in $/hr
Downtime cost, E.R ($/hr)
Downtime cost, S.R ($/hr)
Scheduled replacement hours
Total Costs per operating hour
Scheduled replacement hours
0
1
2
4
500
1000
1500
2000


Availability in % vs Scheduled replacement hours
Availability in %
99
99.1
99.2
99.3
99.4
99.5
99.6
99.7
500
1000
1500
2000
Scheduled Replacement hours


Costs per operating hour
cost in $/hr
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
Scheduled replacement hours
Downtime Costs per operating hour
Downtime cost in $/hr
Downtime cost, E.R ($/hr)
Downtime cost, S.R ($/hr)
Scheduled replacement hours
Total Costs per operating hour
Total cost in $/operating hr
Scheduled replacement hours


Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours


Costs per operating hour
cost in $/hr
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
Scheduled replacement hours
Downtime Costs per operating hour
Downtime cost in $/hr
Downtime cost, E.R ($/hr)
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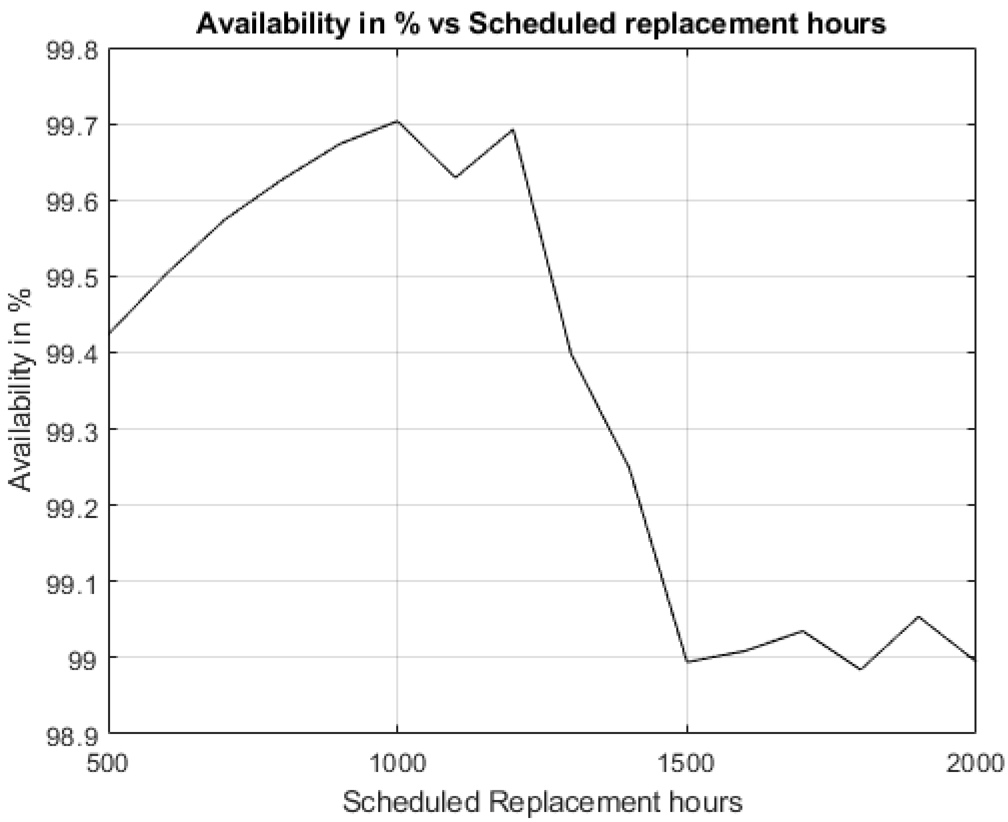
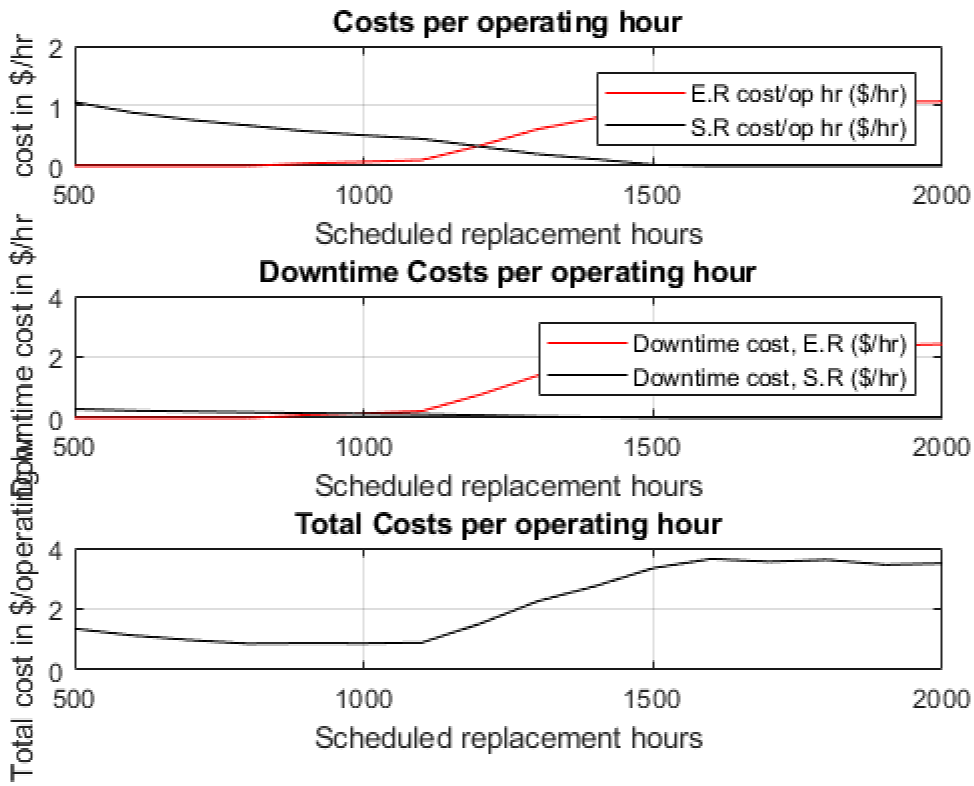
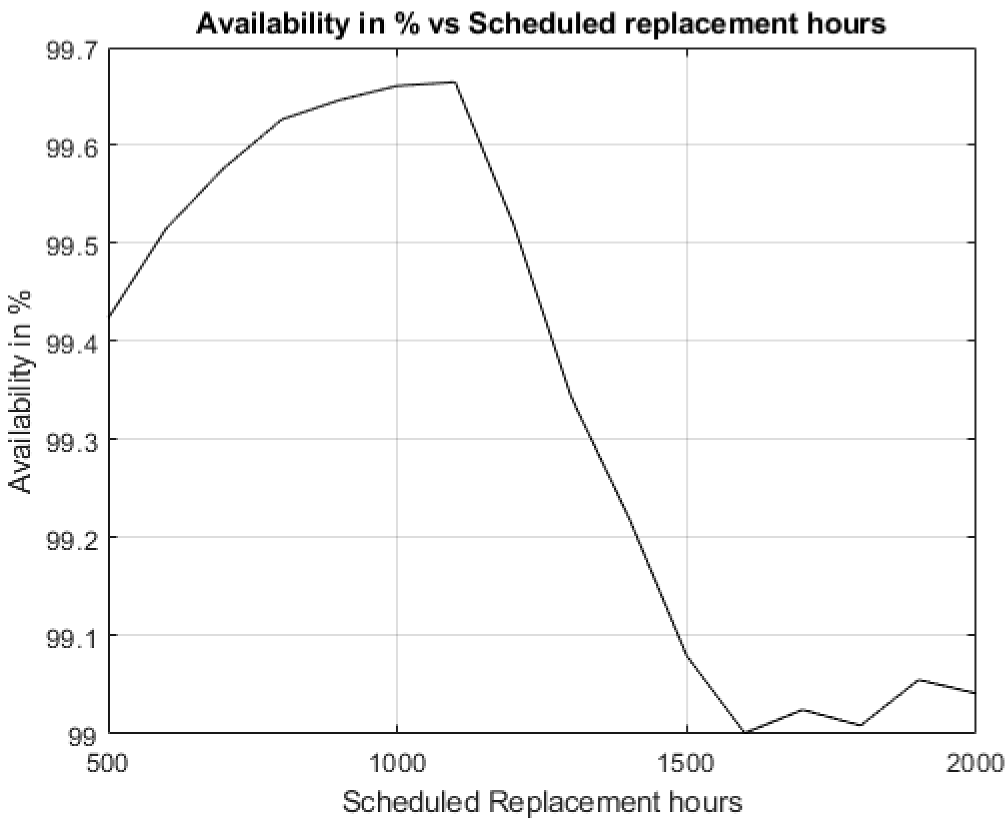
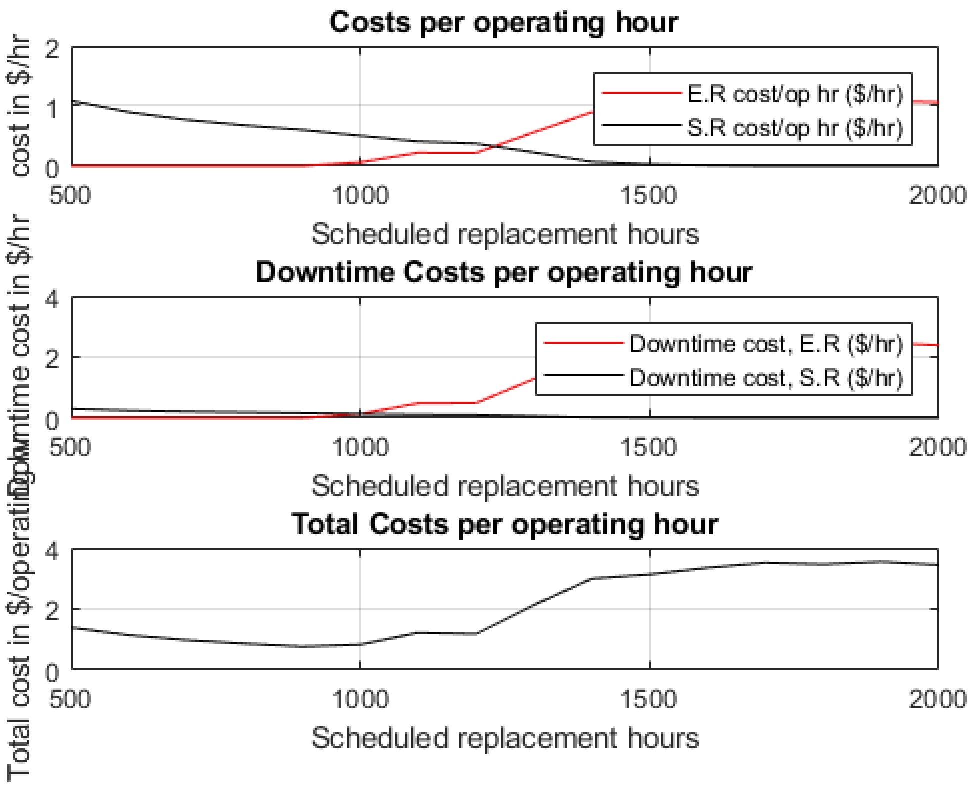
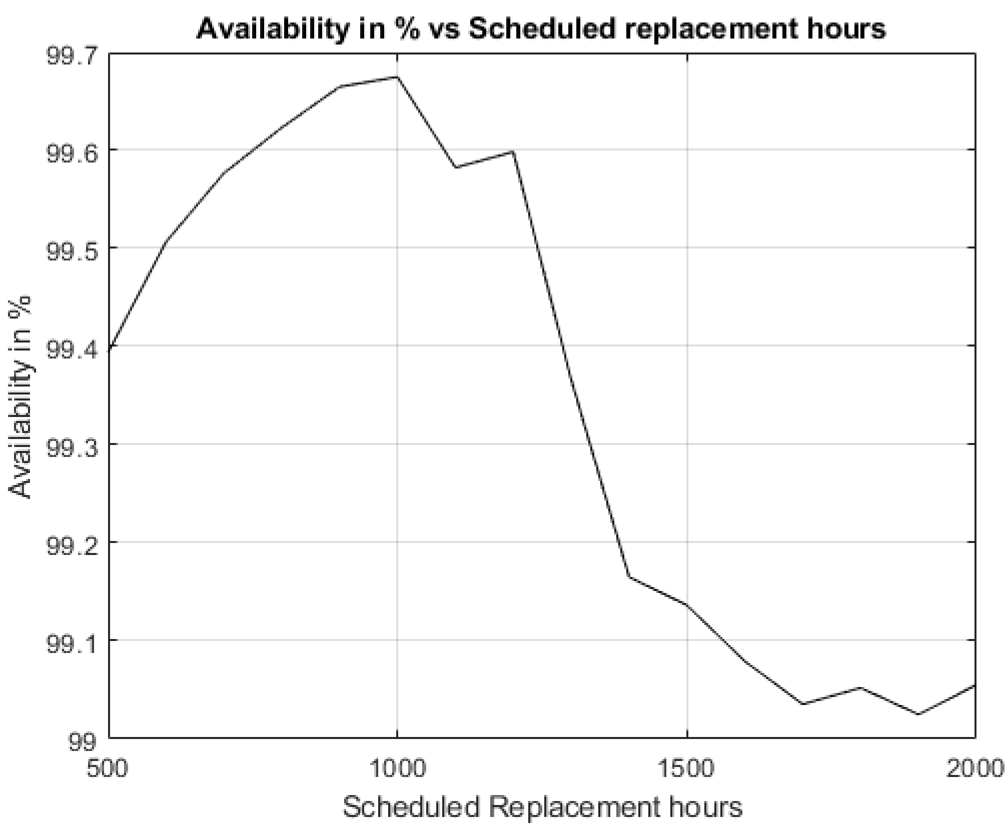
Scheduled replacement hours
Total Costs per operating hour
Total cost in $/operating
Scheduled replacement hours

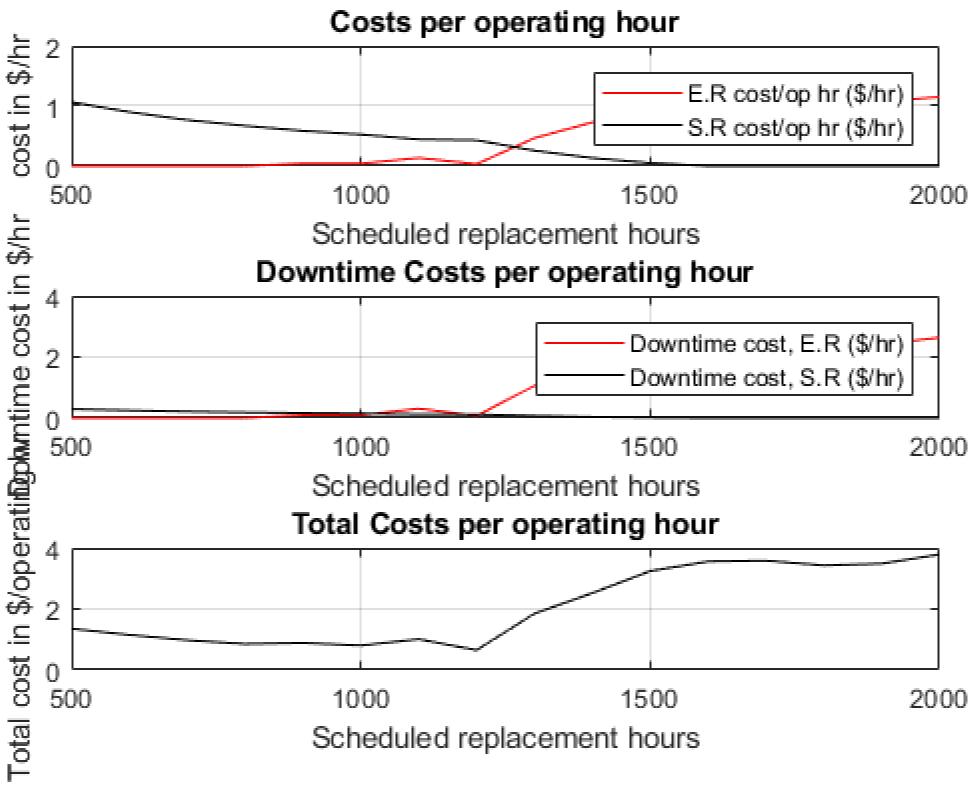

Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours

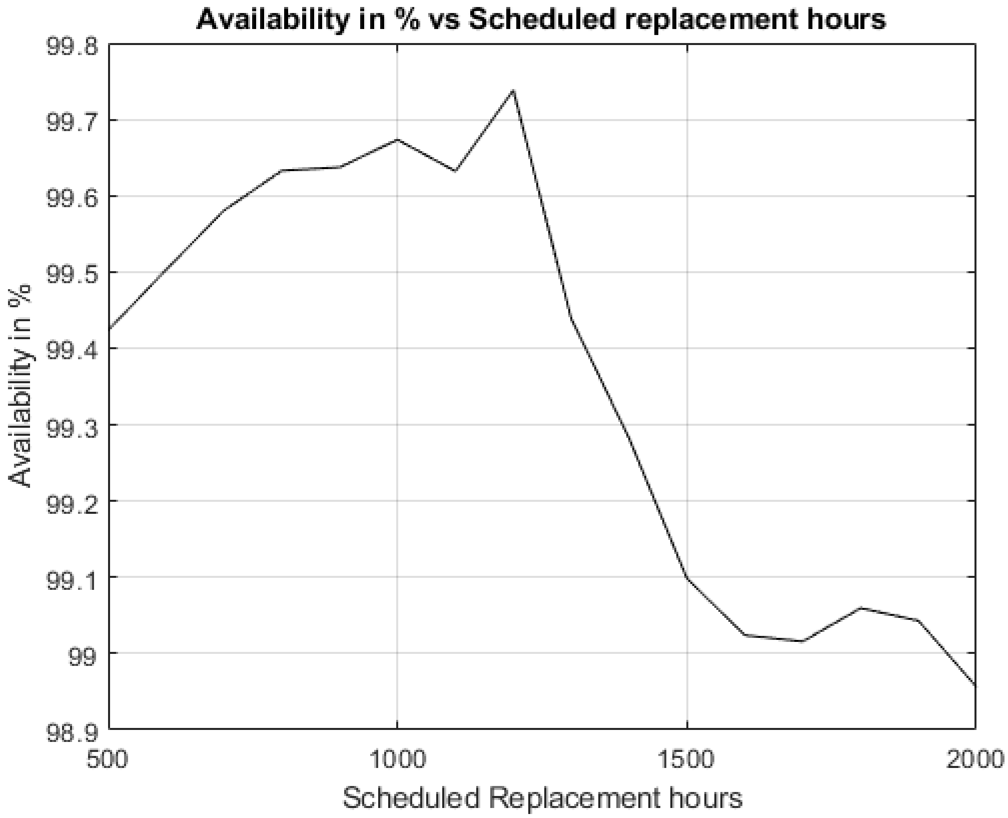

Costs per operating hour
cost in $/hr
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
Scheduled replacement hours
Downtime Costs per operating hour
Downtime cost in $/hr
Downtime cost, E.R ($/hr)
Downtime cost, S.R ($/hr)
Scheduled replacement hours
Total Costs per operating hour
Total cost in $/operating hr
Scheduled replacement hours

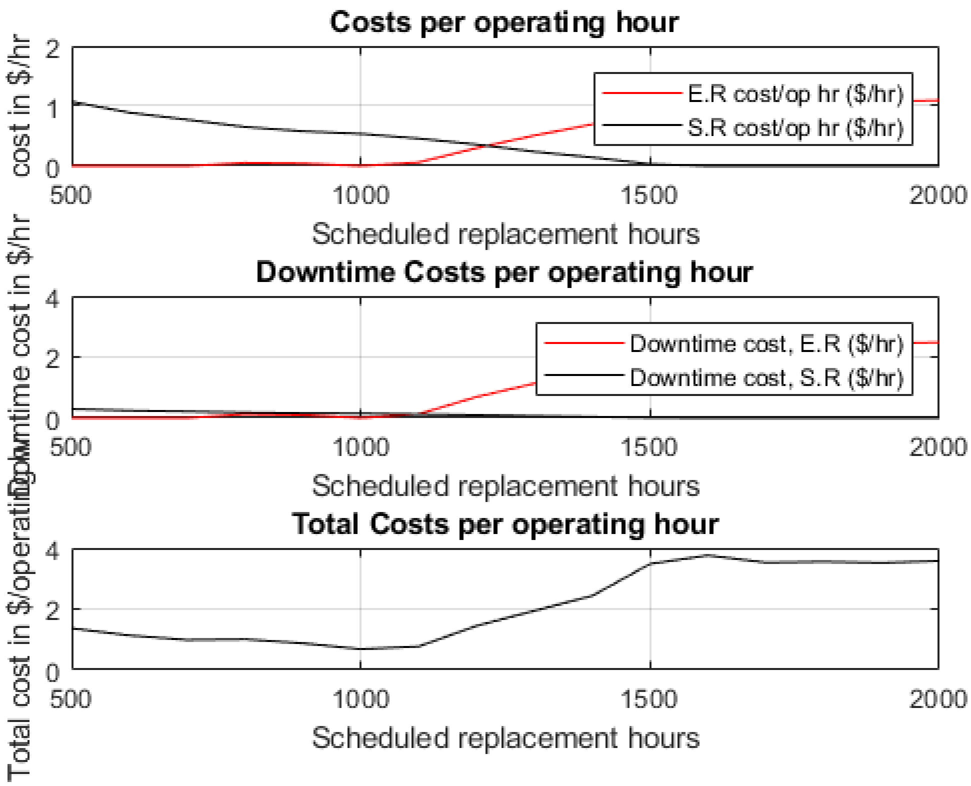

Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours

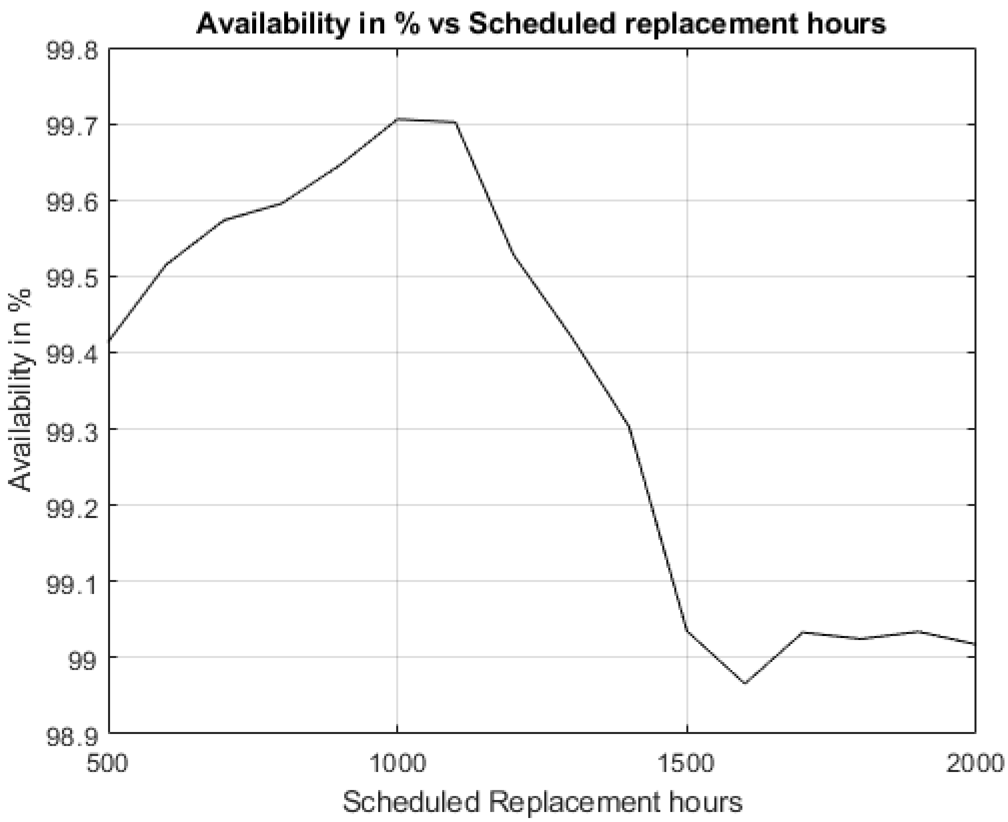

Costs per operating hour
cost in $/hr
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
Scheduled replacement hours
Downtime Costs per operating hour
Downtime cost in $/hr
Downtime cost, E.R ($/hr)
Downtime cost, S.R ($/hr)
Scheduled replacement hours
Total Costs per operating hour
Total cost in $/operating hr
Scheduled replacement hours

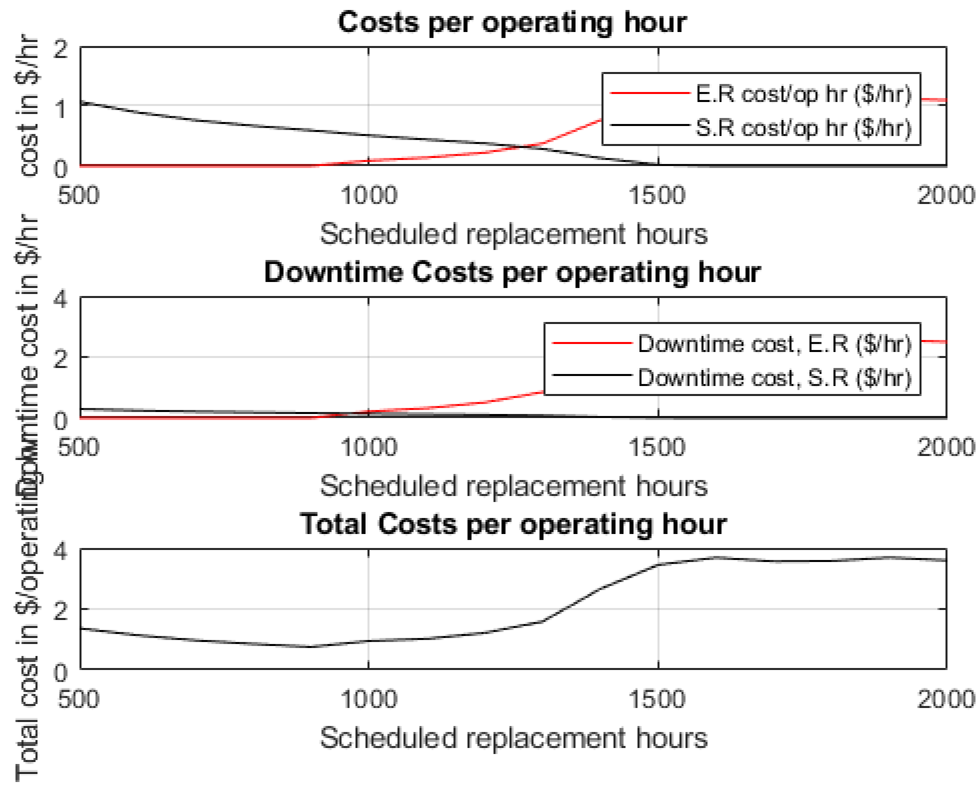

Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours


Costs per operating hour
cost in $/hr
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
Scheduled replacement hours
Downtime Costs per operating hour
Downtime cost in $/hr
Downtime cost, E.R ($/hr)
Downtime cost, S.R ($/hr)
Scheduled replacement hours
Total Costs per operating hour
Total cost in $/operating hr
Scheduled replacement hours

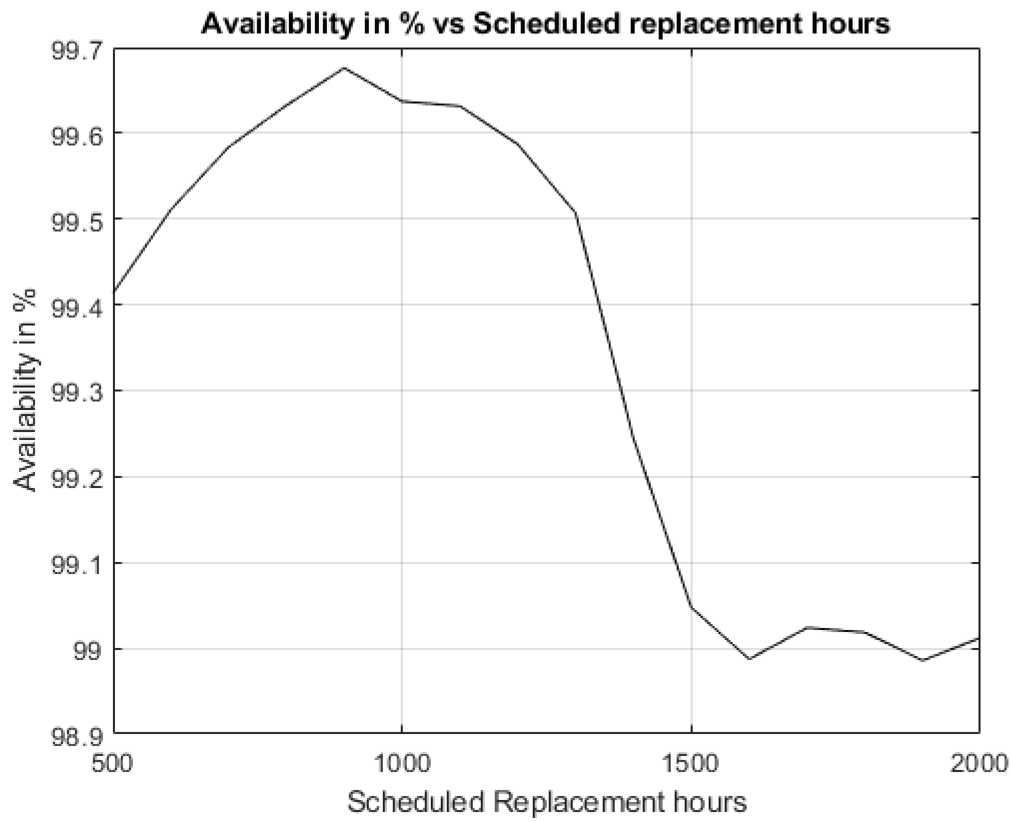

Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours


Costs per operating hour
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
cost in $/hr
Scheduled replacement hours
Downtime Costs per operating hour
Downtime cost, E.R ($/hr)
Downtime cost, S.R ($/hr)
Scheduled replacement hours
Total Costs per operating hour
Scheduled replacement hours

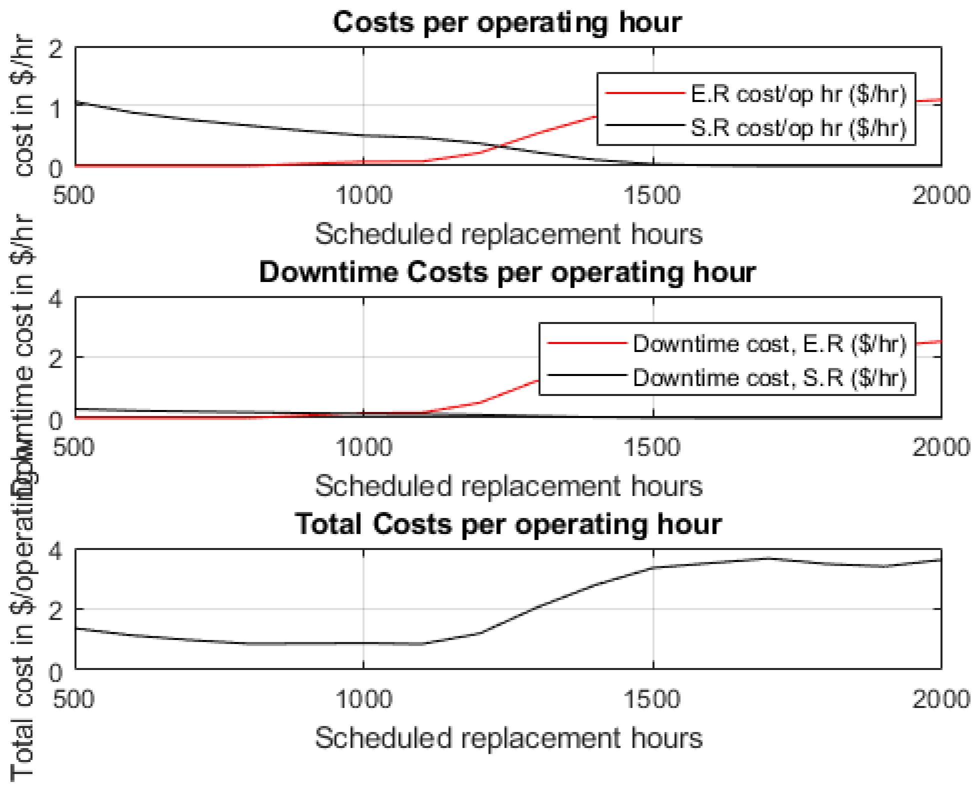

Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours

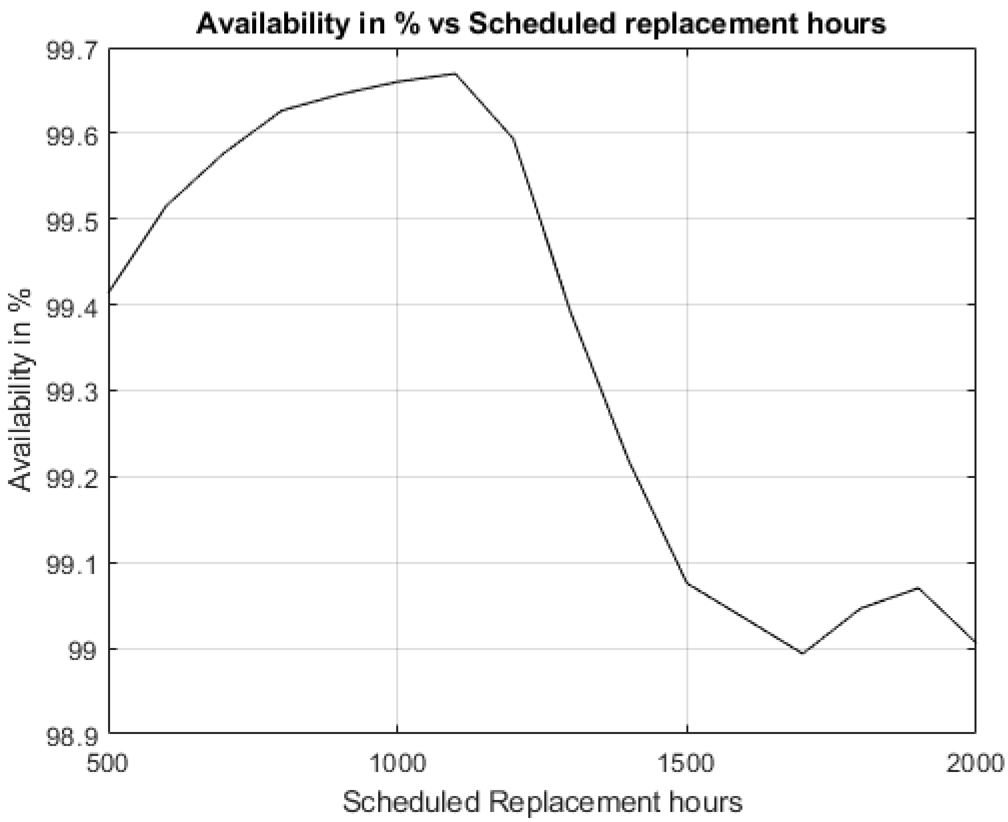


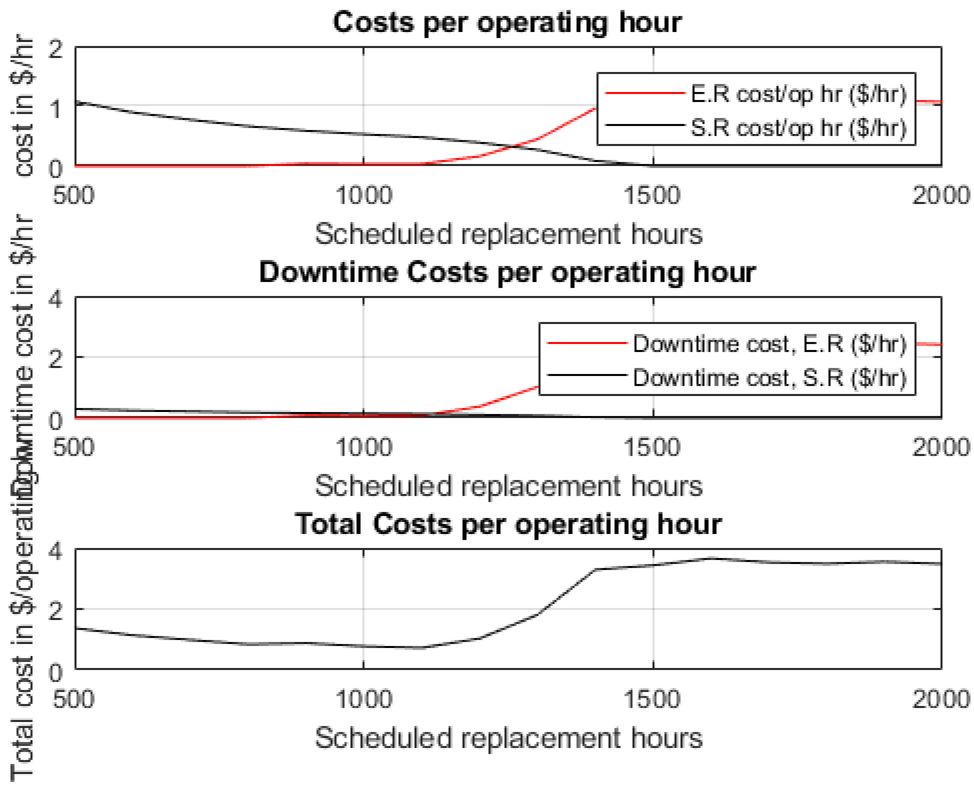
Costs per operating hour
cost in $/hr
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
Scheduled replacement hours
Downtime Costs per operating hour
Downtime cost in $/hr
Downtime cost, E.R ($/hr)
Downtime cost, S.R ($/hr)
Scheduled replacement hours
Total Costs per operating hour
Total cost in $/operating hr
Scheduled replacement hours



Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours


Costs per operating hour
cost in $/hr
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
Scheduled replacement hours
Downtime Costs per operating hour
Downtime cost in $/hr
Downtime cost, E.R ($/hr)
Downtime cost, S.R ($/hr)
Scheduled replacement hours
Total Costs per operating hour
Total cost in $/operating hr
Scheduled replacement hours


Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours



Costs per operating hour
cost in $/hr
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
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Downtime Costs per operating hour
Downtime cost in $/hr
Downtime cost, E.R ($/hr)
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Total Costs per operating hour
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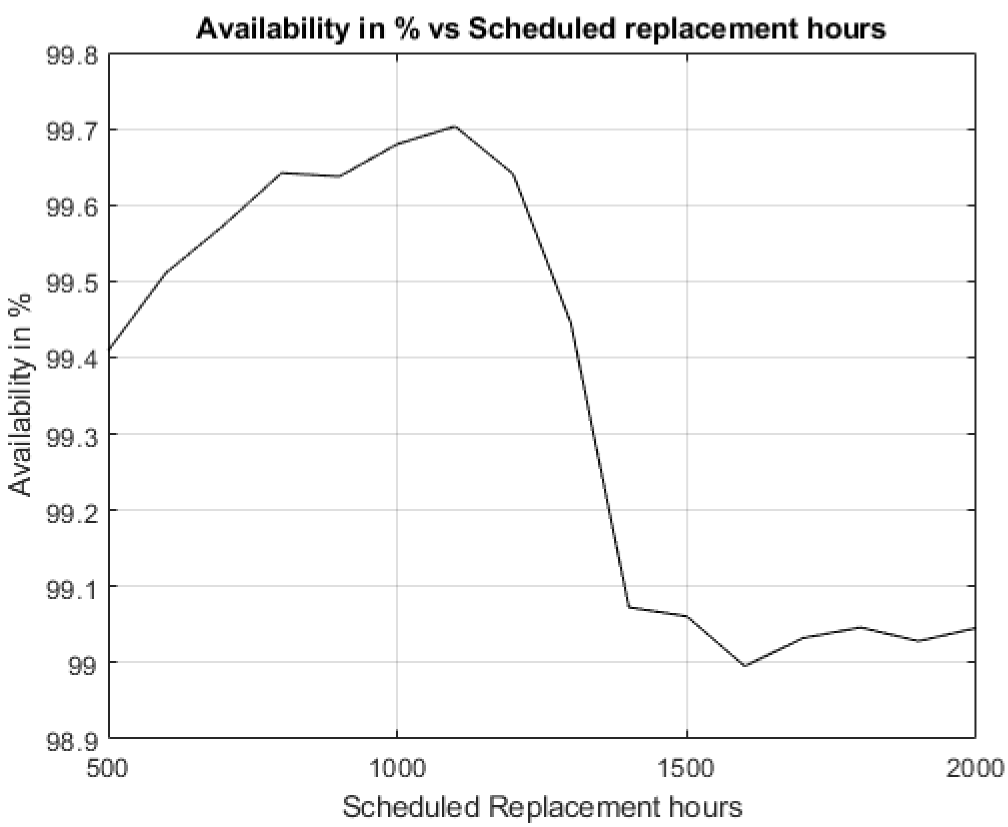
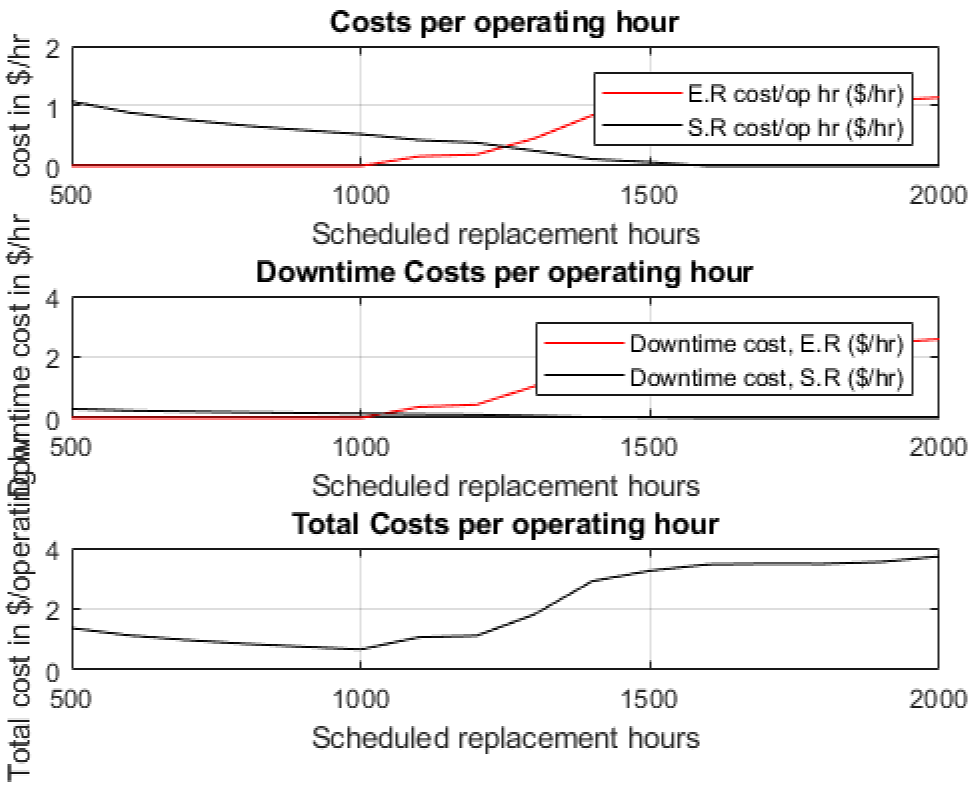
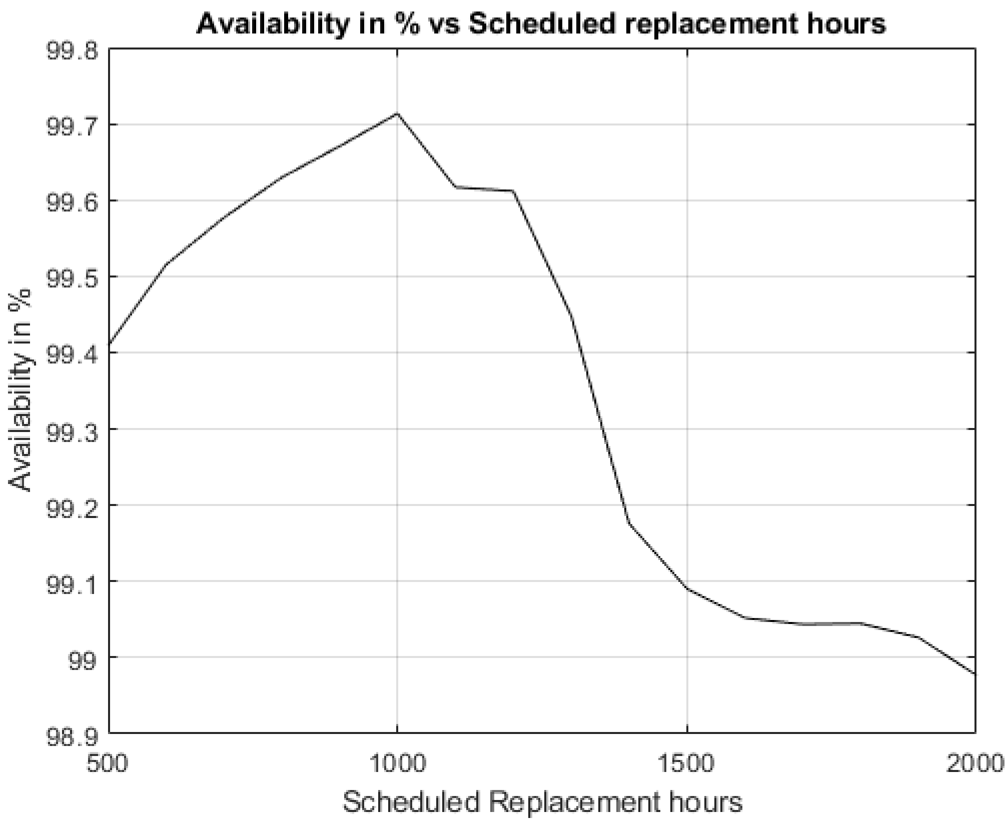
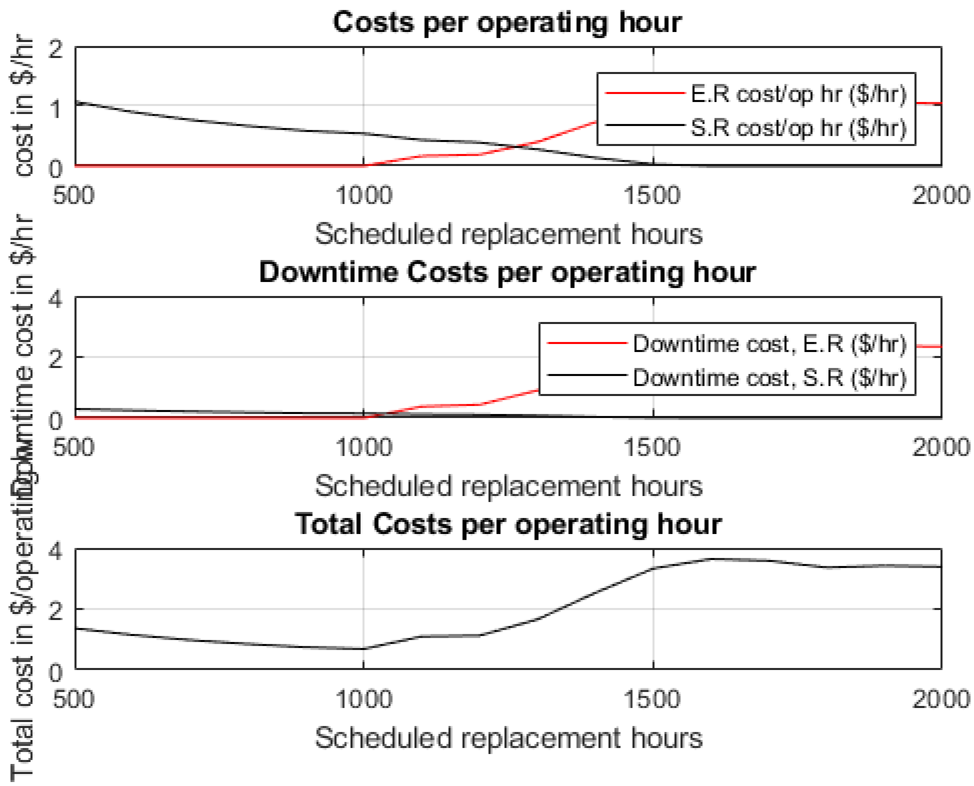
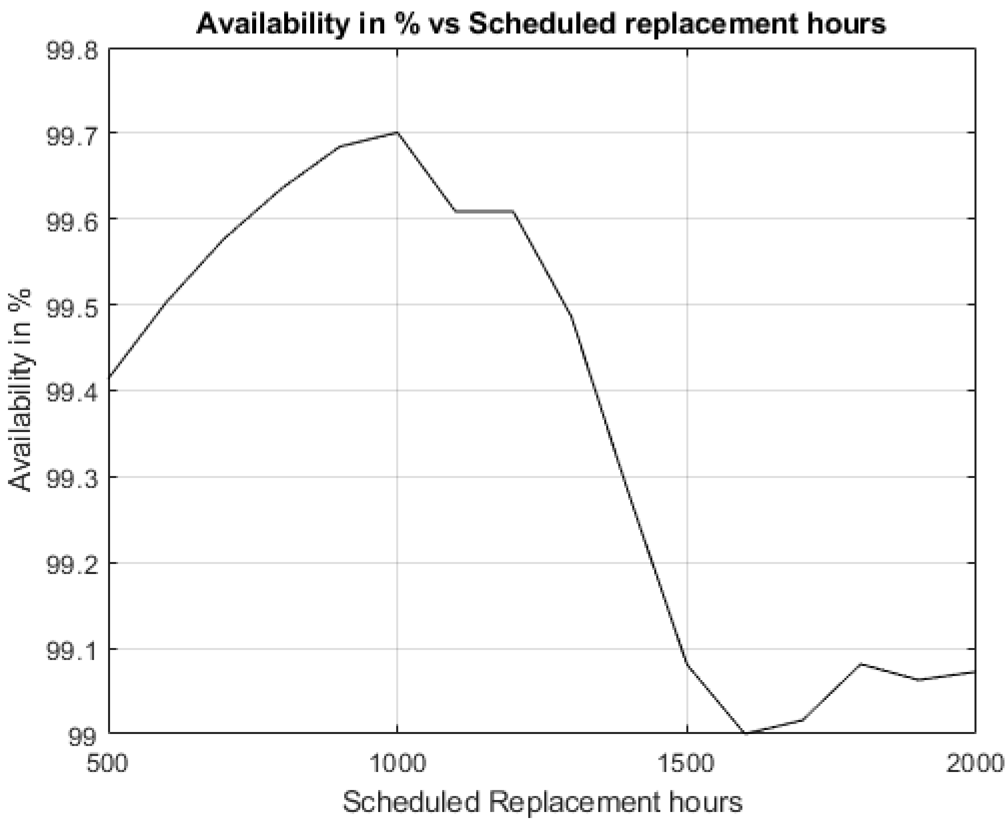


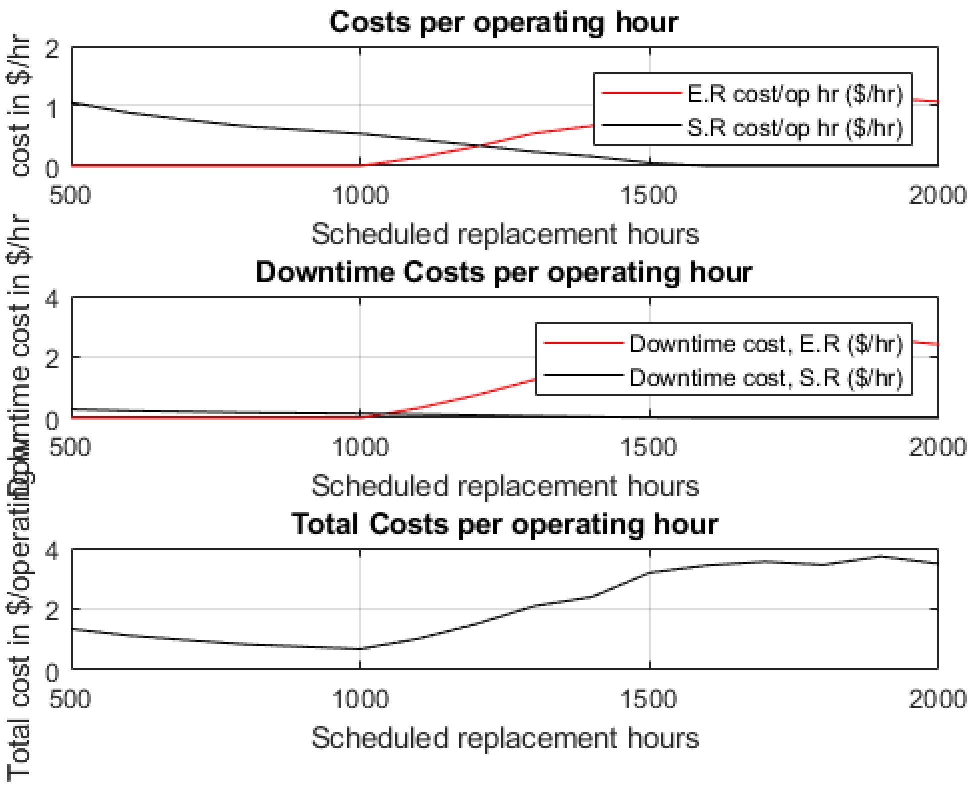
Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours


Costs per operating hour
cost in $/hr
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
Scheduled replacement hours
Downtime Costs per operating hour
Downtime cost in $/hr
Downtime cost, E.R ($/hr)
Downtime cost, S.R ($/hr)
Scheduled replacement hours
Total Costs per operating hour
Total cost in $/operating hour
Scheduled replacement hours
500
1000
1500
2000

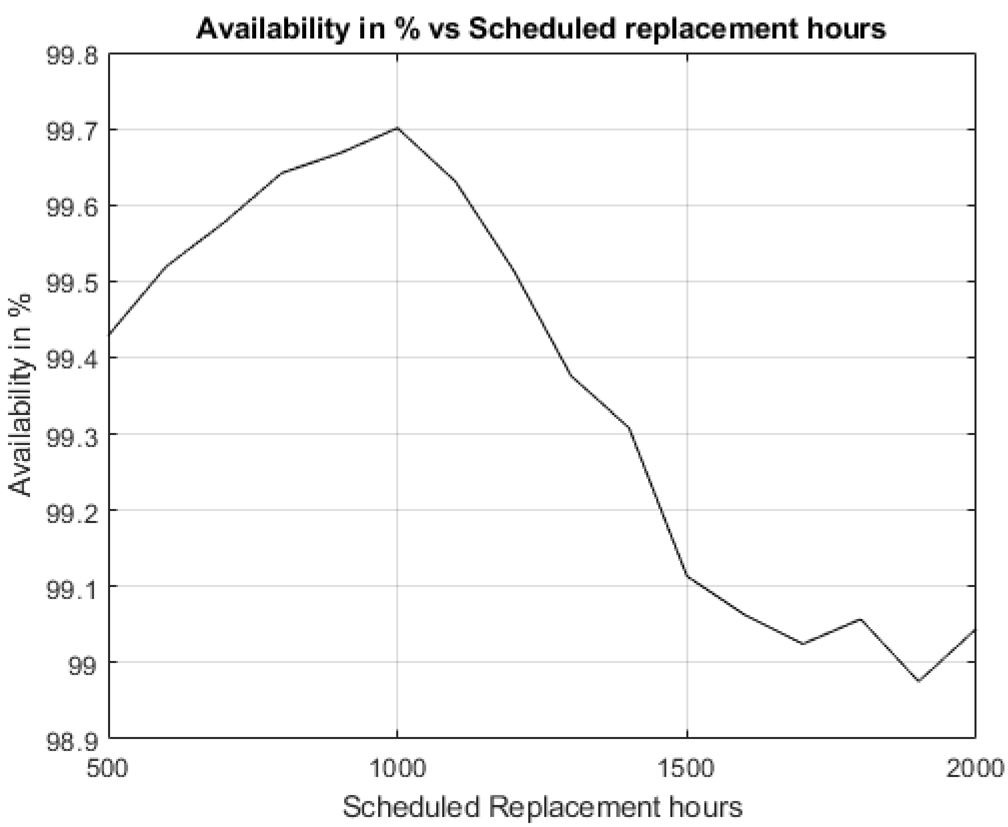

Availability in % vs Scheduled replacement hours
Availability in %
98.9
99
99.1
99.2
99.3
99.4
99.5
99.6
99.7
99.8
500
1000
1500
2000
Scheduled Replacement hours


Costs per operating hour
cost in $/hr
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
Scheduled replacement hours
Downtime Costs per operating hour
Downtime cost in $/hr
Downtime cost, E.R ($/hr)
Downtime cost, S.R ($/hr)
Scheduled replacement hours
Total Costs per operating hour
Total cost in $/operating hr
Scheduled replacement hours

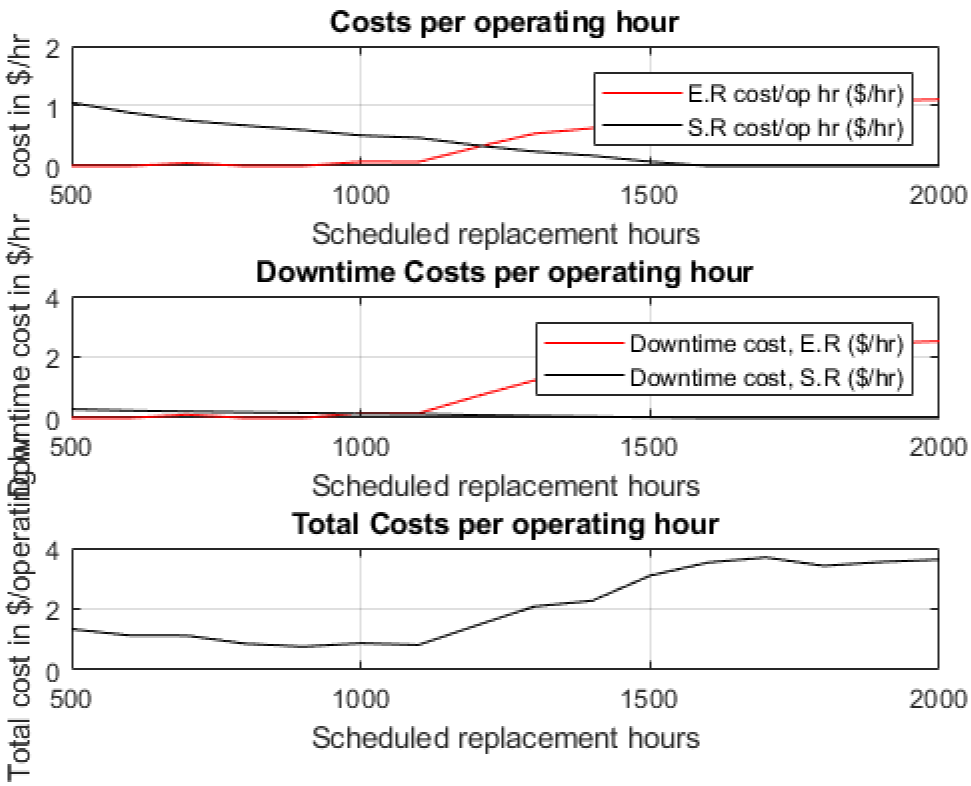

Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours

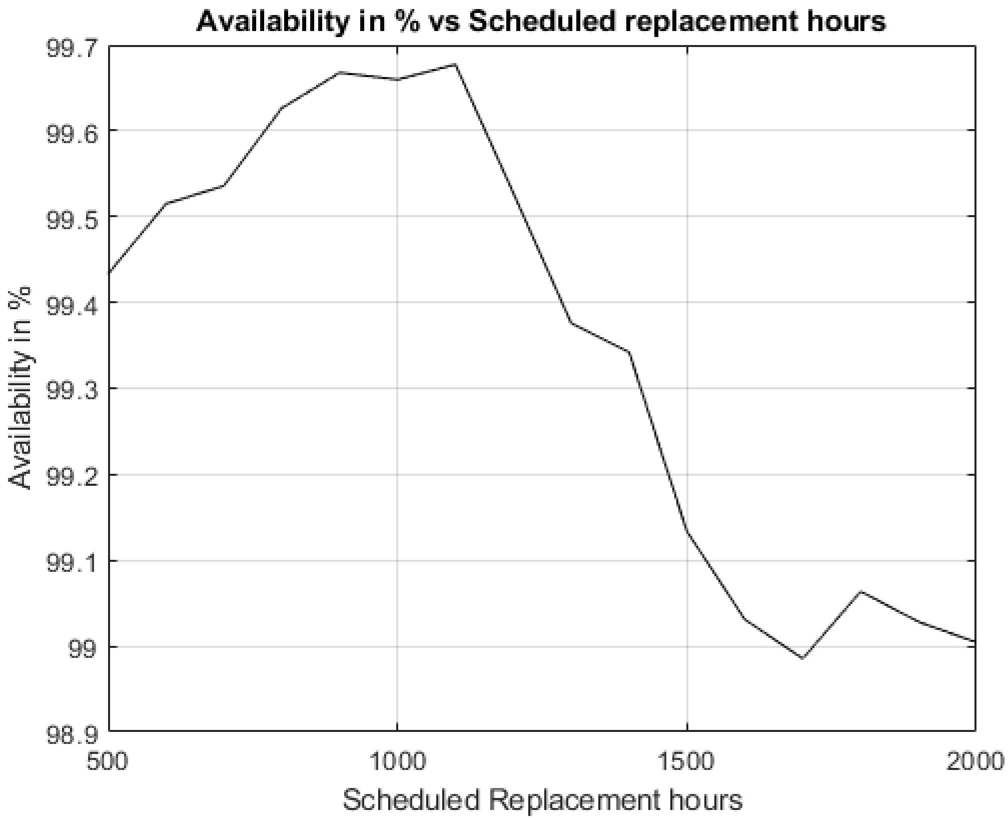


Costs per operating hour
cost in $/hr
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
Scheduled replacement hours
Downtime Costs per operating hour
Downtime cost in $/hr
Downtime cost, E.R ($/hr)
Downtime cost, S.R ($/hr)
Scheduled replacement hours
Total Costs per operating hour
Total cost in $/operating hr
Scheduled replacement hours



Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours


Costs per operating hour
cost in $/hr
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
Scheduled replacement hours
Downtime Costs per operating hour
Downtime cost in $/hr
Downtime cost, E.R ($/hr)
Downtime cost, S.R ($/hr)
Scheduled replacement hours
Total Costs per operating hour
Scheduled replacement hours
0
1
2
4
500
1000
1500
2000


Availability in % vs Scheduled replacement hours
Availability in %
98.9
99
99.1
99.2
99.3
99.4
99.5
99.6
99.7
500
1000
1500
2000
Scheduled Replacement hours

Sub-System 2: Cooling System Output Data

Time	Description
500	Operation
3	Scheduled Replacement
500	Operation
3	Scheduled Replacement
500	Operation
3	Scheduled Replacement
500	Operation
3	Scheduled Replacement
500	Operation
3	Scheduled Replacement
500	Operation
3	Scheduled Replacement
500	Operation
3	Scheduled Replacement
500	Operation
3	Scheduled Replacement
500	Operation
2	Scheduled Replacement
500	Operation
3	Scheduled Replacement
500	Operation
3	Scheduled Replacement
500	Operation
3	Scheduled Replacement
500	Operation
3	Scheduled Replacement
500	Operation
3	Scheduled Replacement
500	Operation
3	Scheduled Replacement
500	Operation
3	Scheduled Replacement
500	Operation
3	Scheduled Replacement
500	Operation
2	Scheduled Replacement
500	Operation
3	Scheduled Replacement
500	Operation
3	Scheduled Replacement
500	Operation
3	Scheduled Replacement
500	Operation
3	Scheduled Replacement

Parameters	Counts
TOT (hr)	20000
TST (hr)	116
TET (hr)	0
TT (hr)	20116
Availability (%)	99.42
NS	40
NE	0

Jobs	Costs
Scheduled replacement cost per operating hr	1.064
Emergency replacement cost per operating hr	0
Downtime Cost (For Schedule replacement) per operating hr	0.29
Downtime Cost (emergency replacment) per operating hr	0
Sum	1.354

Others	Value
Alpha level in model	0.05
Schedule hr	500
Min Wait time in hr (emergency)	2
Max wait time in hr (emergency)	8
Min wait time in hr (Schedule)	0.5
Max wait time in hr (Schedule)	1
Downtime cost (scheduled replacement) $/hr	50
Downtime cost (emergency replacement) $/hr	250
Scrap value	0

500 Operation
2 Scheduled Replacement
500 Operation
3 Scheduled Replacement
500 Operation
3 Scheduled Replacement
500 Operation
2 Scheduled Replacement
500 Operation
3 Scheduled Replacement
500 Operation
3 Scheduled Replacement
500 Operation
3 Scheduled Replacement
500 Operation
3 Scheduled Replacement
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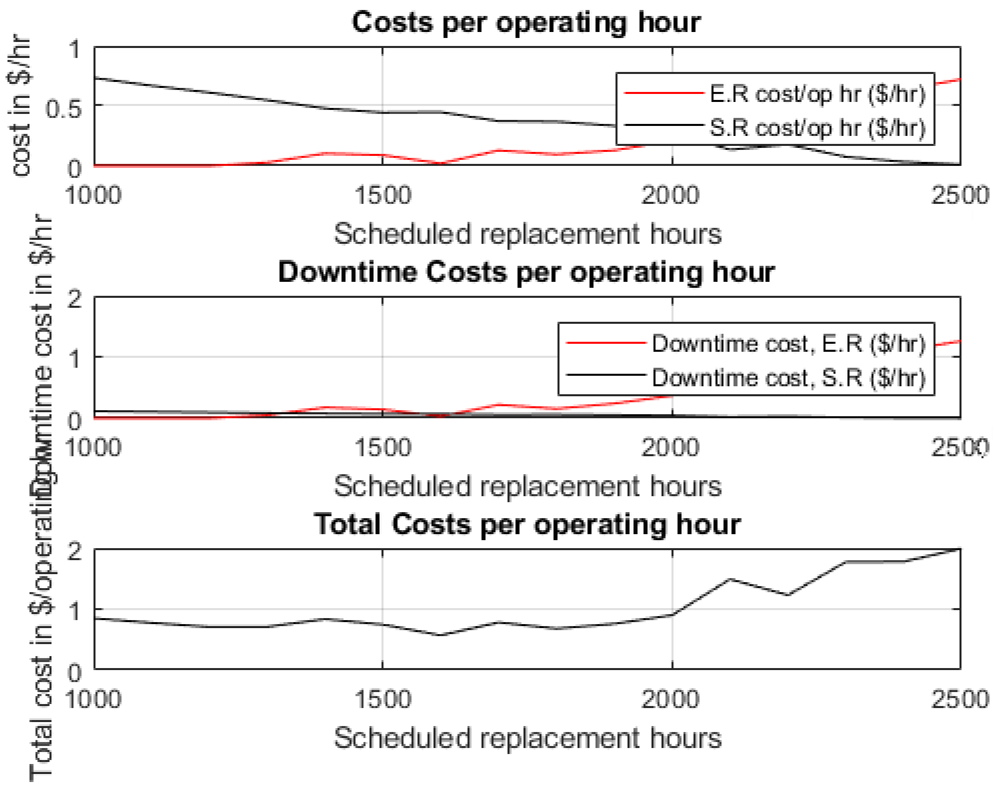
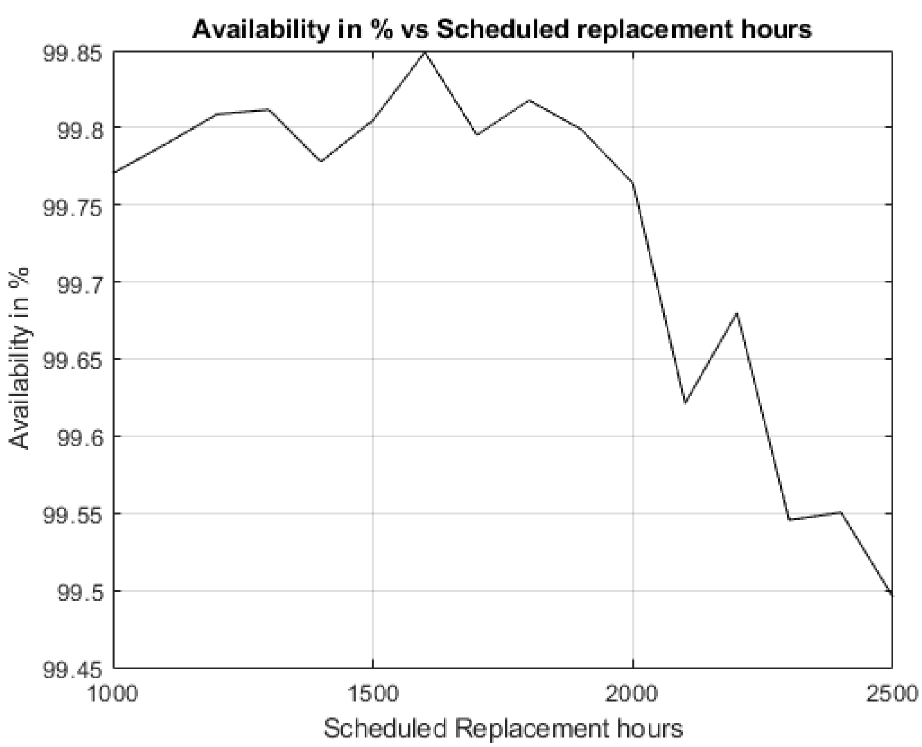
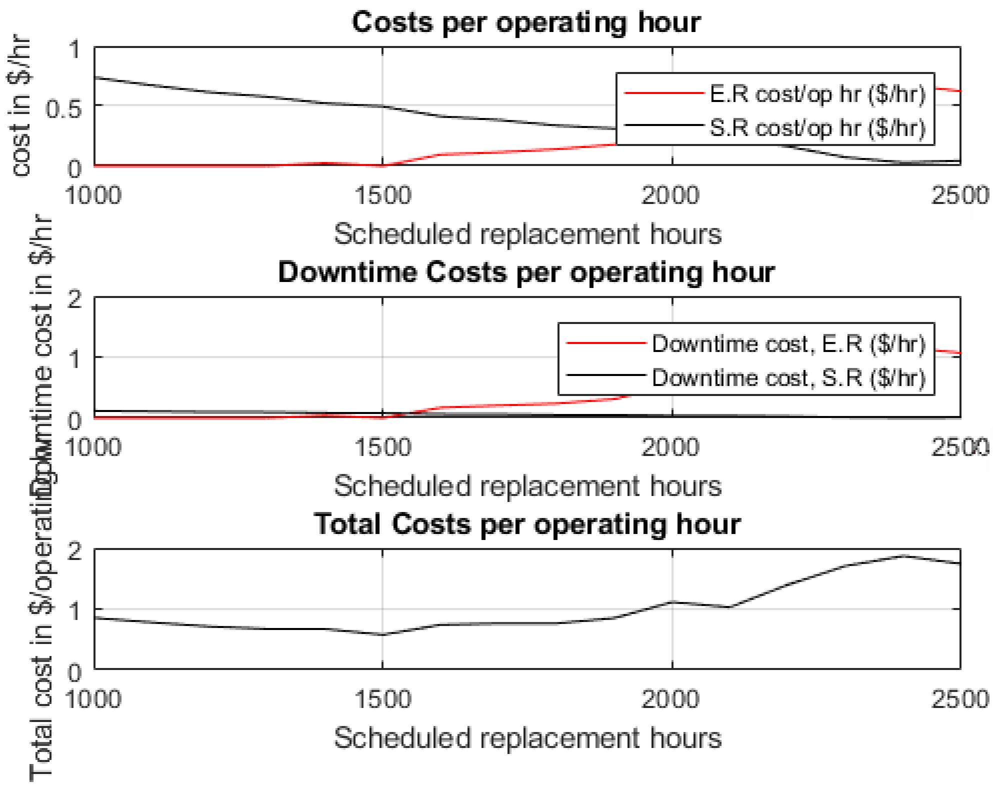
3 Scheduled Replacement
500 Operation
3 Scheduled Replacement
500 Operation
3 Scheduled Replacement
500 Operation
3 Scheduled Replacement
500 Operation
3 Scheduled Replacement
500 Operation
3 Scheduled Replacement
500 Operation
3 Scheduled Replacement

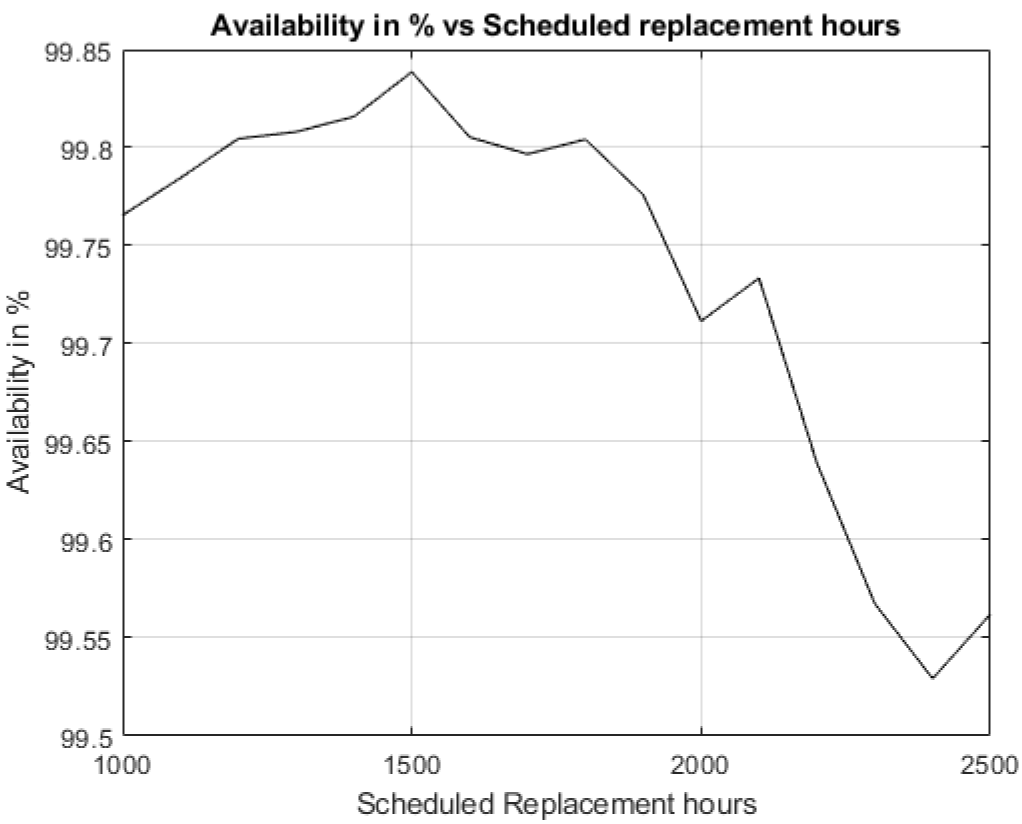
Sub-System 3: DPF System Output Graphs



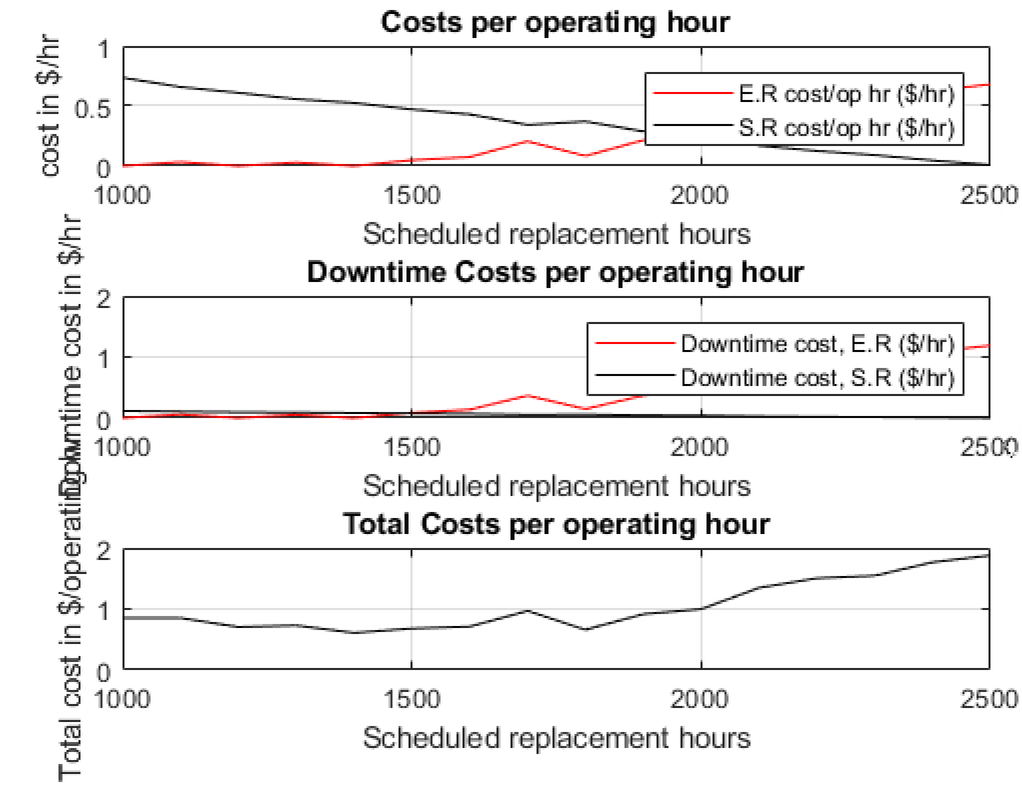


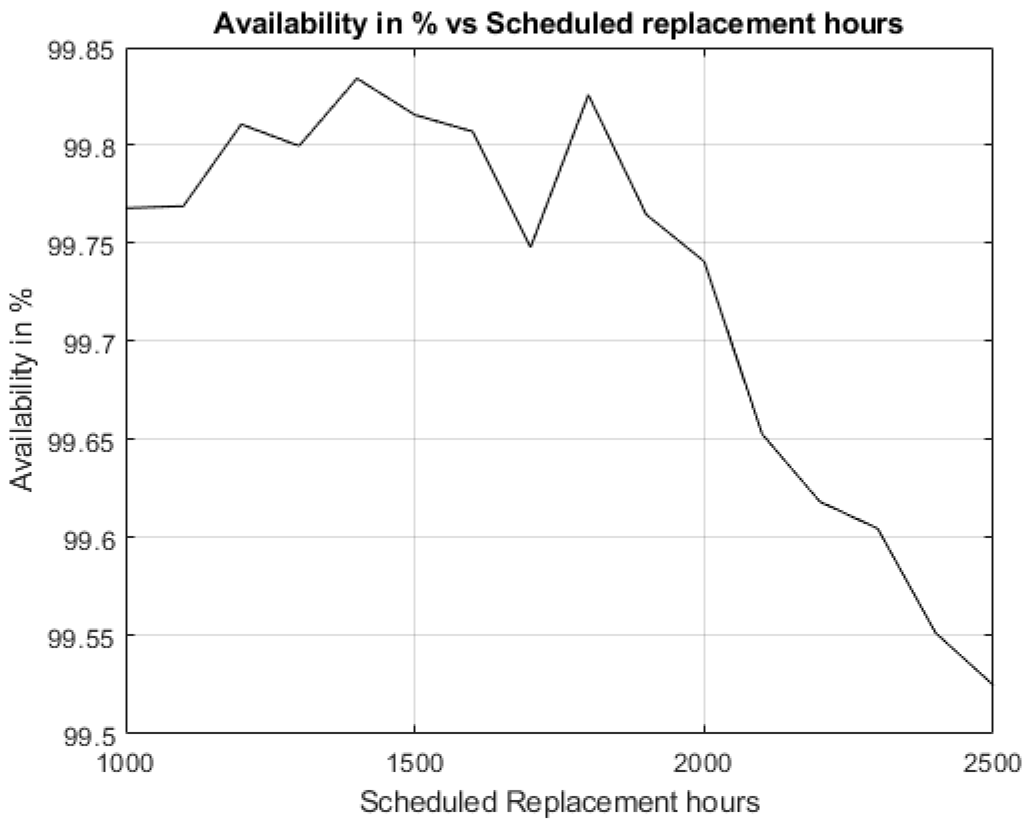


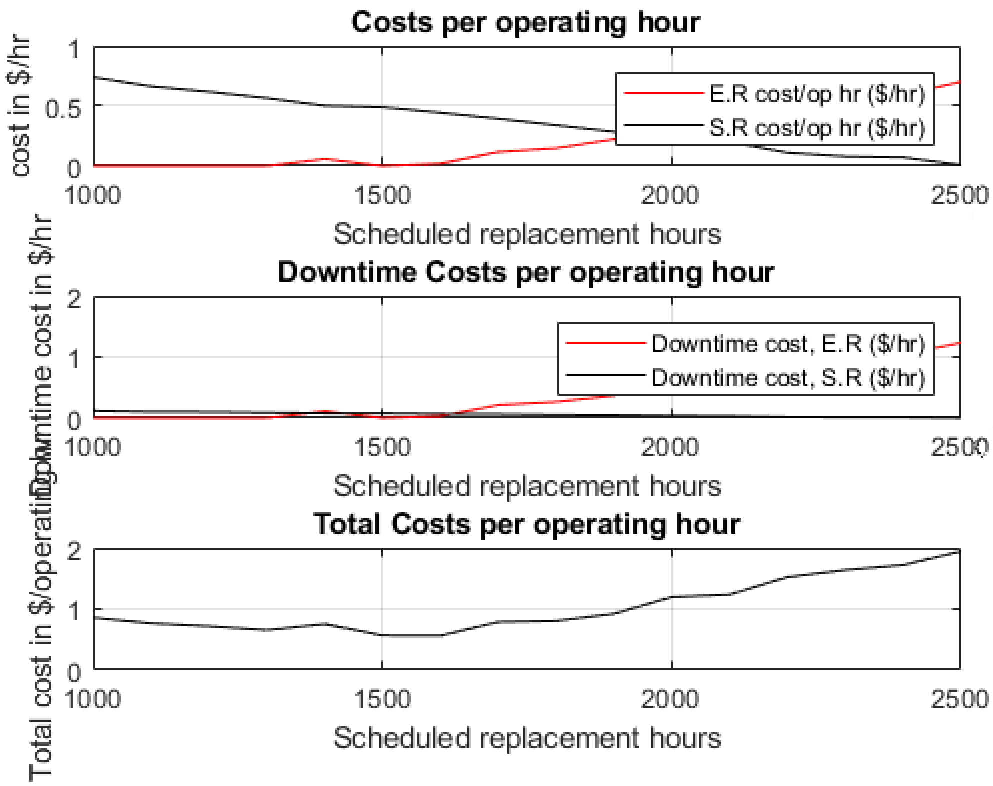
Costs per operating hour
cost in $/hr
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
Scheduled replacement hours
Downtime Costs per operating hour
Downtime cost in $/hr
Downtime cost, E.R ($/hr)
Downtime cost, S.R ($/hr)
Scheduled replacement hours
Total Costs per operating hour
Total cost in $/operating hr
Scheduled replacement hours



Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours


Costs per operating hour
cost in $/hr
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
Scheduled replacement hours
Downtime Costs per operating hour
Downtime cost in $/hr
Downtime cost, E.R ($/hr)
Downtime cost, S.R ($/hr)
Scheduled replacement hours
Total Costs per operating hour
Total cost in $/operating hr
Scheduled replacement hours


Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours


Costs per operating hour
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E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
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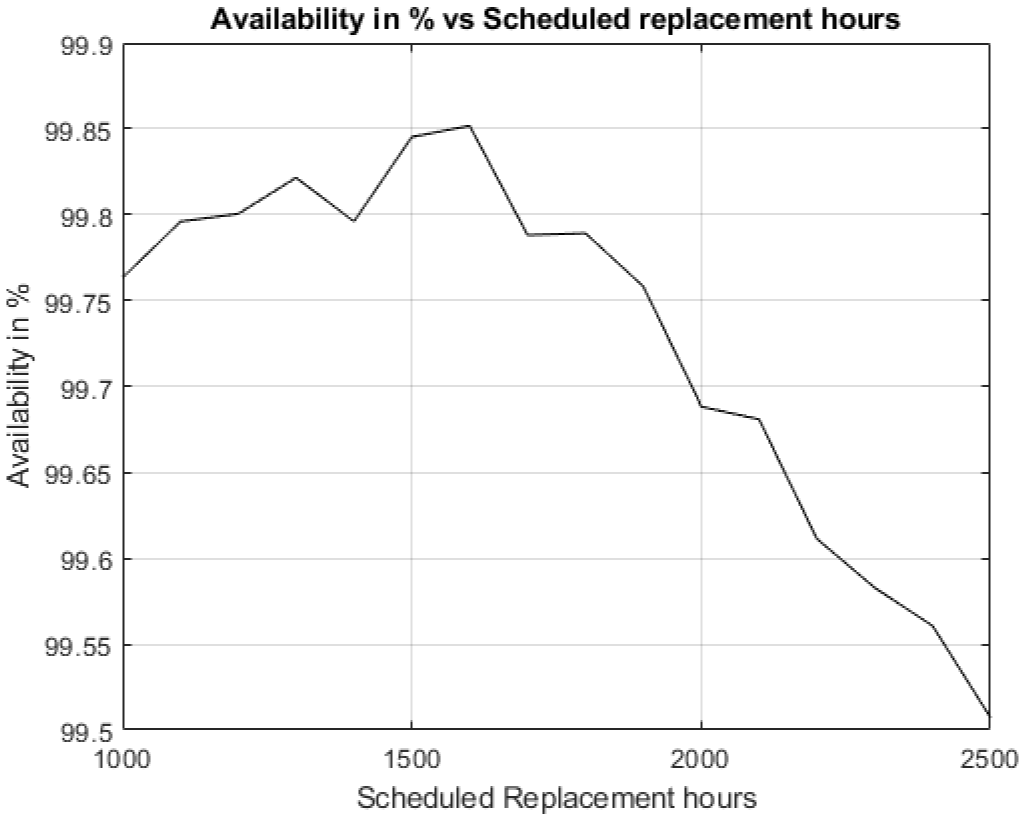
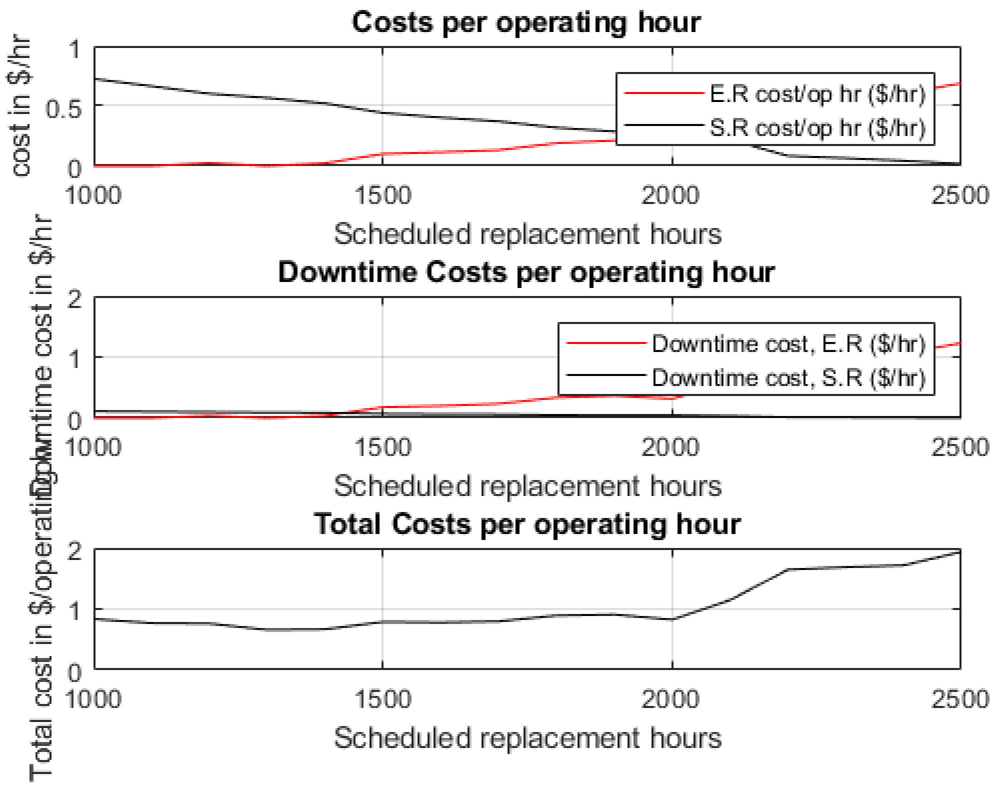
Downtime Costs per operating hour
Downtime cost in $/hr
Downtime cost, E.R ($/hr)
Downtime cost, S.R ($/hr)
Scheduled replacement hours
Total Costs per operating hour
Total cost in $/operating hr
Scheduled replacement hours


Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours


Costs per operating hour
cost in $/hr
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
Scheduled replacement hours
Downtime Costs per operating hour
Downtime cost in $/hr
Downtime cost, E.R ($/hr)
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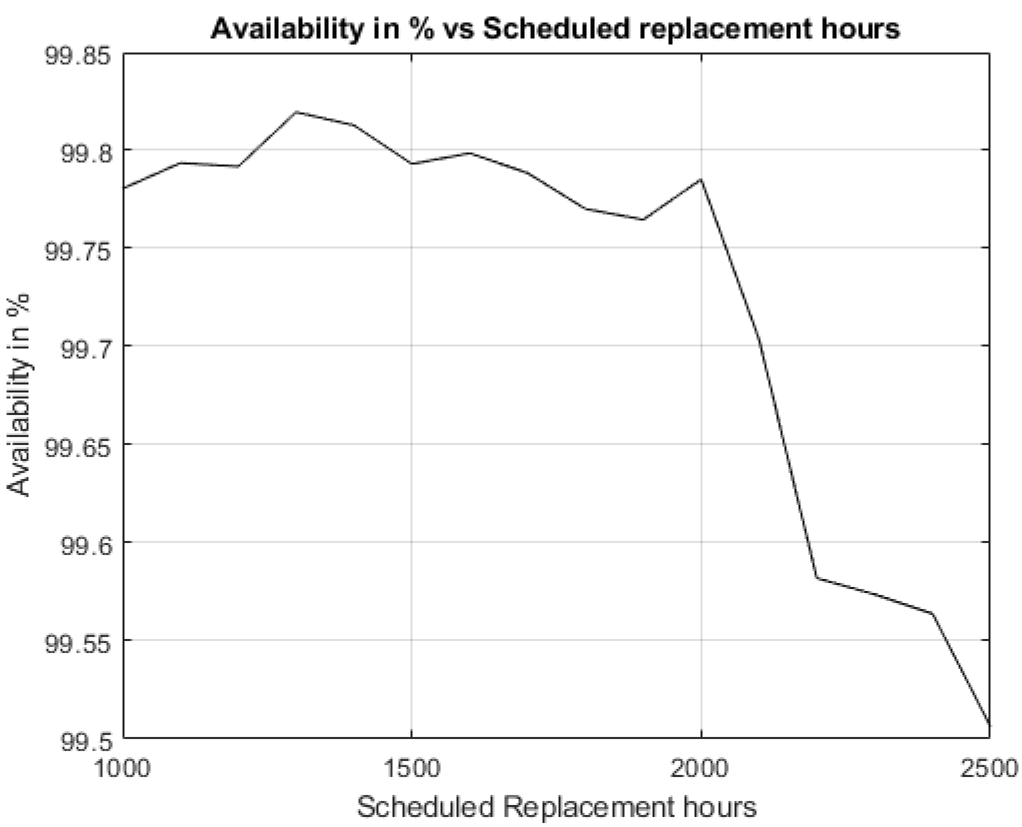
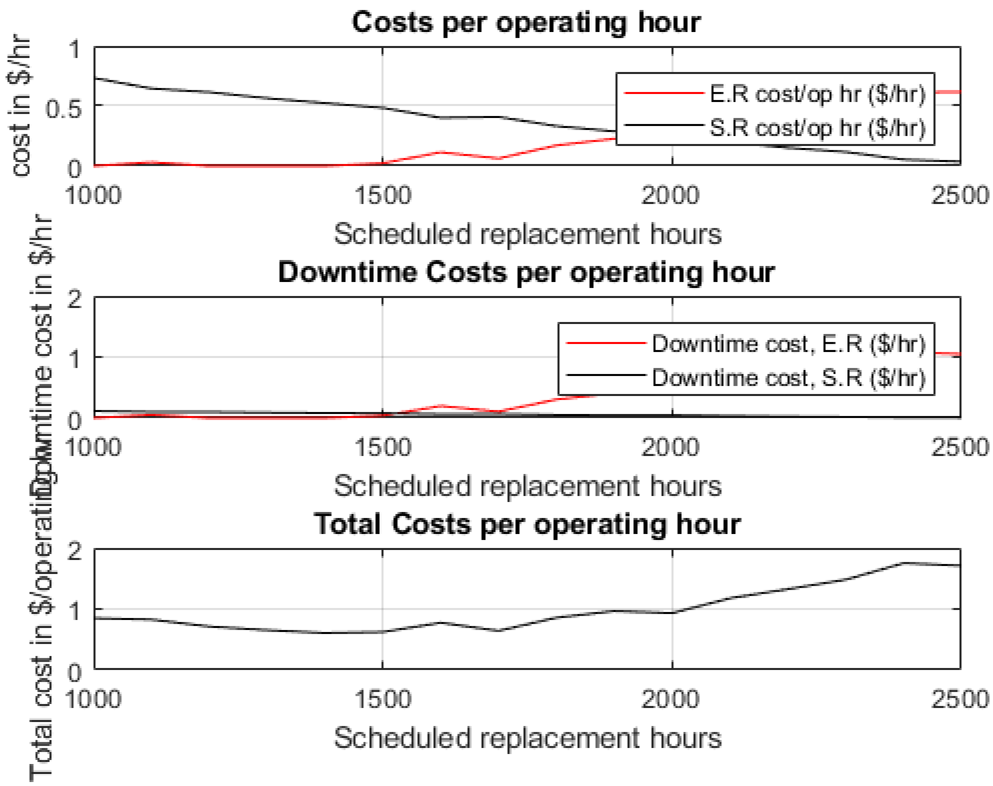
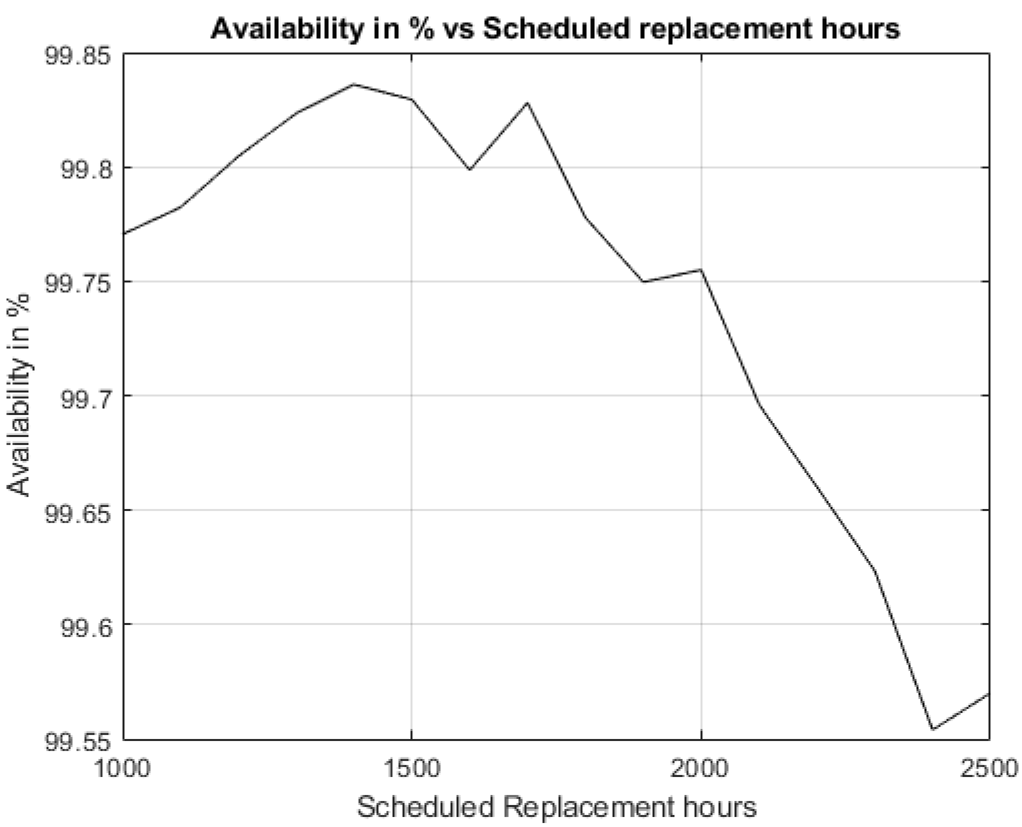
Scheduled replacement hours
Total Costs per operating hour
Total cost in $/operating hr
Scheduled replacement hours

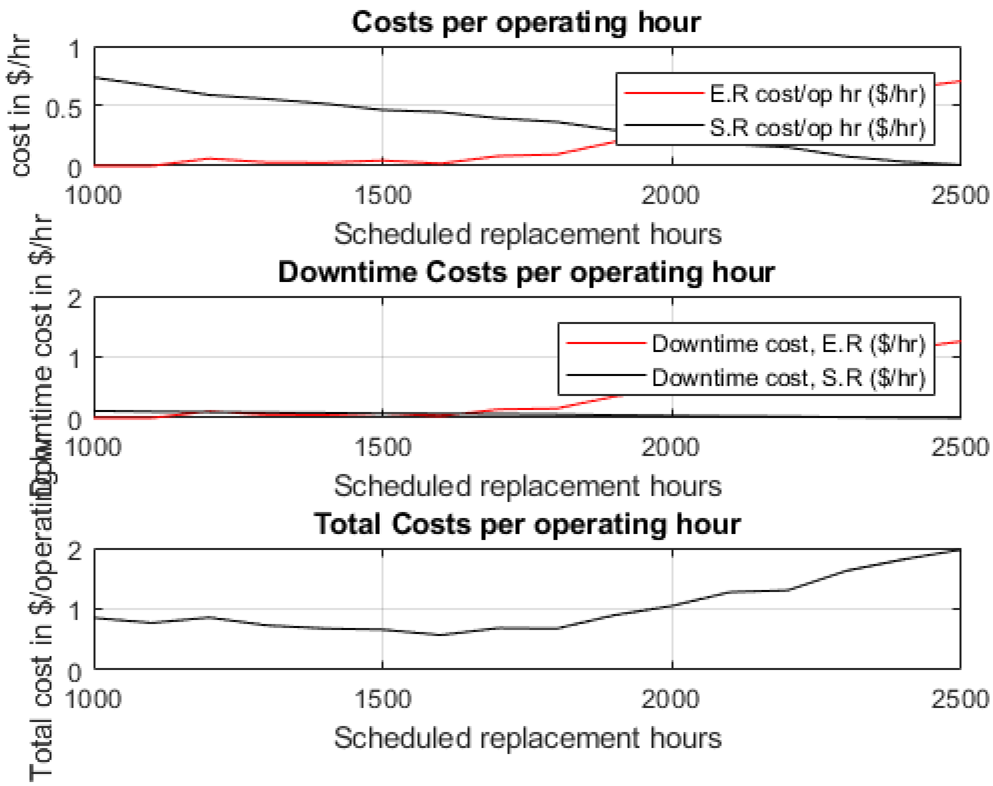

Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours



Costs per operating hour
cost in $/hr
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
Scheduled replacement hours
Downtime Costs per operating hour
Downtime cost in $/hr
Downtime cost, E.R ($/hr)
Downtime cost, S.R ($/hr)
Scheduled replacement hours
Total Costs per operating hour
Total cost in $/operating hr
Scheduled replacement hours



Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours


Costs per operating hour
cost in $/hr
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
Scheduled replacement hours
Downtime Costs per operating hour
Downtime cost in $/hr
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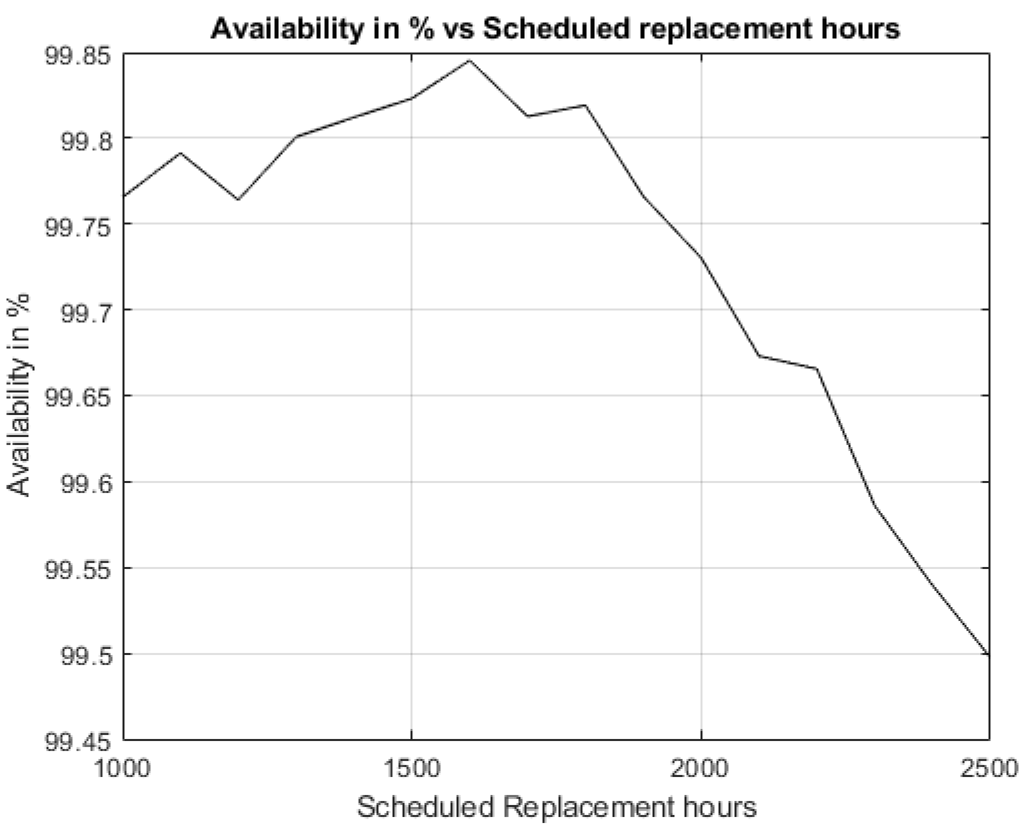
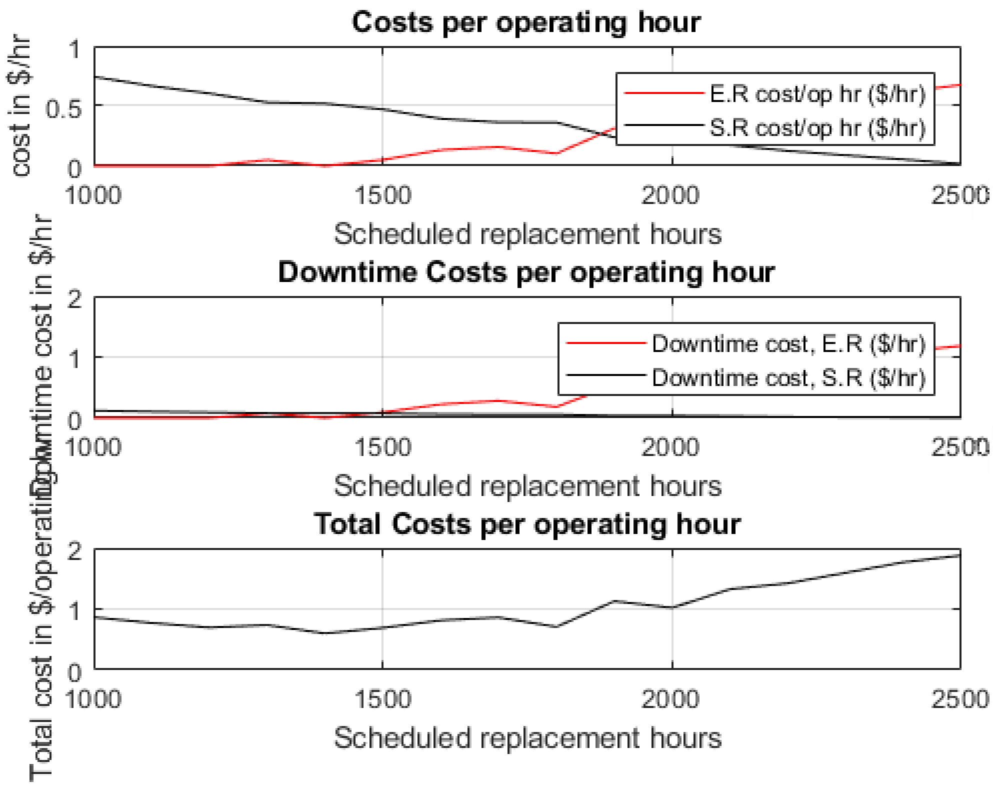
Scheduled replacement hours


Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours


Costs per operating hour
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E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
Scheduled replacement hours
Downtime Costs per operating hour
Downtime cost in $/hr
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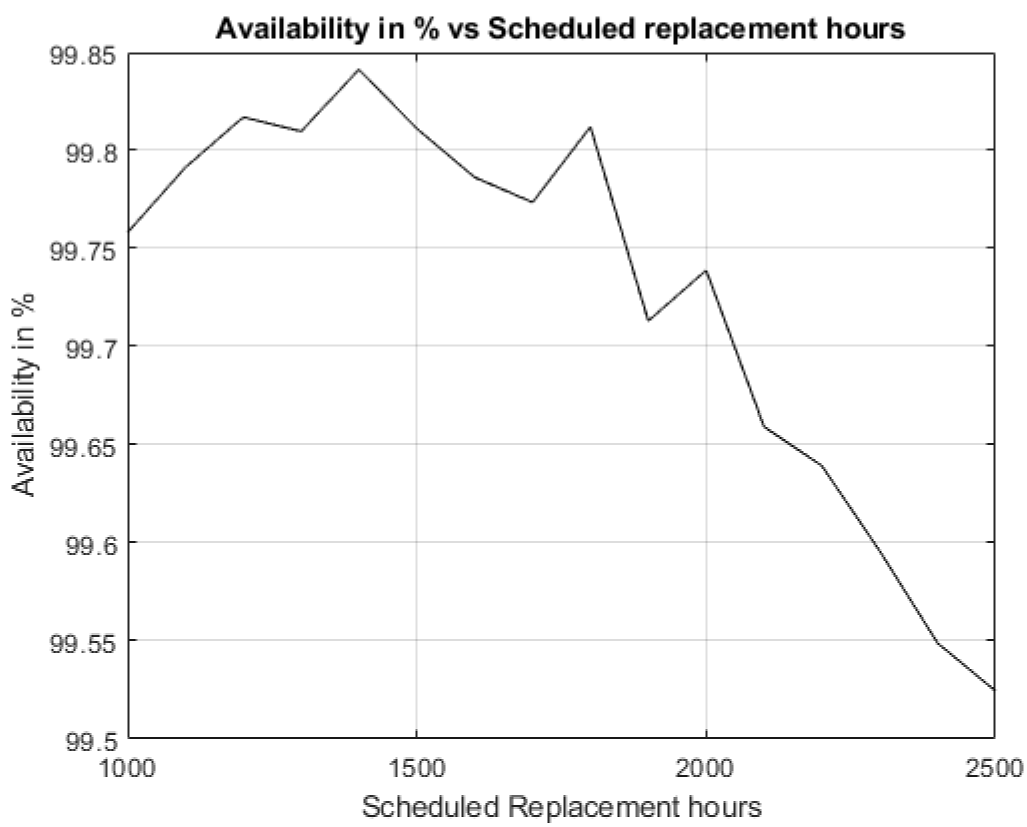
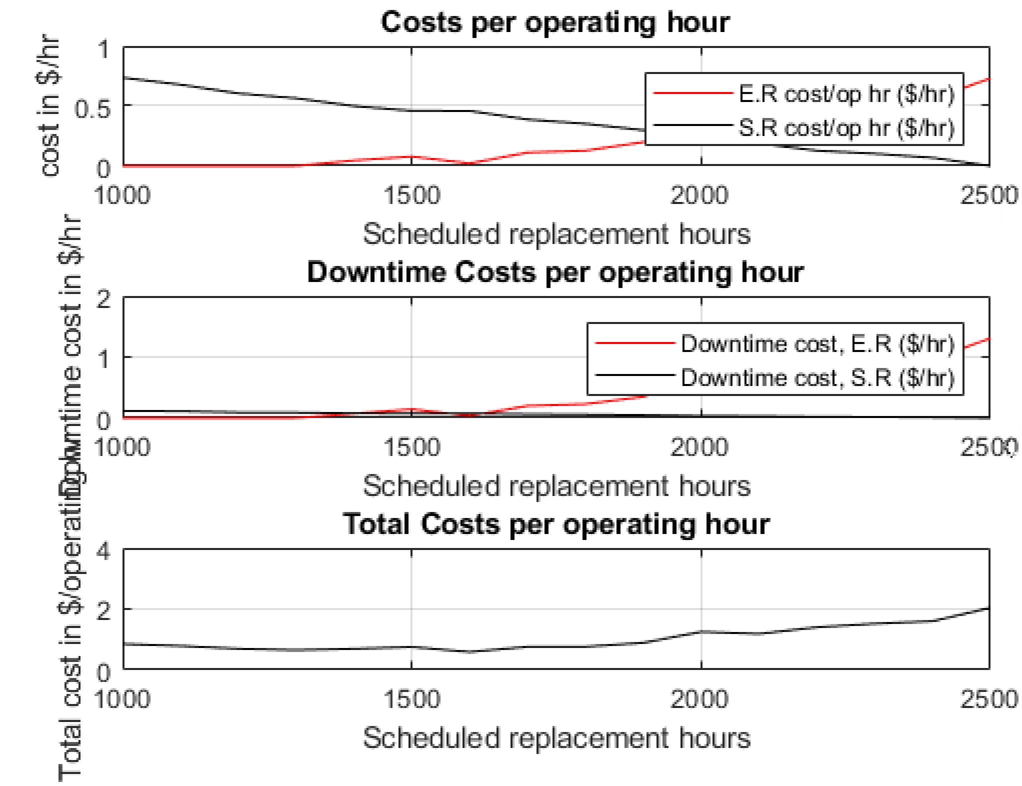
Downtime cost, S.R ($/hr)
Scheduled replacement hours
Total Costs per operating hour
Total cost in $/operating hr
Scheduled replacement hours


Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours


Costs per operating hour
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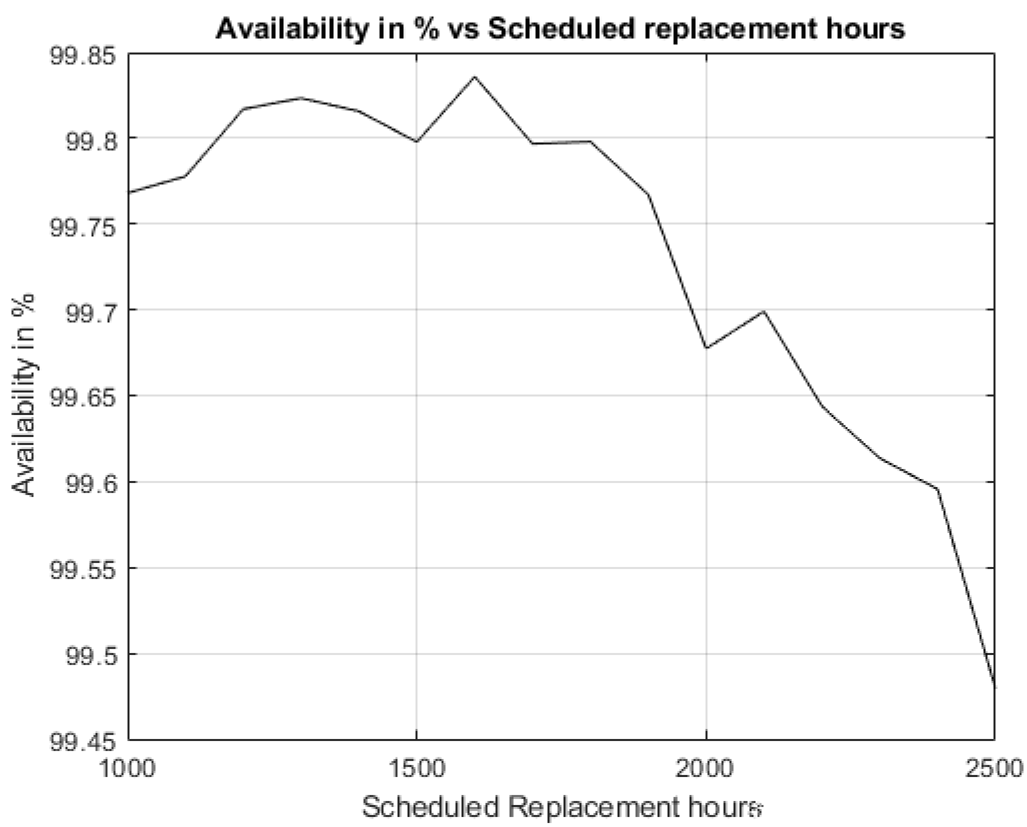
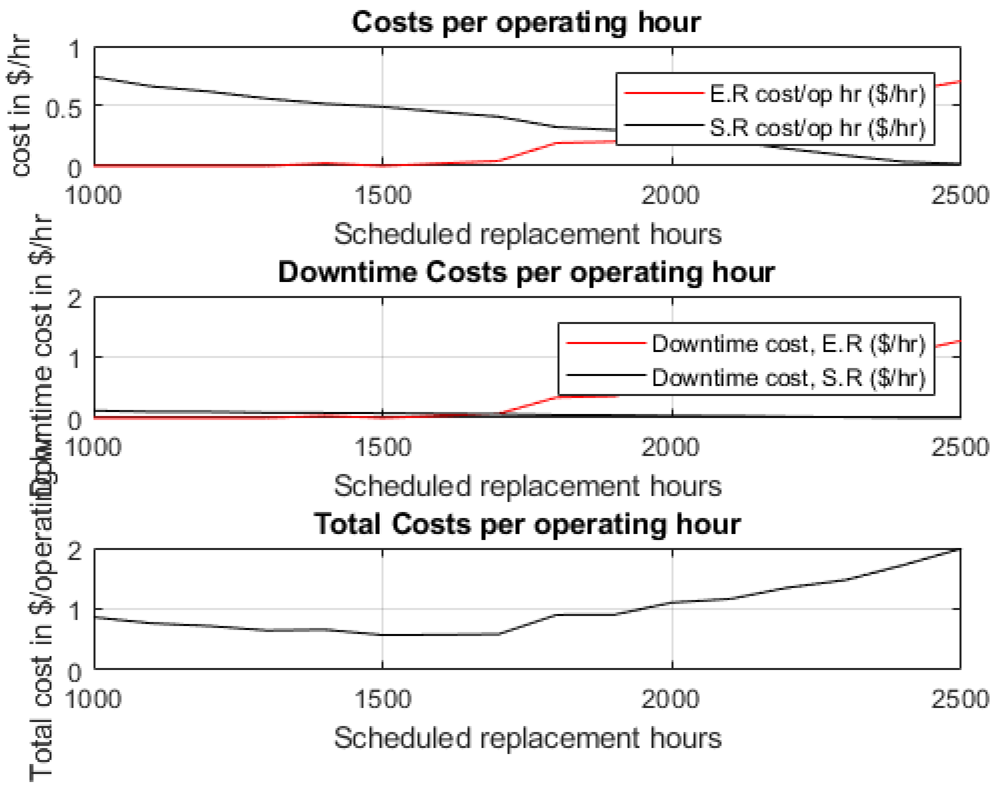
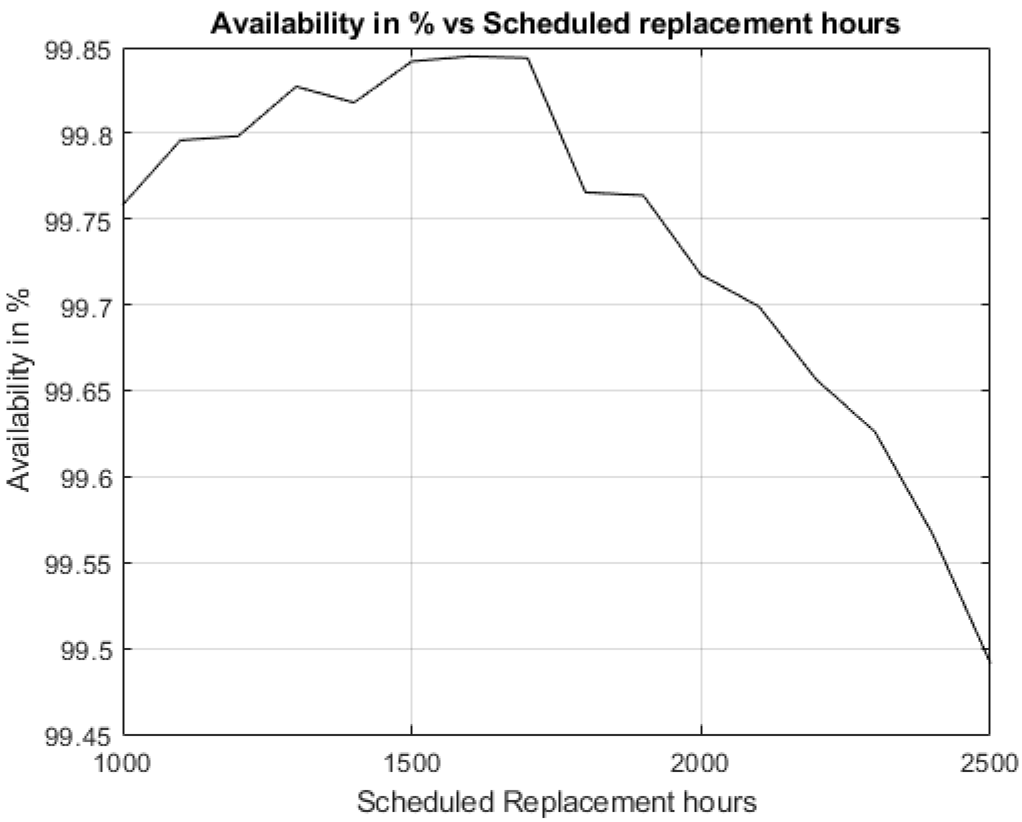
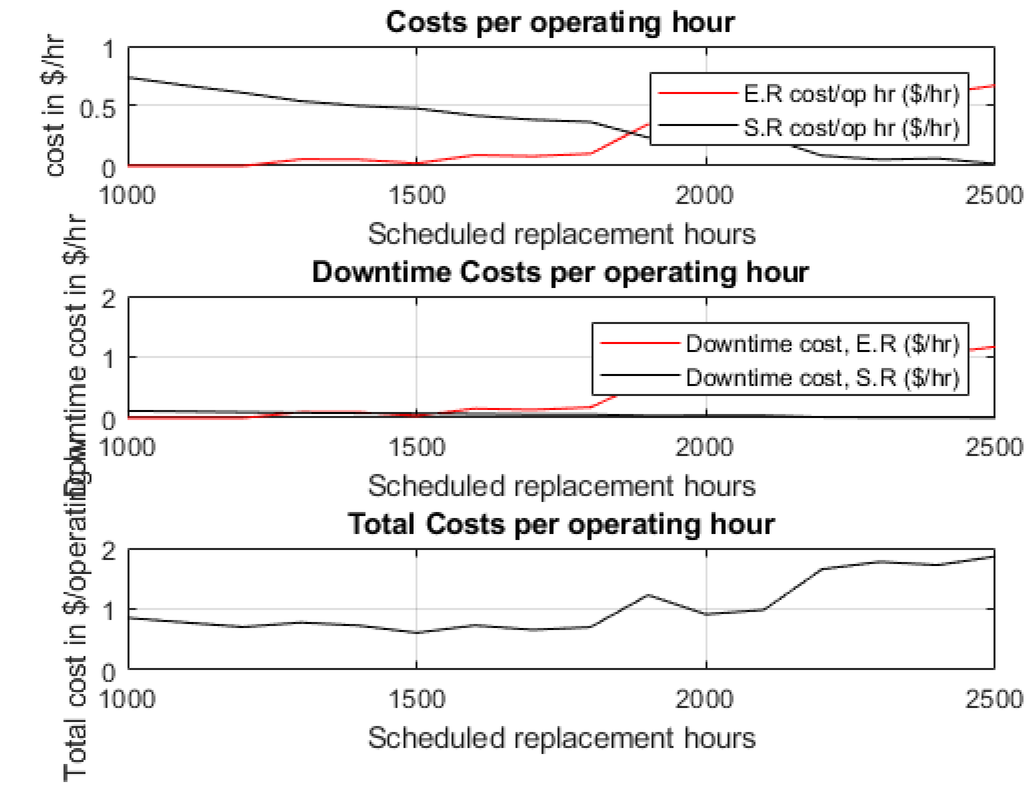
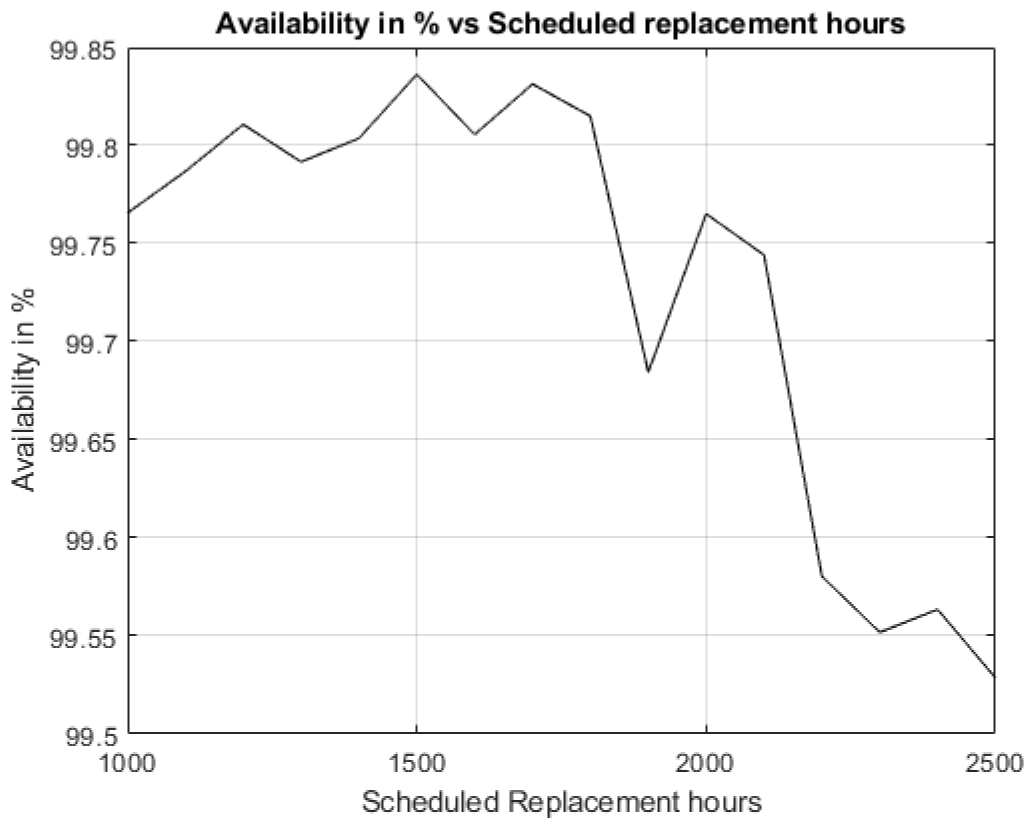
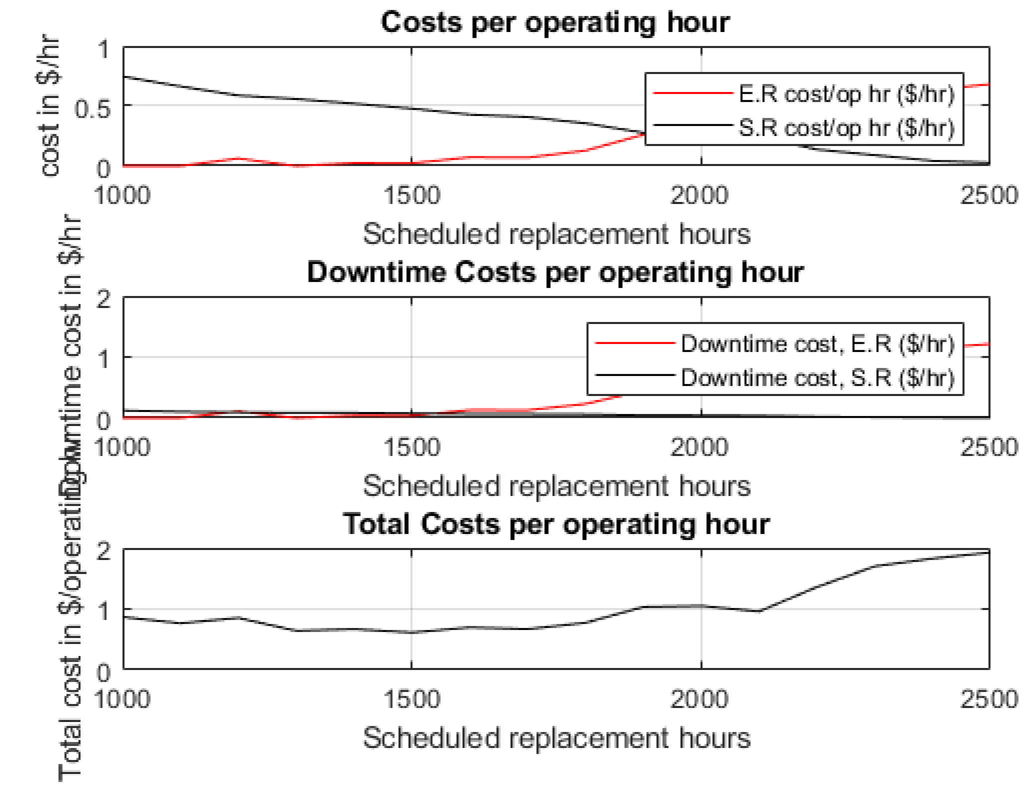

Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours


Costs per operating hour
cost in $/hr
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
Scheduled replacement hours
Downtime Costs per operating hour
Downtime cost, E.R ($/hr)
Downtime cost, S.R ($/hr)
Scheduled replacement hours
Total Costs per operating hour
Scheduled replacement hours


Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours


Costs per operating hour
cost in $/hr
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
Scheduled replacement hours
Downtime Costs per operating hour
Downtime cost in $/hr
Downtime cost, E.R ($/hr)
Downtime cost, S.R ($/hr)
Scheduled replacement hours
Total Costs per operating hour
Total cost in $/operating hr
Scheduled replacement hours


Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours


Costs per operating hour
cost in $/hr
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
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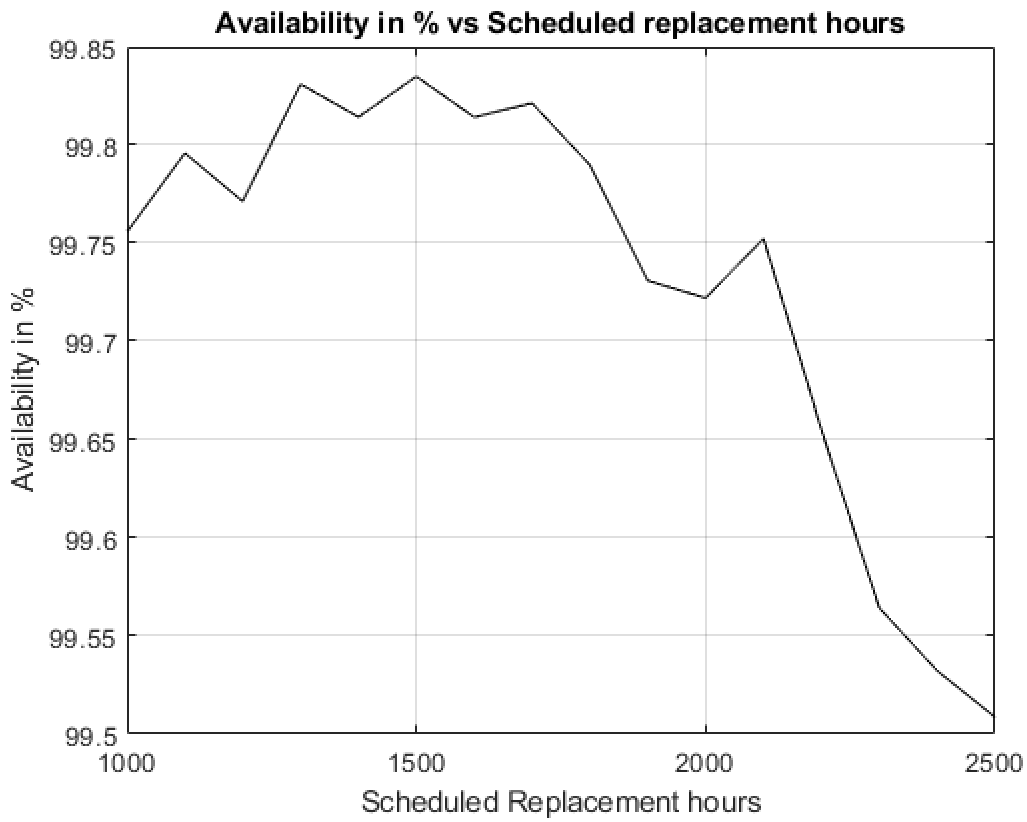
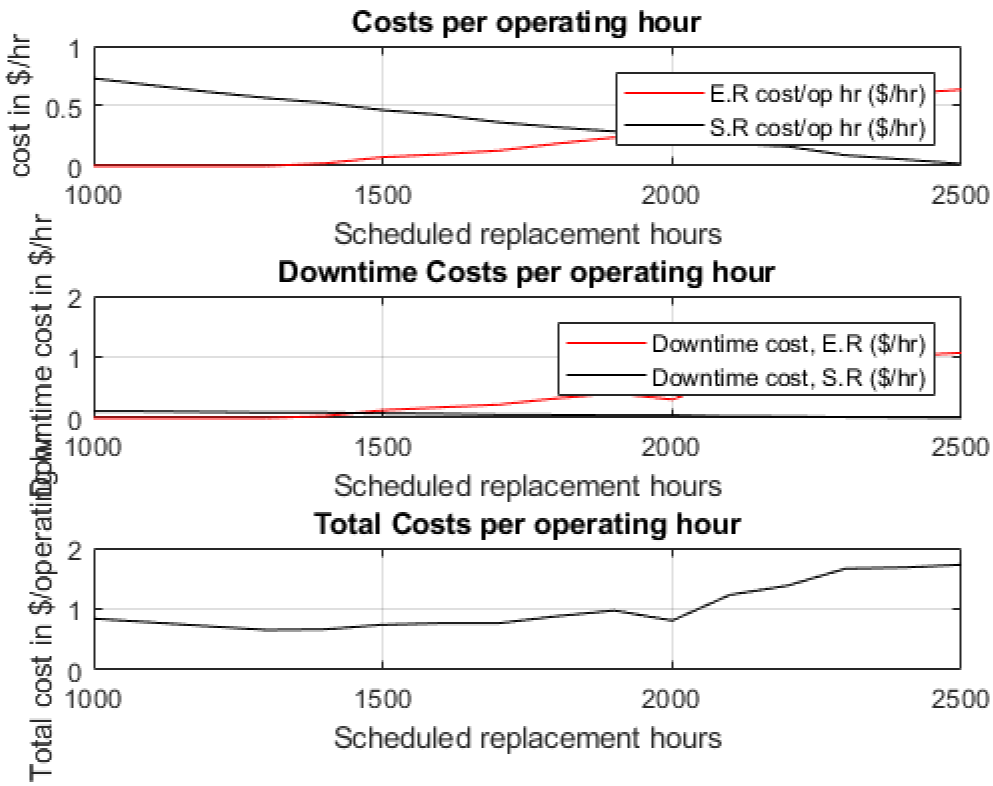
Scheduled replacement hours


Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours


Costs per operating hour
cost in $/hr
1
0.5
0
1000
1500
2000
2500
Scheduled replacement hours
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
Downtime Costs per operating hour
Downtime cost in $/hr
2
1
0
1000
1500
2000
2500
Scheduled replacement hours
Downtime cost, E.R ($/hr)
Downtime cost, S.R ($/hr)
Total Costs per operating hour
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2
1
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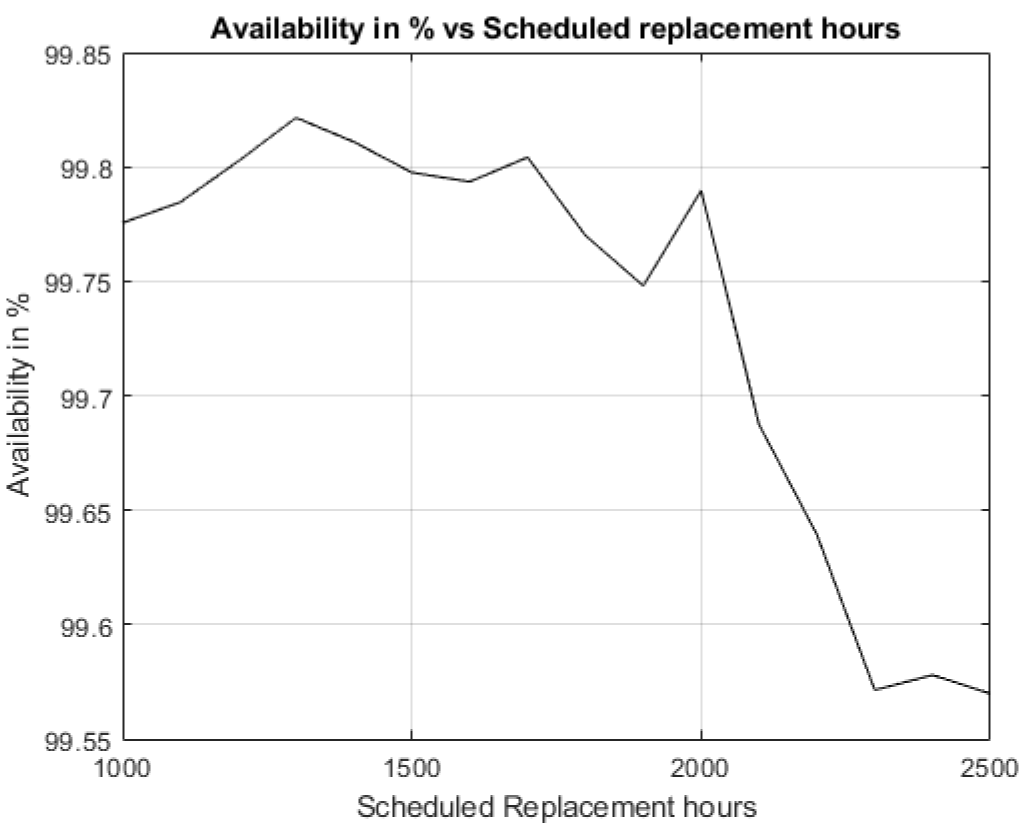
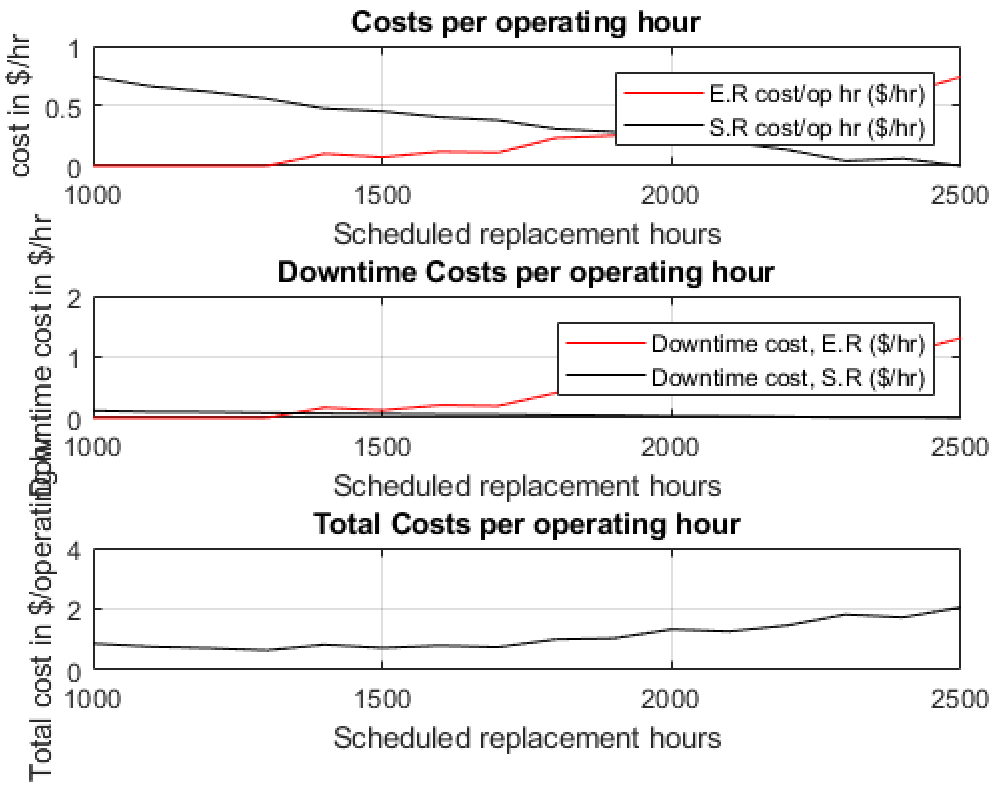
1500
2000
2500
Scheduled replacement hours


Availability in % vs Scheduled replacement hours
Availability in %
99.85
99.8
99.75
99.7
99.65
99.6
99.55
1000
1500
2000
2500
Scheduled Replacement hours


Costs per operating hour
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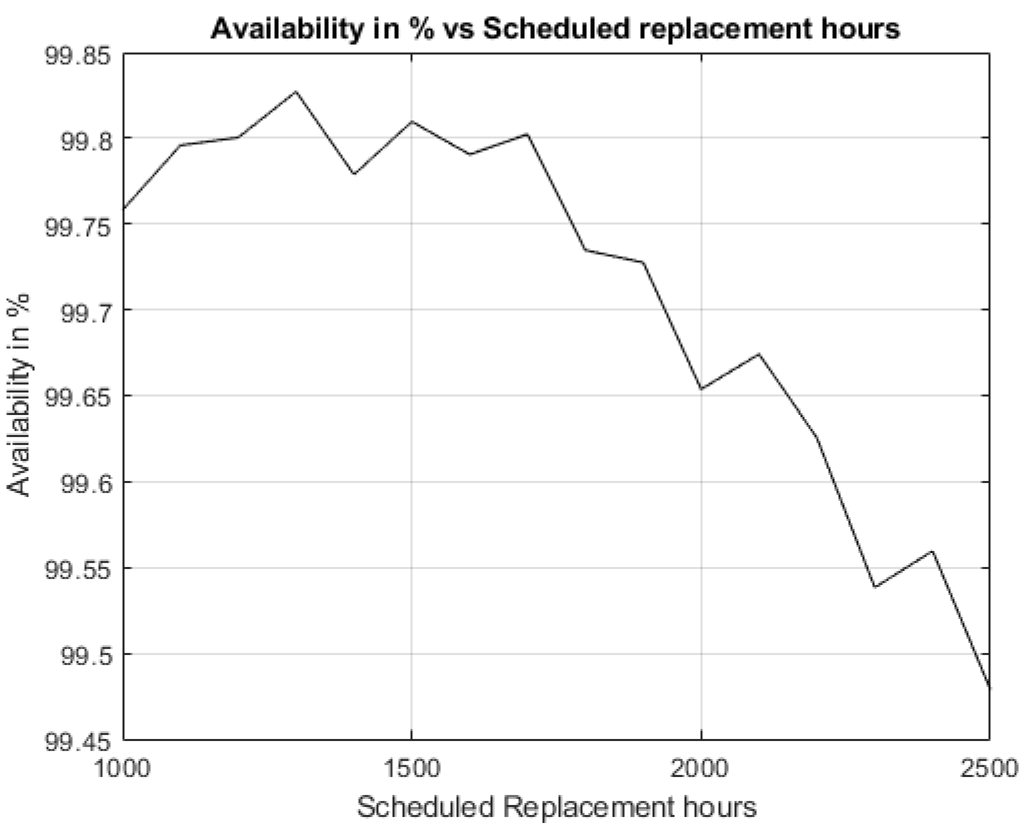
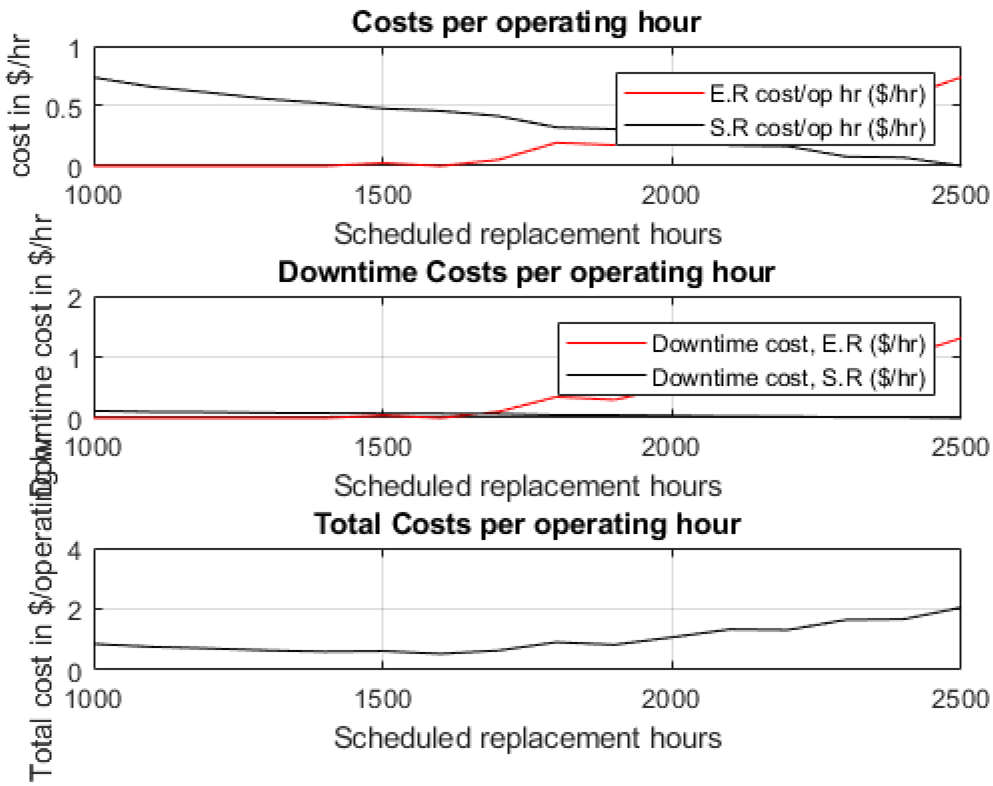

Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours


Costs per operating hour
cost in $/hr
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
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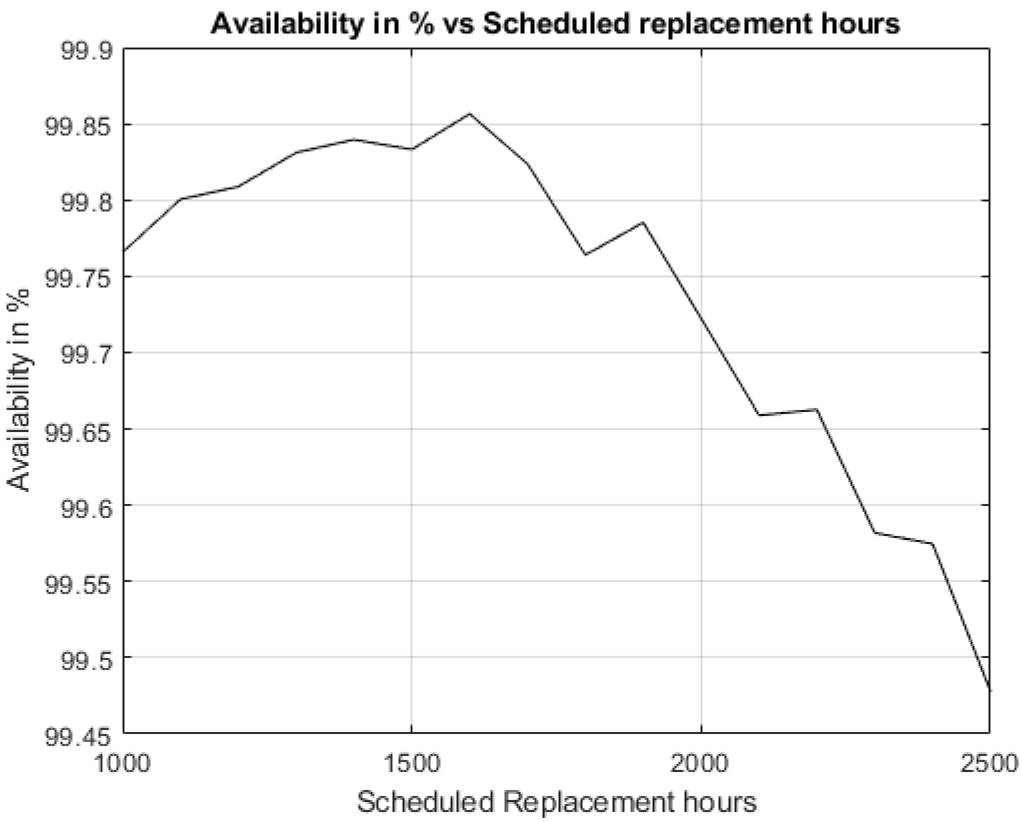
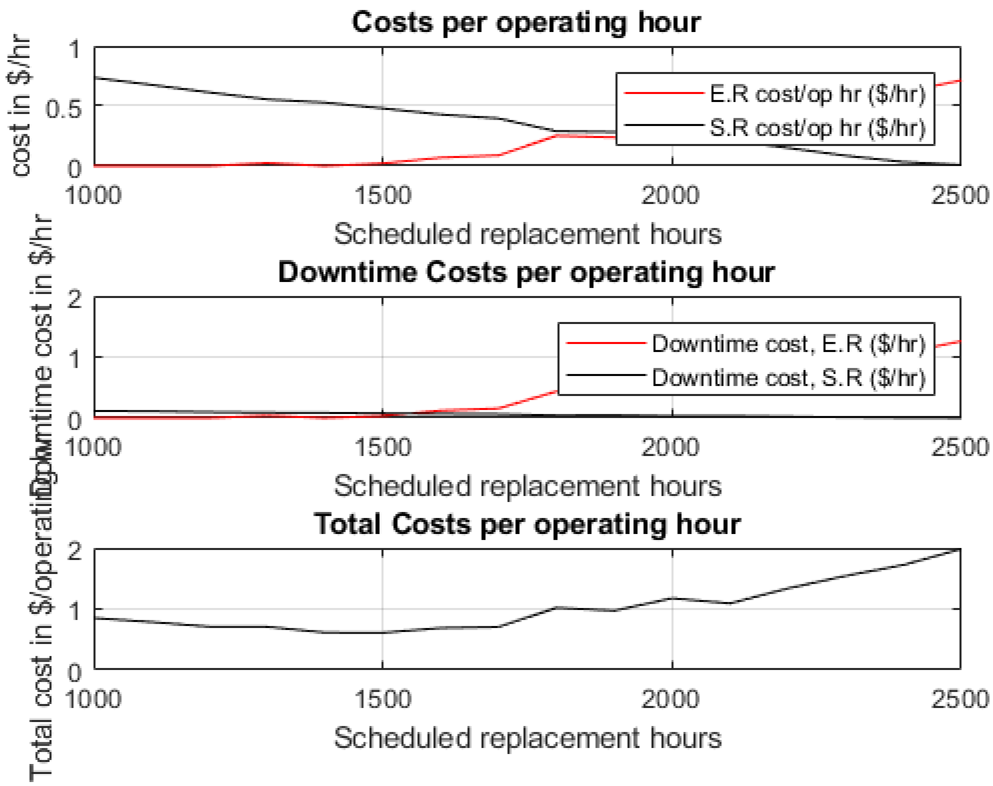

Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours


Costs per operating hour
cost in $/hr
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S.R cost/op hr ($/hr)
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Scheduled replacement hours
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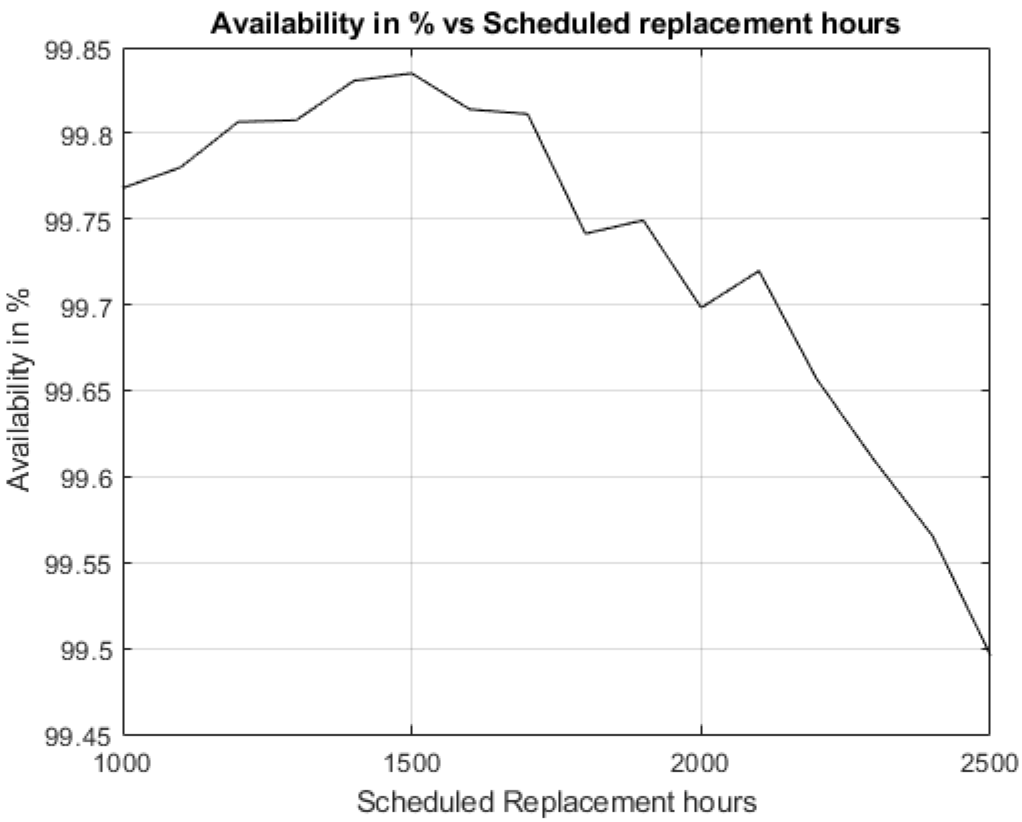
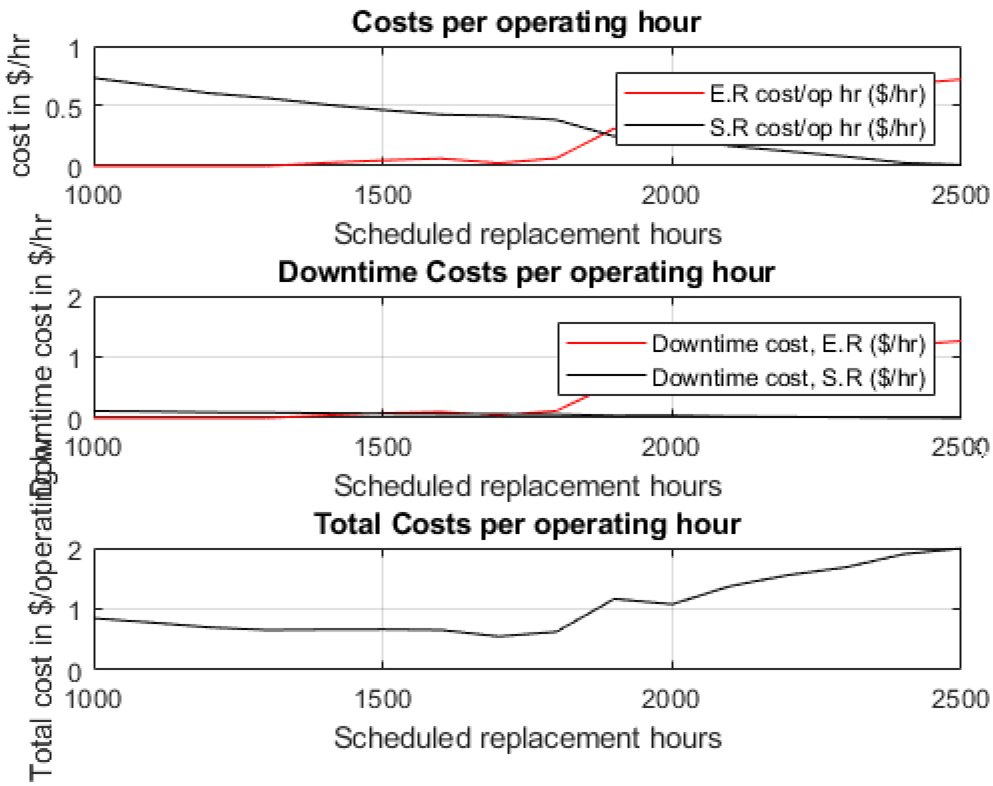
Total cost in $/operating hr
Scheduled replacement hours
1000
1500
2000
2500


Availability in % vs Scheduled replacement hours
Availability in %
99.85
99.8
99.75
99.7
99.65
99.6
99.55
99.5
99.45
1000
1500
2000
2500
Scheduled Replacement hours


Costs per operating hour
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E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
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Scheduled replacement hours
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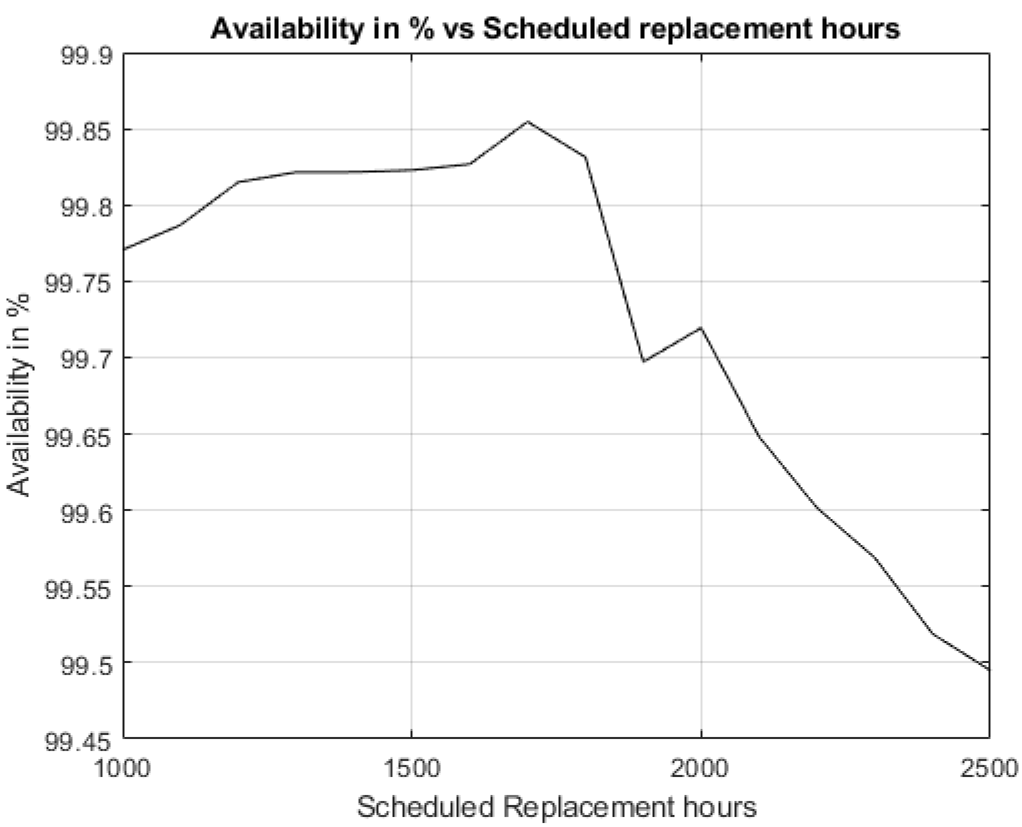
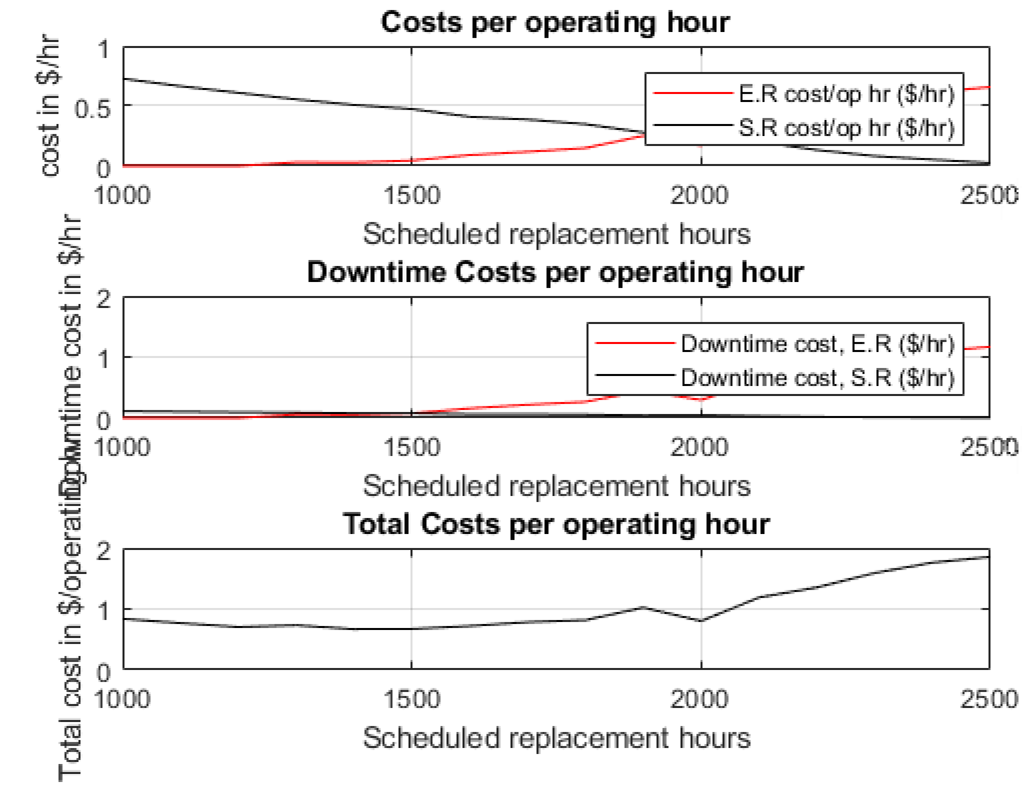

Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours


Costs per operating hour
cost in $/hr
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
Scheduled replacement hours
Downtime Costs per operating hour
Downtime cost in $/hr
Downtime cost, E.R ($/hr)
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Scheduled replacement hours
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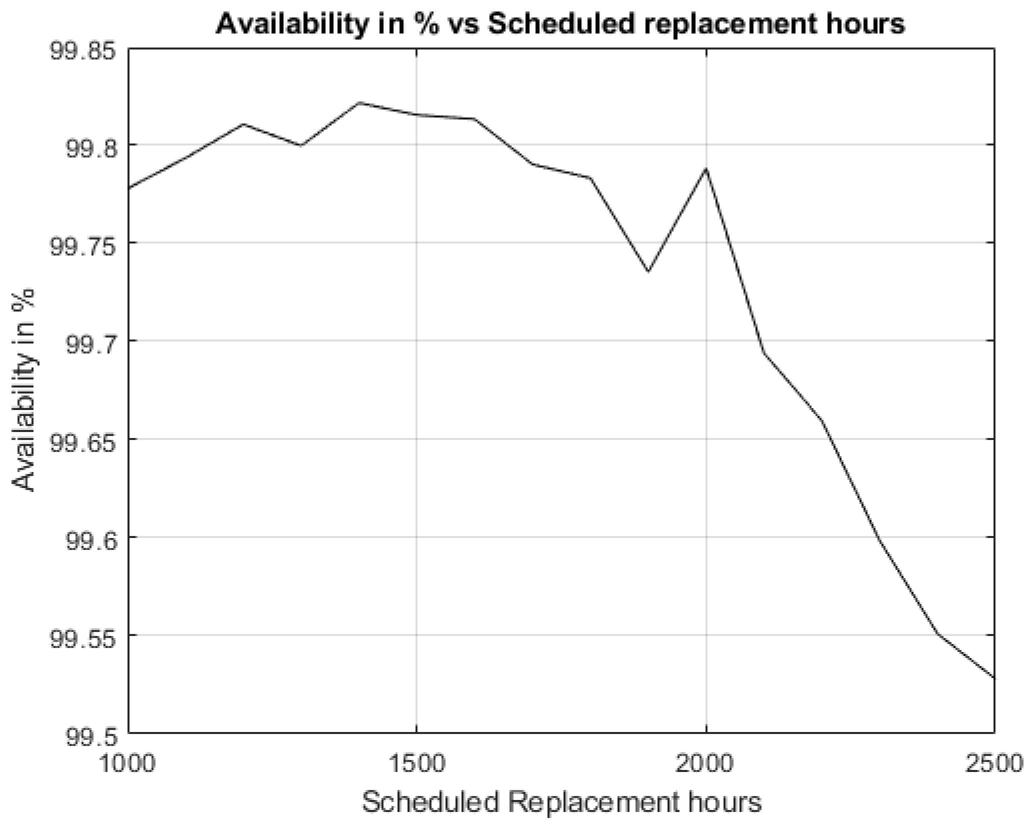
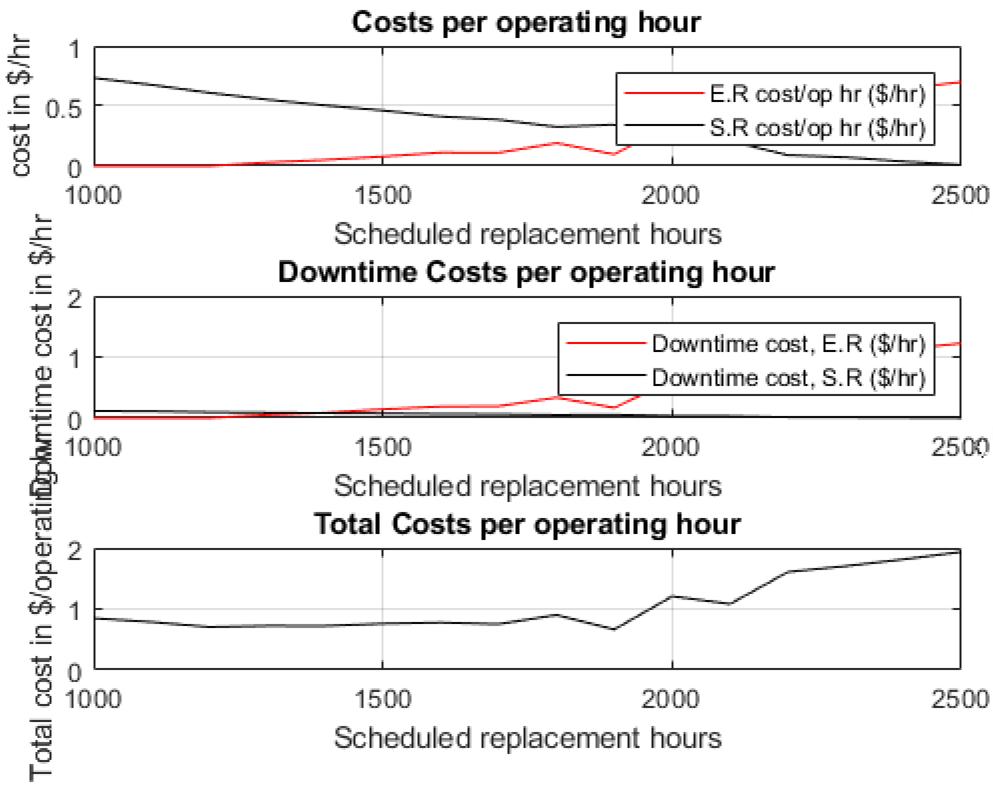
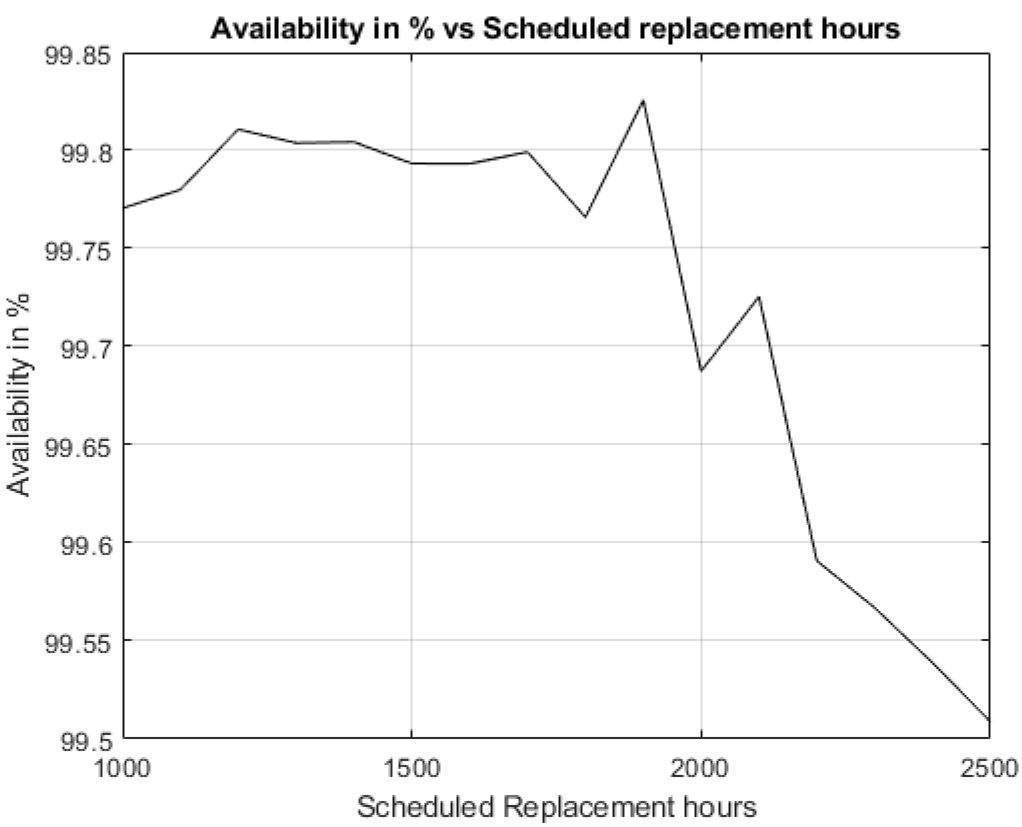
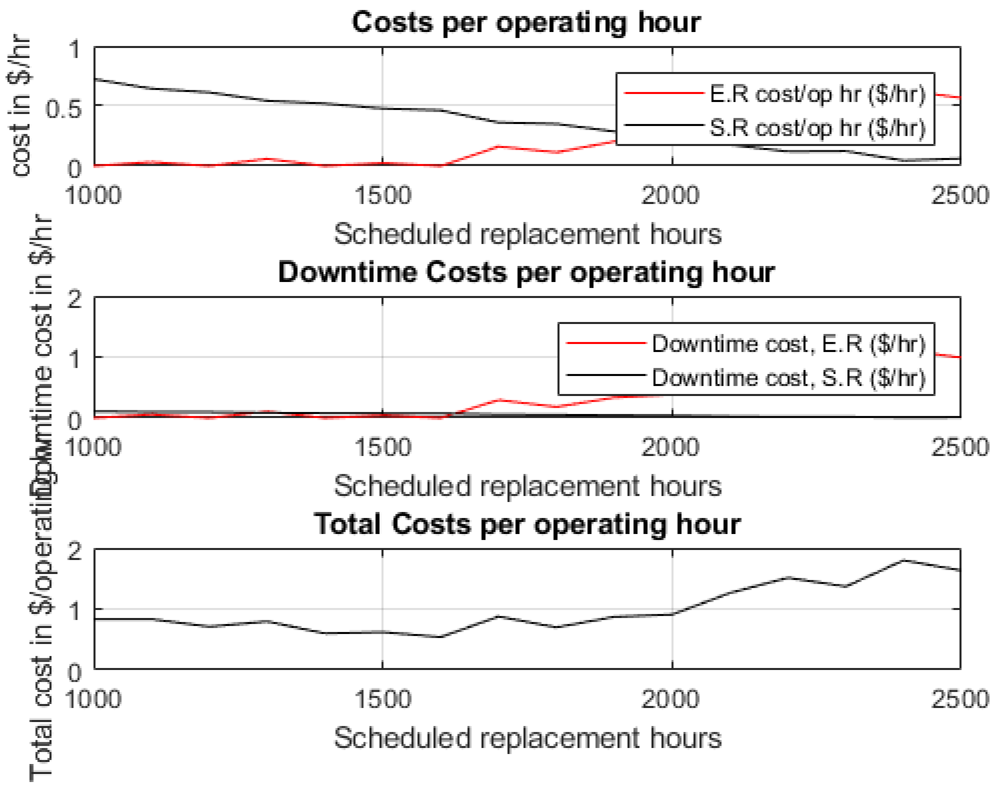

Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours


Costs per operating hour
cost in $/hr
E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
Scheduled replacement hours
Downtime Costs per operating hour
Downtime cost in $/hr
Downtime cost, E.R ($/hr)
Downtime cost, S.R ($/hr)
Scheduled replacement hours
Total Costs per operating hour
Total cost in $/operating hr
Scheduled replacement hours


Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours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E.R cost/op hr ($/hr)
S.R cost/op hr ($/hr)
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Downtime cost in $/hr
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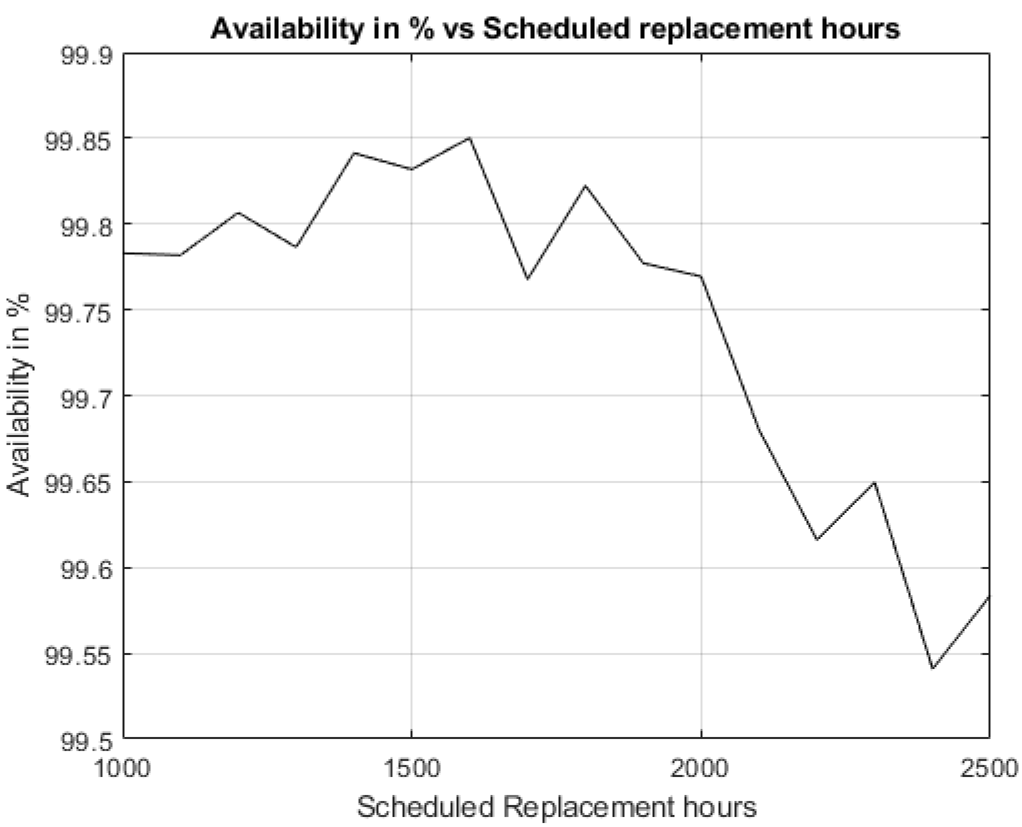
Total Costs per operating hour
Scheduled replacement hours


Availability in % vs Scheduled replacement hours
Availability in %
Scheduled Replacement hours

Sub-System 3: DPF System Output Data

Time	Description
1000	Operation
2	Scheduled Replacement
1000	Operation
3	Scheduled Replacement
1000	Operation
3	Scheduled Replacement
1000	Operation
3	Scheduled Replacement
1000	Operation
2	Scheduled Replacement
1000	Operation
3	Scheduled Replacement
1000	Operation
3	Scheduled Replacement
1000	Operation
2	Scheduled Replacement
1000	Operation
2	Scheduled Replacement
1000	Operation
2	Scheduled Replacement
1000	Operation
2	Scheduled Replacement
1000	Operation
3	Scheduled Replacement
1000	Operation
2	Scheduled Replacement
1000	Operation
3	Scheduled Replacement
1000	Operation
2	Scheduled Replacement
1000	Operation
2	Scheduled Replacement
1000	Operation
2	Scheduled Replacement
1000	Operation
3	Scheduled Replacement
1000	Operation
3	Scheduled Replacement
1000	Operation
3	Scheduled Replacement
1000	Operation
2	Scheduled Replacement
1000	Operation
2	Scheduled Replacement

Parameters	Counts
TOT (hr)	40000
TST (hr)	94
TET (hr)	0
TT (hr)	40094
Availability (%)	99.766
NS	40
NE	0

Jobs	Costs
Scheduled replacement cost per operating hr	0.738
Emergency replacement cost per operating hr	0
Downtime Cost (For Schedule replacement) per operating hr	0.1175
Downtime Cost (emergency replacment) per operating hr	0
Sum	0.8555

Others
Alpha level in model
Schedule hr
Min Wait time in hr (emergency)
Max wait time in hr (emergency)
Min wait time in hr (Schedule)
Max wait time in hr (Schedule)
Downtime cost (scheduled replacement) $/hr
Downtime cost (emergency replacement) $/hr
Scrap value

1000 Operation
2 Scheduled Replacement
1000 Operation
3 Scheduled Replacement
1000 Operation
2 Scheduled Replacement
1000 Operation
3 Scheduled Replacement
1000 Operation
2 Scheduled Replacement
1000 Operation
2 Scheduled Replacement
1000 Operation
2 Scheduled Replacement
1000 Operation
2 Scheduled Replacement
1000 Operation
2 Scheduled Replacement
1000 Operation
2 Scheduled Replacement
1000 Operation
2 Scheduled Replacement
1000 Operation
3 Scheduled Replacement
1000 Operation
2 Scheduled Replacement
1000 Operation
2 Scheduled Replacement
1000 Operation
2 Scheduled Replacement
1000 Operation
2 Scheduled Replacement
1000 Operation
3 Scheduled Replacement
1000 Operation
2 Scheduled Replacement

Appendix D

MATLAB

Modeling & Simulation of non-repairable units

alpha = significant level for modelings

M = vector of scheduled replacement times (hr)

H = vector of time (hr) readings at observations

C = censoring vector of the same size as H: 0 for failure, 1 for operating

H is modelled to Weibull with scale parameter a, shape parameter b.

H1 = emergency replacement times (hr)

H1 is modelled to log normal with mean m1, standard deviation s1

wU1 = maximum wait time (hr) before emergency replacement start

wL1 = minimum wait time (hr) before emergency replacement start

Wait time is uniformly generated random number between wL1 and wU1.

H2 = scheduled replacement times (hr)

H2 is modelled to log normal with mean m2, standard deviation s2.

wU2 = maximum wait time (hr) before scheduled replacement start

wU1 = minimum wait time (hr) before replacement start

Weight time is uniformly generated random number between wL2 and wU2.

n = number of life cycles to simulate.

headS = overhead cost for scheduled replacement ($)

laborS = labour cost ($/hr) for scheduled replacement

headE = overhead cost for emergency replacement ($)

laborE =labour cost ($/hr) for emergency replacement

matCost =material cost ($)

scrap_value = scrap value ($)

Downtime costs

DownCostS = for schedule replacement $/hr

DownCostE = for emergency replacement $/hr

data.xlsx

	A	B	C	D	E	F	G	H	
1	H	C	H1	H2	overhead S	labour S	overhead E	labour E	ma
2	1206	0	1	3.3	100	80	200	80	
3	1380	0	11.5						
4	950	0	7.5						
5	1410	0	10.5						
6	1430	0	11.8						
7	1260	0	12.5						
8	1050	0	10.5						
9	1470	0	10						
10	990	1		3					
11	1050	0	13.5						
12	1450	0	14.5						
13	1400	0	10						
14	1560	0	10						
15	1080	1		2.7					
16	1134	0	11.5						
17	1290	0	11.5						
18	1060	0	5.8						
19	1230	0	6.7						
20	1190	0	5.7						
21	1326	1		3.5					
22	1040	1		2.7					
23	1376	0	7.5						
24	1090	0	5.6						
25	1166	0	5.7						
26	1508	0	6.5						

```
clear

clc

% Read data from excel file.

Data = readtable('COOLING_HOSE.xlsx');

Data = table2array(Data);

H = Data(:,1); C = Data(:,2); H1 = Data(:,3); H2 = Data(:,4);

headS = Data(1,5); laborS = Data(1,6); headE = Data(1,7); laborE = Data(1,8);
```

```
matCost = Data(1,9);

% Clean the empty cells

[a, ~] = find(isnan(H));

H(a,:) = [];

[a, ~] = find(isnan(C));

C(a,:) = [];

[a, ~] = find(isnan(H1));

H1(a,:) = [];

[a, ~] = find(isnan(H2));

H2(a,:) = [];

% User enters alpha, n, scrap_value. (Dialog box)

% ----------------------------------

prompt = {'Enter significant level alpha', 'Number of life cycles to simulate',
'Scrap value in $'};

dlgtitle = 'Input box 1';

dims = [1 40];

definput = {'0.05','40', '0'};

answer = inputdlg(prompt, dlgtitle,dims, definput);

alpha = str2double(answer{1});

n = str2double(answer{2});

n = int16(n);                          % Convert to integer.

scrap_value = str2double(answer{3});

% User enters wL1, wU1, wL2, wU2,

% ---------------------------------

prompt = {'Min wait hr for emerg replacement', 'Max wait hr for emerg
replacement', ...

    'Min wait hr for sche replacement', 'Max wait hr for sche replacement'};

dlgtitle = 'Input box 2';

dims = [1 40];
```

```
definput = {'10','20', '10', '12'};

answer = inputdlg(prompt, dlgtitle,dims, definput);

wL1 = str2double(answer{1});

wU1 = str2double(answer{2});

wL2 = str2double(answer{3});

wU2 = str2double(answer{4});

% User enters downtime costs

% --------------------------------

prompt = {'Downtime cost $/hr for schedule replacement', 'Downtime cost $/hr for
emergency replacement'};

dlgtitle = 'Input box 3';

dims = [1 40];

definput = {'50', '250'};

answer = inputdlg(prompt, dlgtitle,dims, definput);

DownCostS = str2double(answer{1});

DownCostE = str2double(answer{2});

% User enters Schedule hrs for planned replacements.

% -------------------------------------------------

prompt = {'Min schedule hr', 'Increment', 'Max schedule hr'};

dlgtitle = 'Input box 4';

dims = [1 40];

definput = {'500','100', '15000'};

answer = inputdlg(prompt, dlgtitle,dims, definput);

start = str2double(answer{1}); step = str2double(answer{2}); last =
str2double(answer{3});

M = start:step:last;

M = M';

warning('off','MATLAB:dispatcher:nameConflict');

warning('off','MATLAB:xlswrite:AddSheet');
```

```
% Call the function simulate
% --------------------------
[Avail,srCost,erCost,TC] = simulate(alpha,M,H,C,H1, ...
wL1,wU1,H2,wL2,wU2,n,headS,laborS,headE,laborE,matCost,DownCostS,DownCostE,scrap_value,start,step,last);
function[Avail,srCost,erCost,TC] = simulate(alpha,M,H,C,H1, ...

wL1,wU1,H2,wL2,wU2,n,headS,laborS,headE,laborE,matCost,DownCostS,DownCostE,scrap_value,start,step,last)


    % Model the Time to failure (TTF = H) data using Weibull.
    [para, ci] = wblfit(H, alpha, C);


    % Extract shape paramenter a, shape parameter b.
    a = para(1); b = para(2);


    fprintf('WEIBULL MODEL FOR TTF \n')
    fprintf('--------------------------------- \n')
    fprintf('Scale parameter a = %6.3f   \n', a)
    fprintf('Confidence interval for a \n')
    ci(:,1)
    fprintf('\n')


    fprintf('Shape parameter b = %6.3f   \n', b)
    fprintf('Confidence interval for b \n')
    ci(:,2)


    % Model the emergency replacement times H1 to log normal.
    [para1, ci1] = lognfit(H1, alpha);
    m1 = para1(1); % Mean of the emergency repair time
```

```
s1 = para1(2); % Standard deviation



fprintf('LOGNORMAL MODEL FOR EMERGENCY REPLACEMENT TIME \n')
fprintf('------------------------------------------------- \n')
fprintf('Mean for log(H1) = %6.3f   \n', m1)
fprintf('Confidence interval for mean \n')
ci1(:,1)
fprintf('\n')

fprintf('Standard deviation for log(H1) = %6.3f   \n', s1)
fprintf('Confidence interval for standard deviation \n')
ci1(:,2)
fprintf('\n')

% Model the scheduled replacement time H2 to log normal.
[para2, ci2] = lognfit(H2,alpha);
m2 = para2(1);
s2 = para2(2);
fprintf('LOGNORMAL MODEL FOR SCHEDULED REPLACEMENT TIME \n')
fprintf('------------------------------------------------ \n')
fprintf('Mean for log(H2) = %6.3f   \n', m2)
fprintf('Confidence interval for mean \n')
ci2(:,1)
fprintf('\n')

fprintf('Standard deviation for log(H2) = %6.3f   \n', s2)
fprintf('Confidence interval for standard deviation \n')
```

```
ci2(:,2)
fprintf('\n')

% ------------------------------
% Monte Carlo Simulation
% ------------------------------

% Pre-allocate
T = zeros(2*n,1);         % Time column
D = zeros(2*n,1);         % Description column
D = string(D);

srCost = zeros(length(M),1);
erCost = zeros(length(M),1);

srDownCost = zeros(length(M),1);
erDownCost = zeros(length(M),1);

Avail = zeros(length(M),1);
TC = zeros(length(M),1);

for k = 1:1:length(M)
    TOT = 0;             % Total operating time
    TST = 0;             % Total scheduled replacement time
    TET = 0;             % Total emergency replacement time.
    TT = 0;              % Total time

    NS = 0;              % Total number of inspections
```

```
    NE = 0;               % Total number of replacements.

    m = M(k);             % Scheduled replacement time.
    j = 0;                % Set counter for row number.

    for i = 1:1:n
        j = j+1;
        r = rand;
        t = wblinv(r,a,b);
        if t < m                    % Failed before scheduled replacement.
            T(j) = ceil(t);         % Operation before failure.
            D(j) = "Operation";
            TOT = TOT + T(j);

            j = j + 1;
            D(j) = "Emergency Replacement";
            r = rand;
            t = logninv(r,m1,s1);
            T(j) = ceil(t + wL1 + (wU1 - wL1)*rand);
            TET = TET + T(j);
            NE = NE + 1;

        else
            T(j)  =ceil(m);
            D(j) = "Operation";
            TOT = TOT + T(j);

            j = j + 1;
```

```
                D(j) = "Scheduled Replacement";

                r = rand;

                t = logninv(r,m2,s2);

                T(j) = ceil(t + wL2 + (wU2 - wL2)*rand);

                TST  =TST + T(j);

                NS = NS + 1;


            end

        end


        % First Table.

        % -------------

        Time = T; Description = D;

        Table = table(Time,Description);


        filename = sprintf('COOLING_HOSE(%d,%d)(%d,%d)(%d,%d)(m=%d,%d,%d).xlsx',
wL1, wU1, wL2,wU2,...

            DownCostS, DownCostE, start, step, last);

        writetable(Table, filename, 'Sheet',k,'Range','A1');




        % Second table.

        % ---------------

        TT = TOT + TST + TET;       % Total time in hr.

        Avail(k) = (TOT/TT)*100;


        Parameters = ["TOT (hr)", "TST (hr)", "TET (hr)", "TT (hr)",
"Availability (%)", "NS", "NE"]';

        Parameters = string(Parameters);
```

```
        Counts = [TOT, TST, TET, TT, Avail(k), NS, NE]';

        Table2 = table(Parameters, Counts);

        writetable(Table2, filename, 'Sheet', k, 'Range','D1');


        % Third table.

        % --------------


        % Total cost of scheduled replacements per operating hour.

        srCost(k) = ( TST*laborS + NS*(headS + matCost - scrap_value) )/TOT;


        % Total cost of emergency replacements per operating hour.

        erCost(k) = ( TET*laborE + NE*(headE + matCost) )/TOT;


        % Total Downtime cost for scheduled/emergency replacement per operating
hour

        srDownCost(k) = DownCostS*TST/TOT;

        erDownCost(k) = DownCostE*TET/TOT;


        % Total cost

        TC(k) = srCost(k) + erCost(k) + srDownCost(k) + erDownCost(k);




        Jobs = ["Scheduled replacement cost per operating hr", "Emergency
replacement cost per operating hr",...

            "Downtime Cost (For Schedule replacement) per operating hr"...

            "Downtime Cost (emergency replacment) per operating hr","Sum"]';

        Jobs = string(Jobs);

        Costs = [srCost(k), erCost(k), srDownCost(k), erDownCost(k), TC(k)]';
```

```
        Table3 = table(Jobs, Costs);

        writetable(Table3, filename, 'Sheet', k, 'Range', 'D11');


        %{

        % Fourth table.

        % --------------


        % Total cost of scheduled replacements per total hour.

        srCost(k) = ( TST*laborS + NS*(headS + matCost - scrap_value) )/TT;


        % Total cost of emergency replacements per total hour.

        erCost(k) = ( TET*laborE + NE*(headE + matCost) )/TT;


        TC(k) = srCost(k) + erCost(k);


        Jobs = ["Scheduled replacement cost per total hr", "Emergency replacement
cost per total hr", "Sum"]';

        Jobs = string(Jobs);

        Costs = [srCost(k), erCost(k), TC(k)]';

        Table3 = table(Jobs, Costs);

        writetable(Table3, filename, 'Sheet', k, 'Range', 'D19');

        %}




        % Fifth Table.

        Others = ["Alpha level in model","Schedule hr","Min Wait time in hr
(emergency)", "Max wait time in hr (emergency)",...

            "Min wait time in hr (Schedule)", "Max wait time in hr
(Schedule)",...
```

```
            "Downtime cost (scheduled replacement) $/hr","Downtime cost
(emergency replacement) $/hr", "Scrap value"]';

        Others = string(Others);

        Value = [alpha, m, wL1, wU1, wL2, wU2, DownCostS, DownCostE,
scrap_value]';

        Table4 = table(Others,Value);

        writetable(Table4, filename, 'Sheet',k,'Range', 'G1');


    end


    %{

    % Plot Costs.

    % ------------


    figure

    plot(M,erCost,'r-', M,srCost,'b-', M,TC,'k-')

    xlabel('Scheduled Replacement hours')

    ylabel('Cost in $')

    title('Costs per operating hrs')

    legend('Emergency replacement cost per operating hr ($)', 'Scheduled
replacement cost per operatiing hr ($)', 'Sum')

    grid()

    %}



   % Plot Costs.

    % ------------


    figure
```

```
subplot(3,1,1)

plot(M,erCost,'r-', M,srCost, 'k-')

xlabel('Scheduled replacement hours')

ylabel('cost in $/hr')

title('Costs per operating hour')

legend('E.R cost/op hr ($/hr)', 'S.R cost/op hr ($/hr)')

grid()


subplot(3,1,2)

plot(M,erDownCost,'r-', M,srDownCost,'k-')

xlabel('Scheduled replacement hours')

ylabel('Downtime cost in $/hr')


title('Downtime Costs per operating hour')

legend('Downtime cost, E.R ($/hr)', 'Downtime cost, S.R ($/hr)')

grid()


subplot(3,1,3)

plot(M,TC,'k-')

xlabel('Scheduled replacement hours')

ylabel('Total cost in $/operating hr')

title('Total Costs per operating hour')

grid()




% Plot availabilities.

% ----------------------
```

```
    figure

    plot(M, Avail, 'k-')

    xlabel('Scheduled Replacement hours')

    ylabel('Availability in %')

    title('Availability in % vs Scheduled replacement hours')

    grid()



end
```