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EMMANUEL OLUWADAMILOLA ADELE

OPPORTUNISTIC INSPECTION POLICY FOR GROUNDWATER WELL-HEADS ADDRESSING DEFAULT

Recife
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Dissertation submitted to the Post-Graduate Program of Production Engineering of Federal University of Pernambuco, to obtain the Master´s Degree in Production Engineering.

Concentration Area: Operations Research.

Advisor: Prof. Dr. Cristiano Alexandre Virginio Cavalcante.

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This work is dedicated to God, the giver of life, sound health, Knowledge and Understanding.

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"Persistent questioning and healthy inquisitiveness are the first requisite for acquiring learning of any kind."

MAHATMA GANDHI

ABSTRACT

This dissertation presents an optimized maintenance policy framework for critical groundwater systems, with a specific focus on groundwater well-heads and submersible pumps. The model introduces default probabilities to account for scenarios where maintenance actions cannot be executed due to external impediments, such as logistical constraints or operational failures. These default probabilities are integrated into an opportunistic inspection model, allowing for a more flexible and resilient approach to system maintenance. Through optimization modeling and comprehensive sensitivity analyses, the study investigates how decision variables such as time to scheduled inspection and the start of the window of opportunity interact to influence the overall cost rate and system reliability. Results demonstrate that increasing default probabilities and higher replacement costs are associated with a rise in total cost rates, reflecting the increased financial burden of system failures and missed maintenance opportunities. However, raising the frequency of inspections and allowing for longer defect detection times significantly reduce the cost rate, highlighting the importance of efficient scheduling and the effective use of inspection windows.

Additionally, the findings suggest that decreasing opportunity costs widens the opportunity window for maintenance actions, leading to more flexible and cost-effective maintenance schedules. This work emphasizes the need for proactive strategies that prioritize inspection and timely interventions, particularly in environments where defaults and unforeseen failures are more likely. The research contributes practical insights into optimizing maintenance schedules for single-component systems and has applications for industries relying on such systems subject to default, where reliability and cost management are critical. The optimized maintenance policies proposed in this study provide a robust foundation for improving the long-term sustainability and operational efficiency of essential infrastructure systems.

Keywords: Maintenance Policy; Opportunistic Inspection; Default; Groundwater Systems; Cost-effectiveness.

RESUMO

Esta dissertação apresenta uma estrutura de política de manutenção otimizada para sistemas críticos de águas subterrâneas, com foco específico em cabeças de poços de águas subterrâneas e bombas submersíveis. O modelo introduz probabilidades padrão para contabilizar cenários em que ações de manutenção não podem ser executadas devido a impedimentos externos, como restrições logísticas ou falhas operacionais. Essas probabilidades padrão são integradas a um modelo de inspeção oportunista, permitindo uma abordagem mais flexível e resiliente à manutenção do sistema. Por meio de modelagem de otimização e análises de sensibilidade abrangentes, o estudo investiga como variáveis de decisão, como tempo para inspeção programada e o início da janela de oportunidade, interagem para influenciar a taxa de custo geral e a confiabilidade do sistema. Os resultados demonstram que o aumento das probabilidades de inadimplência e maiores custos de substituição estão associados a um aumento nas taxas de custo total, refletindo o aumento da carga financeira de falhas do sistema e oportunidades de manutenção perdidas. No entanto, aumentar a frequência das inspeções e permitir tempos de detecção de defeitos mais longos reduz significativamente a taxa de custo, destacando a importância do agendamento eficiente e do uso eficaz das janelas de inspeção.

Além disso, as descobertas sugerem que a redução dos custos de oportunidade amplia a janela de oportunidade para ações de manutenção, levando a cronogramas de manutenção mais flexíveis e econômicos. Este trabalho enfatiza a necessidade de estratégias proativas que priorizem a inspeção e intervenções oportunas, particularmente em ambientes onde inadimplências e falhas imprevistas são mais prováveis. A pesquisa contribui com insights práticos para otimizar cronogramas de manutenção para sistemas de componente único e tem aplicações para indústrias que dependem de tais sistemas sujeitos a inadimplência, onde a confiabilidade e o gerenciamento de custos são críticos. As políticas de manutenção otimizadas propostas neste estudo fornecem uma base sólida para melhorar a sustentabilidade de longo prazo e a eficiência operacional de sistemas de infraestrutura essenciais.

Palavras-chave: Política de Manutenção; Inspeção Oportunista; Inadimplência; Sistemas de Águas Subterrâneas; Custo-efetividade.

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LIST OF ABBREVIATIONS

CBM	Condition-based Maintenance
IoT	Internet of Things
LNG	Liquefied Natural Gas
O&M	Operations and Maintenance
PM	Preventive Maintenance
PPPM	Preplanned Preventive Maintenance
SODA	Strategic Options Development and Analysis
SPM	Scheduled Preventive Maintenance
TBM	Time-based Maintenance

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1 INTRODUCTION

Groundwater is the water that occurs beneath the Earth's surface, saturating the pores and fractures of geological formations. It is a crucial component of the hydrologic cycle, contributing significantly to water supply for both human use and natural ecosystems (ISLAM, 2023). Groundwater is a hidden yet invaluable resource, essential for human consumption, agriculture, and maintaining natural ecosystems. It resides in aquifers, with its movement and availability influenced by geological and hydrological factors (SWAIN *et al.,* 2022). Understanding and managing groundwater involves complex measurement and analysis techniques, ensuring sustainable use and protection of this vital resource. It's important to highlight that the significance of groundwater systems continues to grow, as the reliance on surface water sources with high vulnerability to contamination and depletion is increasingly deemed unsustainable. In this context, the shift towards sustainable groundwater management practices is imperative, as groundwater emerges as a vital alternative to conventional water sources, essential for ensuring long-term environmental sustainability (ELSHALL *et al.,* 2020). The option of utilizing groundwater as a water source is considered only when alternative sources are located at a significant distance from the cities or areas that require water supply.

Important components of groundwater include, aquifer, water table, recharge zone, discharge zone, hydraulic gradient, groundwater flow paths, storage capacity, quality and composition, boundary conditions, groundwater management practices, well-heads. (ZHANG; XU; KANYERERE, 2020; AHMED; ALRAJHI; ALQUWAIZANY, 2021; LAPWORTH *et. al.*, 2022). Groundwater well-heads are vital components of a groundwater, providing protection, access, regulation, and monitoring capabilities. The well-head serves as the surface structure where the well casing terminates and where various components necessary for accessing and managing groundwater are housed. Groundwater well-heads are often situated in remote locations, and the essential equipment they house, such as pumps, valves, and switches, necessitates frequent maintenance inspections (MORA *et al.,* 2013). Properly designed and maintained well-heads are essential for ensuring the safety and sustainability of groundwater resources (REINECKE *et al.*, 2019).

The maintenance of crucial systems for water supply, energy generation, and communication networks in many countries is significantly influenced by their remote locations. This isolation results in the transportation of resources such as personnel, equipment, and spare parts being both time-intensive and expensive (CHAOUB *et al.*, 2021; DOS SANTOS PEREIRA *et al.*, 2022). For the particular case of groundwater wells, the situation is even more critical due to the numerous challenges associated with sustainable extraction. Preventing system contamination, while ensuring the quality and availability of groundwater, demands considerable effort and resources.

Studies indicate that a substantial portion of the costs associated with groundwater systems is dedicated to operation and maintenance (O&M) activities (COBBING *et. al.,* 2015). These activities encompass continuous monitoring, water treatment, infrastructure maintenance, and protection measures against pollutants. Effective management of these tasks is crucial to maintaining the long-term viability and safety of groundwater resources (SYAFIUDDIN; BOOPATHY; HADIBARATA, 2020).

A major factor contributing to the increased O&M costs for remote systems is the considerable logistical expenditure involved in their maintenance, which accounts for a large share of the overall maintenance management expenses (NGUYEN *et al.*, 2019; XIA; ZOU, 2023). From the work of Taboada, Diaz-Casas and Yu (2021), factors such as the extreme marine operating environment, distance from maintenance bases, and the necessity of expensive specialized equipment like barges, boats, and vessels further escalate costs compared to onshore installations. Operational challenges in wind farms often arise from unexpected failures and downtime, necessitating efficient maintenance strategies (SHAFIEE, 2014).

The conventional method of scheduled preventive maintenance (SPM) faces significant challenges, particularly in remote regions where logistical constraints are common, and maintenance defaults may occur. Policies that do not account for opportunistic inspections struggle to address these issues effectively, as they lack the flexibility to adapt to unexpected failures or operational impediments (MELO *et al.,* 2023, ADELE *et al.*, 2024). One of the challenges in controlling failure is when a maintainer defaults in planned preventive maintenance actions. System failures as a result of default can have severe consequences, including expensive downtime, lost production, compromised safety, and damage to an organization's brand (AMBARWATI *et al.*, 2024). In this context, a default refers to the inability to perform a planned preventive replacement (ALOTAIBI *et al.,* 2020). Various situations can lead to such default in scheduled maintenance, which include some examples such as; unexpected events (FINKELSTEIN; CHA; LEVITIN, 2020), staffing shortages (SAFAEI; JARDINE, 2018), prioritizing production and revenue over maintenance (BUDAI; DEKKER; NICOLAI, 2008; YANG *et al.*, 2019), pandemic conditions (NICOLA *et al.*, 2020), lack of spare parts (SCALA; RAJGOPAL; NEEDY, 2014), time constraints for maintenance tasks (YANG; REMENYTE-PRESCOTT; ANDREWS, 2017), operator delays (WANG; LI; XIE, 2020), system mission restrictions (KHATAB *et al.*, 2017), information overload (BUDAI; HUISMAN; DEKKER, 2006), poor communication and insufficient information (ANTONOVSKY; POLLOCK; STRAKER, 2016), human errors (REASON; HOBBS, 2017), and adverse environmental conditions (JIAWEN; DEREN; WEI, 2021).

There are some contributions in modeling defaults that can occur due to sudden changes in weather conditions, or the uncertainty about the correct component being brought on the vessel. In the offshore wind energy sector, Zhong *et al.* (2019) addressed this issue by formulating a fuzzy multi-objective non-linear chance-constrained programming model, incorporating novel reliability and cost criteria and constraints. In their investigation of maintaining systems to mitigate risks under erratic climate patterns, Cho *et al.* (2018) addressed the challenge of managing liquefied natural gas (LNG) production, inventory control, and vessel routing in the face of disruptive weather conditions. Anticipating extreme weather events at an LNG plant necessitates rescheduling loading operations to mitigate safety risks. They introduced two mathematical optimization models to handle these potential disruptions. The first model is a two-stage stochastic mixed-integer program designed to maximize expected revenue while minimizing costs associated with weather uncertainties. The second model incorporates decision-makers' risk preferences, enabling 'what-if' analyses by adjusting risk levels. These models were used in tackling this harsh weather conditions as to managing a good liquified natural gas system.

In the context of human error as a potential default in maintenance operations, Antonovsky, Pollock, and Straker (2016), aimed to explore the relationship between maintenance staff perceptions of organizational effectiveness and operational reliability in petroleum operations, offering valuable insights into the human factors influencing system reliability. This investigation underscores the significance of considering qualitative perspectives alongside traditional metrics in understanding and improving operational reliability within complex systems. Maintenance planning in utility systems presents unique challenges due to the intricate interactions between system components and environmental factors, as environmental conditions represent a possible default in maintenance operations. Efficient maintenance management is crucial for ensuring uninterrupted production and high product quality while minimizing system failures and associated production losses (MOKHTAR; CHATEAUNEUF; LAGGOUNE, 2018). Despite the importance of considering defaults in maintenance planning, only a few works consider this aspect in building models to support maintenance planning (maintenance policies).

Research by Melo *et al.* (2023) has highlighted the potential of creating such models in enhancing the efficiency and effectiveness of maintenance systems, thereby minimizing the likelihood effect of defaults and maximizing the longevity of remote systems. The maintenance policy model developed is tailored for remote systems like offshore wind farms, combining periodic inspections and opportunistic replacements. The model features three phases: an initial inspection phase, a wear-out phase for corrective replacements, and a preventive replacement phase. Notably, it introduces an opportunistic phase for early preventive replacements during corrective maintenance. Through numerical analysis, the study explores decision variables across various parameters, highlighting the potential impact of opportunistic maintenance on cost-rate optimization and the importance of flexible maintenance planning. This provides an intriguing rationale for thinking about implementing defaults in systems with an opportunistic inspection. This concept of default is further discussed in the latter part of the study.

Alotaibi *et al.* (2023) developed a modified-opportunistic inspection in the case of groundwater well-heads, the maintenance policy model proposed integrates both opportunistic and scheduled inspections, reflecting real-world scenarios where inspections balance production, mission priorities, and convenience within regulatory frameworks. It extends the delay time model and is particularly applicable to inspecting remote groundwater well-head pumps, utilizing nearby maintenance interventions as inspection opportunities. The study evaluates policy outcomes such as cost-rate across various parameter values, demonstrating the model's practical significance in assessing the trade-offs between inspection policy flexibility and system operability, highlighting potential cost savings and reliability enhancements through optimized inspection practices. The proposed model serves as the motivation for the development of the new policy in this paper.

As systems grow more complex and susceptible to maintenance execution failures, the need for robust and adaptable maintenance policies is increasing. This study aims to investigate how maintenance policies can effectively mitigate the impact of these failures, ensuring system operational continuity and efficiency. By examining the relationship between maintenance strategies and the occurrence of defaults, this research seeks to enhance our understanding of optimal maintenance practices in the context of operational uncertainties.

In this study, we explore the complexities of opportunistic inspection for managing remote groundwater well-heads under logistical constraints and the risk of defaults, focusing on addressing real-world challenges. Through detailed examination and analysis, we aim to highlight the effectiveness of opportunistic inspection in maintaining the functionality, sustainability, and resilience of groundwater infrastructure in challenging environments. Additionally, we will introduce a web-based application that implements this maintenance policy, emphasizing the modified opportunistic inspection with the presence of defaults.

1.1 PROBLEM DESCRIPTION

Maintaining critical systems in remote locations, such as groundwater well-heads, presents significant logistical and operational challenges due to their geographical isolation and the necessity for regular inspections. Traditional maintenance policies often struggle to balance flexibility with compliance to safety regulations and operational reliability requirements (BARABADI; MARKESET, 2011; MELANI *et al.*, 2018; MIN, 2014).

Groundwater well-heads play a crucial role in ensuring continuous water supply, yet they face significant operational and maintenance challenges that threaten their reliability. The underground infrastructure comprising wells, pumps, and valves forms the backbone of water distribution systems, vital for meeting daily water demands. However, maintaining these systems presents formidable obstacles (MALA-JETMAROVA; SULTANOVA; SAVIĆ, 2017; CARO; CROSTA; PREVIATI, 2020).

It is crucial to address these maintenance challenges to maintain operational efficiency. Unresolved issues such as unattended faults, which could include operational malfunctions or system failures, not only lead to financial losses and environmental harm but also jeopardize water quality, raising public health concerns and causing dissatisfaction among consumers. Additionally, malfunctioning pumps, which serves as the critical component in this case, in groundwater well-heads can disrupt water flow, resulting in operational disruptions and difficulties in maintaining consistent pressure levels (RAMOS; CARRAVETTA; NABOLA, 2020; ADELE *et al.*, 2023).

To address these challenges, we propose an opportunistic inspection policy that considers defaults integrating both opportunistic and scheduled inspections. Opportunities for inspection arise randomly, triggered by events such as maintenance visits to neighboring systems, where resources like personnel and spare parts are available. An inspection occurs if the time since the last inspection or replacement exceeds a particular threshold, and a mandatory inspection time ensures system integrity (ALOTAIBI *et al.*, 2023). This approach contrasts with traditional models by allowing inspection intervals that embraces opportunities reflecting real-world maintenance scenarios where flexibility optimizes resource utilization and operational continuity.

The policy also addresses unforeseen defaults, where scheduled maintenance activities may be disrupted by unprecedented situations. Defaults are critical as they signify lapses in maintenance adherence, potentially increasing operational risks or failures (CAVALCANTE; LOPES; SCARF, 2021). Effective management of defaults is crucial in our model, influencing cost structures and operational reliability assessments (ADELE *et al.*, 2024).

Therefore, adopting effective maintenance strategies that integrate opportunistic monitoring and scheduled interventions is essential. A comprehensive approach combining opportunistic checks with preventive measures can enhance system reliability, minimize downtime, and optimize maintenance costs. This holistic strategy not only mitigates the risks of equipment failures but also supports sustainable management of groundwater resources.

This study aims to bridge theoretical developments with practical needs in maintenance management for remote systems, offering decision-support tools that balance cost efficiency with operational resilience in critical infrastructure sectors. By analyzing various scenarios and parameter configurations derived from real-world case studies, we seek to provide insights that enhance maintenance planning strategies tailored to enhance the reliability, availability and sustainability of groundwater supply systems, addressing the challenges posed by defaults and ensuring proactive management of maintenance lapses.

1.2 GENERAL AND SPECIFIC OBJECTIVES

The primary goal of this research is to develop and optimize maintenance policies for groundwater well-heads prone to default, focusing on enhancing the system reliability, decision-making processes and operational efficiency.

The specific objectives are:

- Conducting a comprehensive review of current maintenance practices and identifying key characteristics of groundwater well-head systems;
- Analyzing existing mathematical models for maintenance policies applied to groundwater systems in the literature;

- Design adaptive maintenance strategies that leverage historical data and performance indicators to predict and mitigate the risk of defaults;
- Performing sensitivity analyses to evaluate the effectiveness of the implemented maintenance policy;
- Designing a prototype to facilitate the practical application of the proposed maintenance policy.

1.3 JUSTIFICATION AND RELEVANCE

The increasing complexity and geographical dispersion of critical infrastructure systems, such as groundwater well-heads, present significant challenges in maintenance and operational efficiency. As society relies heavily on these systems for essential resources like clean water, ensuring their reliability and functionality becomes imperative (GORELICK; ZHENG, 2015). The logistical hurdles in accessing and maintaining these remote systems often lead to delays and disruptions, exacerbating the risk of defaults in scheduled maintenance activities.

Groundwater well-heads, much like offshore wind turbines and other remote systems, play a crucial role in supporting daily life and economic activities. They are fundamental to the supply of water for domestic, agricultural, and industrial use (JACOBY, 2017). The failure to adequately maintain these systems can result in substantial financial losses, environmental damage, and public health risks due to compromised water quality. Given the pressing global issues of water scarcity and climate change, the sustainable management of groundwater resources is of paramount importance (JASECHKO; PERRONE, 2021; SAYRE; TARAZ, 2019).

Maintenance policies play a crucial role in ensuring the reliability, performance, and safety of industrial systems. However, in real-world scenarios, planned maintenance activities may not always be executed as scheduled, leading to defaults or failures to carry out maintenance tasks (ALOTAIBI *et al.*, 2020). Traditional maintenance approaches are often inadequate, as they do not account for the unpredictability and logistical difficulties inherent in managing such widespread infrastructure. Consequently, understanding how different maintenance policies interact with defaults becomes essential for optimizing maintenance strategies and minimizing system downtime. This necessitates the development of advanced maintenance models that incorporate predictive monitoring and opportunistic intervention to enhance system reliability and efficiency (CAVALCANTE; LOPES; SCARF, 2021; MELO *et al.*, 2023).

Defaults in maintenance planning pose significant challenges for industrial operations across various sectors, including manufacturing (DOMBROWSKI; RICHTER; KRENKEL, 2017), healthcare (HUANG *et al.*, 2024), energy (TCHAKOUA *et al.*, 2014), supply chain (GAONKAR; VISWANADHAM, 2007) and infrastructure (ZIO, 2009). Failure to address defaults can result in increased system downtime, reduced productivity, and higher maintenance costs. By studying maintenance policies in the context of defaults, organizations can develop more robust strategies that are resilient against unexpected disruptions, ultimately improving system reliability and efficiency (HOSSAIN *et al.,* 2021).

Despite the importance of defaults in maintenance planning, there is a notable gap in the literature regarding how different maintenance policies account for and mitigate the effects of defaults. Existing research often focuses on ideal scenarios where maintenance activities are executed as planned, overlooking the reality of defaults and their impact on system reliability (BUDAI; HUISMAN; DEKKER, 2006; GEORGE-WILLIAMS; PATELLI, 2017; FINKELSTEIN; CHA; LEVITIN, 2020).

In light of these factors, this study aims to develop and implement a robust maintenance strategy tailored specifically for groundwater well-heads. By integrating advanced monitoring techniques and proactive maintenance policies, the research seeks to minimize downtime and optimize operational costs. This approach not only addresses the immediate maintenance challenges but also contributes to the long-term sustainability and resilience of groundwater supply systems.

The relevance of this research extends beyond academic interest, impacting public policy, environmental conservation, and resource management. It provides valuable insights for policymakers, engineers, and environmental scientists striving to enhance the efficiency and reliability of critical infrastructure systems. Organizations can increase operational efficiency, decrease system downtime, and optimize maintenance strategies by establishing best practices for managing defaults. Furthermore, the findings of this study have the potential to inform decision-making processes and encourage innovation in maintenance management.

1.4 STRUCTURE OF THE WORK

This work is organized into five chapters: introduction, theoretical framework and literature review, development of the proposed model, numerical application, and conclusion. The first chapter covers the initial considerations of the study, problem description, including its justification, relevance and objectives. The second chapter provides the theoretical background necessary for the research, along with recent studies related to the topic. It presents concepts related to corrective, preventive, and opportunistic maintenance, delay time models, default, and groundwater system. In the third chapter, the system under study is characterized, and the proposed model is formulated. The fourth chapter focuses on the numerical application of the model within the explored context, including analyses and discussions on its implementation. Finally, the fifth chapter presents the research conclusions, limitations, and suggestions for future work.

2 THEORETICAL BACKGROUND AND LITERATURE REVIEW

Maintenance planning is an essential component of industrial systems, particularly in infrastructure that requires continuous operation, such as groundwater supply networks. Effective maintenance plans contribute to the prevention of unforeseen breakdowns, the optimization of operational efficiency, and cost control. Hence, the need to model good and resilient maintenance policies for the sustenance of these systems.

This literature review delves into research on defaults in maintenance policies, their impact on system performance, and measures to reduce their consequences. It also investigates groundwater systems, with a focus on wellheads and submersible pumps, which are critical components in water distribution and require systematic maintenance procedures. This study attempts to improve maintenance decision-making under real-world constraints by examining existing research in these areas.

2.1 MAINTENANCE

In industrial operations, maintenance is indispensable, ensuring that production systems operate smoothly and efficiently. Its primary purpose is to keep machinery and equipment in peak condition, thereby preventing unexpected breakdowns and extending their operational life. This not only enhances productivity but also ensures worker safety and operational sustainability (FRANCIOSI *et al.*, 2018; TORTORA *et al.*, 2021; FRANCIOSI *et al.*, 2020).

Maintenance approaches can be categorized into several types: corrective, preventive, predictive, and opportunistic, each offering unique benefits and suitable applications (Li; Wang; Lin, 2020; CAVALCANTE; LOPES, 2015).

Corrective maintenance, also known as reactive maintenance, involves repairing equipment after a failure has occurred. While this approach can lead to significant disruptions and higher costs due to unplanned downtime, it can be appropriate for non-critical systems where immediate impact from failures is minimal (BAL; SATOGLU, 2018; BERDINYAZOV *et al.*, 2009).

Preventive maintenance focuses on preventing equipment failures through regular inspections and scheduled maintenance activities. This proactive approach helps to identify and address potential issues before they cause breakdowns, thereby improving reliability and performance. Although preventive maintenance reduces unexpected downtime and repair costs, it requires a well-organized schedule and sufficient resources (MUCHIRI *et al.*, 2014, KHANLARI; MOHAMMADI; SOHRABI, 2008; FORSTHOFFER, 2017).

Predictive maintenance leverages real-time data and advanced monitoring technologies to predict potential equipment failures (NASKOS *et al.*, 2019). By analyzing key operational parameters such as vibration, temperature, and pressure, predictive maintenance can detect early signs of deterioration and initiate interventions before a failure occurs. This approach optimizes maintenance schedules and minimizes unplanned downtime, making it especially beneficial for critical assets (ZONTA *et al.*, 2020; RESENDE *et al.*, 2021).

Opportunistic maintenance capitalizes on planned or unexpected downtime to perform maintenance tasks. This strategy is particularly effective in complex systems with interdependent components. By coordinating maintenance during periods of inactivity or alongside other maintenance activities, opportunistic maintenance can reduce overall costs and enhance system efficiency (HU; SHEN; SHEN, 2020; GENG; AZARIAN; PECHT, 2015).

Maintaining remote systems, such as water distribution networks, offshore wind farms, or remote oil and gas facilities, presents unique challenges. Servicing equipment spread over large areas requires advanced logistical planning and resource management (REN *et al.*, 2021). The integration of remote monitoring technologies, such as IoT sensors and drones, significantly enhances the ability to track equipment performance and respond promptly to maintenance needs (MOURTZIS; ANGELOPOULOS; PANOPOULOS, 2020; ULLO; SINHA, 2021; GNONI *et al.*, 2020).

Effective maintenance management in these remote systems requires a combination of preventive, predictive, and opportunistic strategies. While remote monitoring technologies facilitate real-time tracking of equipment performance and enable timely decision-making, it is essential for the maintenance team to physically visit the site to perform the necessary maintenance actions. Automated inspection tools can enhance efficiency in these hard-to-reach locations, but the execution of maintenance tasks must still involve on-site intervention by qualified personnel.

The significance of maintenance extends beyond preventing equipment failures. Properly maintained systems contribute to higher productivity, improved product quality, and enhanced safety. Moreover, effective maintenance practices lead to substantial cost savings by reducing the frequency and severity of breakdowns, minimizing downtime, and optimizing resource use.

In sectors like energy production, manufacturing, and transportation, maintenance is also crucial for regulatory compliance and environmental sustainability. For instance, regular maintenance of power generation and distribution systems ensures grid stability and prevents outages. In manufacturing, consistent maintenance of machinery and production lines ensures product quality and meets delivery schedules (AN *et al.*, 2022; JASIULEWICZ-KACZMAREK; LEGUTKO; KLUK, 2023).

Ultimately, maintenance is a complex but essential discipline for the efficient operation of industrial systems. Employing a combination of corrective, preventive, predictive, and opportunistic strategies can enhance equipment reliability, reduce operational risks, and achieve significant cost savings. The choice of maintenance strategy should be tailored to the specific needs of the equipment and operational context, ensuring that maintenance activities are both effective and efficient. As technology evolves, integrating data-driven maintenance practices will further enhance the ability to predict and prevent equipment failures, driving continuous improvement in maintenance management.

The subsequent sections delve into the maintenance types implemented in the developed work.

2.1.1 CORRECTIVE MAINTENANCE

Corrective Maintenance, also known as breakdown maintenance, involves repairing or replacing components only after they have failed (MOLĘDA *et al.*, 2023). While this approach minimizes upfront costs and planning efforts, it often leads to unexpected downtime, higher repair costs, and potential secondary damages.

Corrective maintenance is a critical strategy within industrial operations, involving repair or replacement actions that are performed after a system has experienced a failure or significant malfunction (WANG *et al.*, 2014). This approach focuses on restoring the system to its operational state following an unexpected breakdown. Unlike preventive maintenance, which aims to avert failures through regular upkeep, corrective maintenance is inherently reactive, addressing issues only once they arise (ZONTA *et al.*, 2020).

One of the primary characteristics of corrective maintenance is its unpredictability. Equipment failures are often stochastic, meaning their occurrence and timing are random and not easily forecasted. As a result, corrective maintenance requires a high level of preparedness and flexibility within the maintenance team to respond swiftly to unexpected problems (YEPEZ; ALSAYYED; AHMAD, 2019). This can include having readily available spare parts, skilled personnel on standby, and efficient diagnostic tools to quickly identify and rectify issues (SLEPTCHENKO; HEIJDEN, 2016).

An illustrative example of corrective maintenance can be seen in the context of manufacturing lines. Consider a scenario where a conveyor belt in a factory suddenly stops working due to a motor failure. The maintenance team must act quickly to identify the fault, procure or use available spare parts, and repair or replace the motor to get the conveyor belt running again. During this downtime, the production process is halted, potentially leading to significant financial losses and delays in meeting production targets (LI *et al.*, 2015; COMERIO, 2006; NWANYA; UDOFIA; AJAYI, 2017).

While corrective maintenance can be costlier and more disruptive compared to preventive approaches, it is sometimes unavoidable. In certain situations, the costs and logistics of preventive maintenance may not be justified, especially for non-critical components or systems where failures do not significantly impact overall operations (WAEYENBERGH; PINTELON, 2002; STENSTRÖM *et al.*, 2016). For instance, replacing a light bulb in an office or repairing a minor plumbing issue can be efficiently managed through corrective maintenance without major repercussions.

However, relying heavily on corrective maintenance for critical systems can be risky and costly. In industries such as power generation, aviation, or healthcare, equipment failure can lead to severe consequences, including safety hazards, regulatory non-compliance, and substantial economic losses (BOURASSA; GAUTHIER; ABDUL-NOUR, 2016). For example, in a power plant, a turbine failure can lead to prolonged outages (CARAZAS; SOUZA, 2010), necessitating expensive emergency repairs and potentially causing widespread power shortages.

To mitigate the risks associated with corrective maintenance, organizations often adopt a balanced approach that combines elements of both corrective and preventive maintenance (WU; ZUO, 2010; KENNÉ; NKEUNGOUE, 2008). This hybrid strategy allows them to handle unexpected breakdowns efficiently while also implementing measures to prevent frequent or severe failures. For instance, regular inspections and condition monitoring can help identify early signs of wear and tear, enabling timely corrective actions before a complete failure occurs (MOURA *et al.*, 2014).

Additionally, advancements in technology, such as predictive maintenance and IoT-enabled monitoring systems, are transforming the landscape of maintenance management

(CIVERCHIA et al., 2017; RESENDE *et al.*, 2021). These technologies allow for real-time monitoring of equipment health, predictive analytics to forecast potential failures, and automated maintenance scheduling. By leveraging such tools, organizations can reduce the frequency and impact of corrective maintenance, optimizing their maintenance operations for better efficiency and reliability (PECHT; KANG, 2019).

Corrective maintenance plays a vital role in maintaining the functionality of industrial systems, especially when failures are unpredictable and unavoidable. While it can be more disruptive and costlier compared to preventive maintenance, it remains an essential strategy for managing unexpected breakdowns. By integrating corrective maintenance with preventive and predictive approaches, organizations can achieve a robust maintenance framework that minimizes downtime, enhances operational efficiency, and ensures the reliability of critical systems.

2.1.2 PREVENTIVE MAINTENANCE

Preventive maintenance involves systematic inspection, detection, correction, and prevention of incipient failures before they become major issues (TINGA, 2010). This strategy is characterized by scheduled and planned maintenance actions designed to extend the lifespan and efficiency of equipment and systems, thereby reducing the likelihood of unexpected breakdowns. Unlike corrective maintenance, which reacts to equipment failures, preventive maintenance aims to prevent them from occurring in the first place (YANG *et al.*, 2018; CAVALCANTE; LOPES, 2015).

The primary objective of preventive maintenance is to reduce the probability of equipment failure by regularly performing maintenance tasks that keep systems running efficiently (JAFARY; NAGARAJU; FIONDELLA, 2017). This approach helps in maintaining optimal operating conditions and can significantly minimize downtime and the associated costs of emergency repairs (KHANLARI; MOHAMMADI; SOHRABI, 2008; LIAO; PAN; XI, 2010). Preventive maintenance is crucial for ensuring the reliability, safety, and productivity of industrial systems.

Time-based maintenance (TBM) is performed at scheduled intervals based on calendar time or equipment runtime. This type of maintenance includes tasks such as cleaning, lubricating, adjusting, and replacing parts at predetermined intervals, regardless of the equipment's current condition. The idea is to perform maintenance at regular intervals to prevent the likelihood of unexpected failures (SYAMSUNDAR; NAIKAN; WU, 2021; YANG; ZHAO; MA, 2018). Condition-based maintenance (CBM) involves monitoring the actual condition of the equipment to decide what maintenance needs to be done. This type of maintenance relies on various indicators of equipment performance, such as vibration analysis, thermography, oil analysis, and other diagnostic tools. Maintenance actions are performed when indicators show that the equipment's condition is deteriorating, thereby preventing failure (GOYAL; PABLA, 2015; KUMAR *et al.*, 2018; QUATRINI *et al.*, 2020).

Implementing an effective preventive maintenance program involves several key steps. First, maintain an up-to-date inventory of all equipment and systems, including detailed documentation of their maintenance requirements, operational history, and performance metrics (POPPE *et al.*, 2017). Next, develop a comprehensive schedule for regular inspections and maintenance activities. This schedule should be based on the manufacturer’s recommendations, industry standards, and historical data on equipment performance (CAVALCANTE; LOPES; SCARF, 2021). Ensure that maintenance personnel are adequately trained and equipped with the necessary skills to perform preventive maintenance tasks effectively. Ongoing training programs should be established to keep the maintenance team updated with the latest techniques and technologies (DALKILIC, 2017). Implement condition monitoring systems to continuously assess the performance and health of equipment. Use data analytics to predict potential failures and optimize maintenance schedules (NIU; YANG, 2010). Regularly review and analyze maintenance activities and outcomes. Use this feedback to improve maintenance strategies, refine schedules, and enhance the overall effectiveness of the preventive maintenance program.

Preventive maintenance actions include routine inspections, lubrication, adjustments, parts replacement, and cleaning. Routine inspections involve checking equipment for signs of wear and tear, corrosion, leaks, or other issues that could lead to failure. Inspections help in identifying potential problems early, allowing for timely corrective actions (SCARF *et al.*, 2024). Regular lubrication of moving parts reduces friction and wear, preventing overheating and extending the life of components. This is a simple yet effective preventive maintenance task that can prevent significant damage. Adjusting equipment settings and alignments ensures that machines operate within their optimal parameters, reducing stress on components and preventing premature failure. (LIU *et al.*, 2020; FREITAS, 2017) Replacing worn or aging parts before they fail can prevent unexpected breakdowns. This includes replacing belts, bearings, seals, and other consumable components. Keeping equipment clean from dust, debris, and contaminants can prevent many operational issues. Regular cleaning helps maintain efficient operation and reduces the risk of overheating or clogging (HARDT *et al.*, 2021).

While preventive maintenance offers numerous benefits, it also presents challenges. These include the initial cost of setting up a comprehensive PM program, the need for skilled personnel, and the potential for over-maintenance if not properly managed. It is crucial to strike a balance between too much and too little maintenance to avoid unnecessary costs and downtime. Preventive maintenance is a proactive approach that plays a vital role in maintaining the efficiency, reliability, and longevity of equipment and systems.

By implementing a well-structured PM program, organizations can achieve significant cost savings, minimize downtime, and enhance the overall performance of their operations (SCHREIBER, 2020). Effective preventive maintenance requires careful planning, regular monitoring, and continuous improvement to adapt to the evolving needs of the equipment and operational environment.

2.1.3 OPPORTUNISTIC MAINTENANCE

Opportunistic maintenance is a strategic approach in which maintenance activities are coordinated to coincide with other scheduled maintenance or operational downtimes within a system. This method seeks to capitalize on existing maintenance opportunities to perform additional tasks, thus reducing overall costs and minimizing disruptions to the production process (BA *et al.*, 2017; COLLEDANI; MAGNANINI; TOLIO, 2018).

In practice, opportunistic maintenance involves leveraging the downtime of one component or subsystem to perform maintenance on another (WANG; LU; REN, 2020; CAVALCANTE *et al.*, 2024). For example, if a production line is halted to repair a malfunctioning pump, it would be efficient to use this downtime to perform preventive maintenance on other components of the system that are accessible during this period. This proactive strategy aims to maximize the utilization of maintenance resources and reduce the frequency of unplanned shutdowns (YANG *et al.*, 2018).

The decision-making process for opportunistic maintenance relies on defining the conditions under which these opportunities should be taken. Instead of scheduling maintenance based solely on time intervals or the wear and tear of individual components, opportunistic maintenance identifies and exploits windows of opportunity created by other maintenance activities. This requires a dynamic and flexible maintenance plan that can adapt to the operational status and maintenance needs of the entire system (CAVALCANTE; LOPES; SCARF, 2018; SCARF; CAVALCANTE; LOPES, 2018).

Economic and structural interdependencies among system components often drive opportunistic maintenance. Economically, performing maintenance on multiple components simultaneously can lead to significant cost savings, as it reduces the labor and logistical expenses associated with multiple separate maintenance events (MELO *et al.,* 2023; CAVALCANTE *et al.*, 2024). Structurally, components that are interconnected or that affect each other's operation can benefit from synchronized maintenance efforts. For instance, if the failure of one component necessitates the shutdown of another, it makes sense to maintain both components during the same downtime (LIU *et al.,* 2022; ATASHGAR; ABDOLLAHZADEH, 2016).

The benefits of opportunistic maintenance extend beyond cost savings. By optimizing the timing and scope of maintenance activities, this approach enhances the reliability and longevity of system components (BA *et al.,* 2017). It reduces the risk of unexpected failures, thereby improving the overall efficiency and productivity of the system. Additionally, it allows maintenance teams to plan and execute their tasks more effectively, ensuring that they have the necessary resources and access to perform comprehensive maintenance (ATASHGAR; ABDOLLAHZADEH, 2016; KOOCHAKI *et al.,* 2012).

Opportunistic maintenance is particularly advantageous in industries with remote systems, such as wind farms (XIA *et al.,* 2021, MELO *et al.,* 2023), energy grids (LI; HUANG; SOARES, 2022; YILDIRIM; GEBRAEEL; SUN, 2017), and remote transportation networks (HE *et al.*, 2020, DAVIES; ANDREWS, 2022). In these scenarios, reducing the frequency and duration of maintenance interventions is crucial for minimizing operational disruptions and maintaining high levels of service availability.

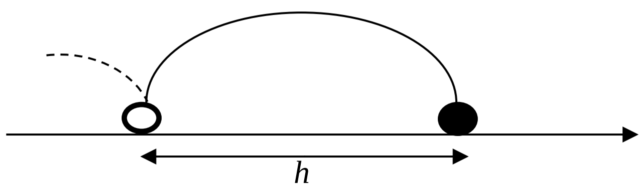
Overall, opportunistic maintenance is a forward-thinking approach that integrates maintenance activities into the broader operational schedule of a system. By identifying and exploiting opportunities for maintenance during planned downtimes, this strategy ensures efficient use of resources, reduces costs, and enhances the reliability and performance of the system. This method requires careful planning and coordination but offers significant benefits in terms of system uptime and maintenance efficiency.

2.2 DELAY-TIME

The delay time concept is a crucial element in the strategic planning of maintenance activities, particularly for systems requiring regular inspections to detect defects before failures occur. Introduced by Christer and Waller (1984), this concept models system degradation and helps establish optimal inspection intervals to minimize long-term maintenance costs.

Delay time concept posits that a system can exist in three states: good, defective, and failed. The transition from a good to a defective state marks the onset of a defect, and if this defect is not addressed, it will eventually lead to system failure after a specific period known as the delay time (h). This interval is the critical window from defect occurrence to equipment failure. By modeling this interval, maintenance can be scheduled proactively to detect and address defects during the defect phase, thereby preventing failures and minimizing downtime (CHRISTER, 1999).

Figure 1 – Delay-Time Concept



Source: Adapted from Wang (2008).

The figure illustrates the delay time concept in a maintenance context, where the arrival of a defect is followed by system failure. The delay time, represented as *h*, is the interval between the detection of the defect and the occurrence of the failure. This delay is critical for maintenance management, as it emphasizes the importance of timely intervention to prevent the defect from leading to a system failure. Understanding this delay time is essential for optimizing maintenance strategies and minimizing downtime.

The primary goal of using the delay time model is to determine the optimal timing for inspections. Conducting inspections too frequently can lead to unnecessary maintenance costs, while infrequent inspections increase the risk of undetected defects causing failures. Thus, the delay time model helps balance these factors to minimize total maintenance costs and ensure system reliability.

This concept has been applied across various industries with significant success. In the manufacturing sector, Jones, Jenkinson and Wang (2009) utilized the delay time model to manage maintenance in acetylene black production systems, optimizing inspection times to balance cost and reliability. Similarly, in steel manufacturing, Zhao, Wang and Peng (2015) applied the model to enhance maintenance schedules' efficiency.

In the energy sector, the delay time model has been particularly valuable for complex systems like offshore oil platforms and wind turbines. Wang and Majid (2000) optimized inspection intervals for offshore platforms, demonstrating that incorporating delay time analysis could improve existing maintenance plans. Andrawus *et al.* (2008) applied this approach to wind turbines, focusing on minimizing lifecycle costs through optimized inspection and maintenance intervals.

For geographically distributed systems, the delay time model offers significant benefits. Kuntz, Christie and Venkata (2001) used it to determine optimal inspection frequencies for electrical power distribution feeders, balancing inspection costs with system reliability. Cavalcante, lopes and Scarf (2021) applied this model to develop maintenance policies for distributed systems, specifying the number of necessary inspections and the optimal timing for preventive replacements to enhance system reliability and cost-efficiency.

The delay time concept provides a robust framework for proactive maintenance planning. By accurately modeling the time between defect detection and failure, organizations can optimize their inspection schedules, reduce maintenance costs, and improve system reliability. This approach is particularly advantageous for remote systems where timely maintenance actions are essential for sustaining operational efficiency and minimizing downtime

2.3 DEFAULT

The concept of default is an important factor to be considered and studied in improving maintenance policy development, providing tools for more accurate predictions, enhanced efficiency, and strategic decision-making. Recognition of default as a critical factor influencing maintenance planning and decision-making processes is at the forefront of this research work. Given the significant implications of defaults on maintenance policies and overall organizational performance, there is a growing emphasis on mitigating default risks and improving adherence to planned maintenance schedules.

Defaults are caused by a variety of circumstances, but irrespective of the source, defaults have a substantial impact on system performance and reliability. When maintenance tasks are not carried out correctly, equipment and machinery are more prone to failures, breakdowns, and malfunctions. This not only diminishes operational efficiency but also poses risk to personnel safety and the environment (YAM *et al.*, 2001).

One of the primary challenges associated with defaults is the unpredictability they introduce into maintenance planning (ADELE *et al.*, 2024). Organizations must contend with the uncertainty of whether planned maintenance activities will be carried out as scheduled, making it difficult to maintain system integrity and optimize performance (KSCIUK *et al.*, 2023; ULVDAL *et al.,* 2023; MOGHADAM *et al.,* 2023). Moreover, defaults can disrupt workflow schedules, leading to inefficiencies and potential safety hazards in industrial operations.

Cavalcante, Lopes and Scarf (2021) investigated an inspection and replacement policy for systems subject to defaults, focusing on determining maintenance tasks to schedule at known times within fixed, periodic schedules. Their study, motivated by maintenance policies commonly used for high-value, engineered systems such as wind farms and transportation systems, emphasized the significance of addressing defaults in maintenance planning. By modeling inspections using the delay time concept and considering heterogeneous system lifetimes, the authors explored the cost-rate, system reliability, and average availability of the policy. Their findings underscored the critical role of scheduled time for preventive replacement and effective visit-frequency in policy performance.

Defaults have far-reaching financial consequences in addition to immediate operational difficulties (HUANG *et al.*, 2024). Organizations may face higher expenditures due to emergency repairs, unanticipated downtime, and the need for new parts or equipment. These unexpected costs can stretch budgets and reduce overall profitability, emphasizing the need for handling defaults in maintenance planning (CHIN *et al.*, 2020).

To mitigate the impact of defaults on system reliability and performance, organizations must adopt comprehensive maintenance policies that account for the possibility of defaults and incorporate strategies to minimize their occurrence. This may include implementing proactive maintenance practices, improving resource allocation and scheduling procedures, and enhancing communication and coordination among maintenance teams. Exploring the multifaceted nature of defaults within maintenance policies is a crucial aspect, recognizing their potential to manifest in various forms and lead to a spectrum of consequences.

Alotaibi *et al.* (2020) examined age replacement and block replacement policies considering the possibility of defaults on planned maintenance, where defaults occur when preventive replacements are not executed as planned. The study aimed to assess the robustness of block replacement and age replacement policies, considering their practical implications. The authors highlighted that while age replacement typically exhibits a lower economic cost rate compared to block replacement in scenarios without defaults, block replacement offers simplicity in management due to the lack of necessity for monitoring component age. Defaults were modeled as independent Bernoulli trials, and the study established the existence of a cost-minimizing critical age for replacement in age policies with defaulting under certain conditions of the time-to-failure distribution. Numerical analyses revealed that age replacement is effective under conditions of good maintenance control with a low chance of defaulting, whereas block replacement demonstrates relative robustness to defaulting but is susceptible to lack of knowledge about component reliability.

Defaults in maintenance can range from minor oversights (Hooijberg et al., 2021) to critical lapses (BIN OSMAN; KAEWUNRUEN; JACK, 2018), each carrying distinct implications for system performance and operational integrity. For instance, in some systems, a default might culminate in catastrophic failures, resulting in severe ramifications such as fatalities (TAN *et al.*, 2020; INSLEY; TURKOGLU, 2020), environmental contamination (HÖGBERG, 2013; VINNEM; HAUGEN; OKOH, 2016), and significant production losses (SINGH *et al.*, 2021). It is imperative to acknowledge these diverse manifestations of defaults, as they underscore the complexity inherent in maintenance planning and underscore the need for comprehensive models that accurately reflect real-world dynamics.

In a study by Melo *et al.* (2023), a maintenance policy for remote systems like offshore wind farms is proposed, integrating periodic inspection with opportunistic replacement. This policy comprises three phases: an initial inspection phase to detect early defects, followed by a wear-out phase for corrective replacements, and preventive replacements thereafter. The novel opportunistic phase allows for early preventive replacements in response to identified opportunities. Through numerical analysis, the study evaluates the impact of various parameters on decision variables, including component heterogeneity, restricted access, and defaults. Results highlight the significant influence of opportunities on cost-rate optimization, emphasizing the need for flexible maintenance planning in remote systems with logistical challenges.

Therefore, it is essential to increase contributions to the maintenance aspect in order to further enhance the reliability of industrial systems. By integrating a nuanced understanding of defaults into our model, we aim to capture the intricacies of maintenance decision-making and produce results that align more closely with the complexities of operational realities.

2.4 GROUNDWATER SYSTEM

Groundwater systems are crucial for supplying water to communities, industries, and agricultural operations. These systems typically involve the extraction of water from underground aquifers through wells, which are strategically drilled into the ground (ZHANG *et al.*, 2017). A groundwater well-head is an essential component of this system, serving as the interface between the subterranean aquifer and the above-ground infrastructure. It ensures that the water extracted is efficiently and safely transported to the surface for treatment and distribution.

The natural topographical differences in terrains mean that some areas may have flat regions, while others have slopes and declines. To ensure consistent water supply across these varied landscapes, water utilities often need to elevate water pressure, which is achieved through the installation of pumping stations (PEDROSA, 2015). These pumping stations, or elevating stations, consist of various installations and pumping equipment designed to lift water to higher elevations. They play a vital role in the water supply chain, from water collection and treatment to distribution to end users.

One of the most critical components of a groundwater system is the submersible pump, which is installed within the well to push water to the surface. These pumps are specifically designed to operate underwater and are known for their reliability and efficiency in deep well applications. Submersible pumps are favored over other types of pumps in groundwater systems due to their ability to avoid cavitation, a common issue when the pump is placed above ground and must lift water over a considerable height (BIANCHINI; ROSSI; ANTIPODI, 2018).

Submersible pumps operate on the principle of converting mechanical energy into hydraulic energy through an impeller. The pump's motor is sealed and protected from water ingress, ensuring long-term operation even in challenging conditions. This feature makes them particularly suitable for deep wells where the water level is significantly below the ground surface. In groundwater systems, submersible pumps are typically part of a broader pumping infrastructure that includes suction pipes, discharge connections, and the overall pumping system, often referred to as the moto pump assembly (CARRAVETTA; DERAKHSHAN HOUREH; RAMOS, 2018).

According to Mays (2010), in water supply systems, pumping systems can be used for three main applications: high service, providing pressure and discharging water into distribution networks; boosting pressure within distribution networks or supplying elevated storage tanks; and lifting water from the source to treatment or storage facilities. These applications highlight the centrality of pumping systems in ensuring adequate water pressure and volume to meet service demands.

Hydraulic pumps, or turbopumps, which include submersible pumps, are commonly used in water supply systems due to their efficiency and capacity. These pumps are further classified into velocity pumps and positive displacement pumps. Velocity pumps, particularly centrifugal pumps, are widely used because they employ centrifugal force to move water through the system (GIRDHAR; MONIZ, 2005). Centrifugal pumps energize and transfer fluid within the system, with the flow rate varying according to system needs. The fluid is energized by a rotating impeller and displaced radially, moving along paths normal to the pump's axis (JONES; TCHOBANOGLOUS, 2006).

The maintenance of submersible pumps is critical for the overall reliability and efficiency of groundwater systems. Regular maintenance practices include inspecting and replacing worn impellers, checking the integrity of the motor seal, and ensuring that the electrical components are functioning correctly (HATSEY; BIRKIE, 2021). Given that submersible pumps are often located in remote and difficult-to-access areas, a robust maintenance strategy is essential.

Traditional preplanned preventive maintenance (PPPM) approaches can encounter significant challenges in such remote settings. Logistical constraints and the potential for defaults in maintenance schedules necessitate more flexible and adaptive maintenance strategies. A well-structured opportunistic inspection has emerged as a pragmatic solution, offering a dynamic framework for managing well-heads and submersible pumps under these constraints (ALOTAIBI *et al.*, 2023). It integrates opportunistic and scheduled inspections, reflecting real-world scenarios where maintenance activities must balance operational priorities, regulatory requirements, and convenience.

This opportunistic approach extends the delay time model, making it particularly applicable to remote groundwater well-head pumps. By utilizing nearby maintenance interventions as inspection opportunities, this approach optimizes inspection schedules and enhances the reliability of the system. Studies have shown that this method can significantly improve cost efficiency and system reliability by aligning maintenance actions with operational needs and environmental constraints.

For instance, De Sousa Pereira and Morais (2020) proposed a decision model using a multicriteria approach prioritizes maintenance actions in groundwater supply systems. This model, applied in a Brazilian town, demonstrated that improved management priorities and maintenance decision-making benefited both the supply company and the local society compared to traditional practices. The model consists of three phases: problem understanding and data acquisition, a learning process employing the SODA method, and evaluation using the ELECTRE III method.

Furthermore, another study by Blokus-Dziula *et al.* (2023) presented a model for analyzing the operational and maintenance costs of water management systems, supported by specialized software. This model considers various costs, including those associated with preventive inspections, repairs, and additional reliability-related expenses. Through a multistate reliability analysis approach, it identifies the appropriate reliability level for initiating system repairs, optimizing exploitation and repair costs, and enabling estimation of the optimal period between regular inspections while ensuring system safety.

These advanced maintenance models and strategies, including opportunistic inspection and delay time-based policies, underscore the importance of adaptive and flexible maintenance planning in groundwater systems. They highlight the potential for significant cost savings and reliability enhancements through optimized inspection practices, ensuring that groundwater well-heads and submersible pumps continue to operate effectively and efficiently. By integrating these innovative maintenance approaches, water utilities can better manage their resources, improve service reliability, and ensure the sustainability of groundwater systems.

3 SYSTEM CHARACTERIZATION, MAINTENANCE POLICY AND DEVELOPMENT OF THE MODEL

This methodology focuses on developing an opportunistic inspection policy for groundwater well-head maintenance, incorporating the concept of defaults. This approach aims to balance scheduled and opportunistic inspections while addressing real-world logistical challenges and the risks of maintenance defaults. In this methodology, two models are presented: the first is the analytical approach, which encompasses the renewal scenarios and provides a detailed analysis of the formulated model, and the second is the simulation model, which addresses complexities beyond the scope of the analytical approach. This section outlines the system characterization and model development used in the analysis.

3.1 SYSTEM CHARACTERIZATION

In developing our maintenance policy, we consider the system as a component that performs an operational function when placed in a socket. Additionally, this system is part of a larger system or fleet of systems wherein opportunities are generated. The system can exist in one of three states: operational (good, G), operational but defective (D), and non-operational (failed, F). While the system remains functional in both the good and defective states, it ceases to operate upon failure. Failures are immediately obvious, but defects are only detectable through inspections. Upon identifying a defect during an inspection, immediate and instantaneous replacement occurs, referred to as preventive replacement. Similarly, any failure triggers replacement (corrective), renewing the system.

The time the system remains in the good state (G) is modeled as a random variable x, characterized by a specific distribution F, its survival function $\overline{F}$ and its density function f. The time spent in the defective state (D) is another random variable h, with its own distribution G, survival function $\overline{G}$, and density function g. These variables, x and h, are independent of each other. Opportunities for maintenance arise according to a Poisson process with rate λ, meaning the intervals between opportunities are exponentially distributed with mean $1/\lambda$.

3.2 PROPOSED MAINTENANCE POLICY

Inspections are conducted based on a dual-criteria policy: an inspection is carried out either when an opportunity arises and the time since the last inspection or replacement exceeds a threshold S, or at a predetermined time T since the last inspection or replacement, regardless of whether an opportunity has presented itself. The costs associated with these inspections vary depending on the type of inspection performed. Inspections are assumed to be perfect, eliminating the risk of misclassifications (false positives or false negatives) or defect introductions (BERRADE; CAVALCANTE; SCARF, 2013). However, unlike traditional models, our approach incorporates the possibility of defaults, recognizing that planned maintenance may not always occur as scheduled due to resource constraints or other unforeseen factors, leading to potential delays or omissions in the maintenance schedule (ADELE *et al.*, 2024, MELO *et al.*, 2023; ALOTAIBI *et al.*, 2020). The probability of a default occurring is denoted as p. Defaults are integrated into the model to reflect real-world maintenance constraints.

The randomness in maintenance opportunities arises from the reactive nature of maintenance activities, which are often prompted by production halts or the maintenance needs of interdependent systems (SINISTERRA; CAVALCANTE, 2020). However, in certain situations, these opportunities may exhibit a periodic pattern (CAVALCANTE; LOPES; SCARF, 2021). Recognizing and seizing these opportunities, whether random or periodic, is crucial for effective maintenance management. The cost structure for our maintenance policy includes the following components: c_O for opportunistic inspections, c_I for scheduled inspections, c_P for preventive replacements, and c_F for corrective replacements following a failure.

The primary goal is to minimize the long-term cost per unit time, or cost-rate. Our analysis predominantly assumes that the sojourn in the good state (G) follows an exponential distribution, simplifying the model because each negative inspection results in a renewal. This assumption is plausible given the heterogeneity in the lifetimes of components, influenced by varying ages and operating conditions within the system fleet, or the inherent variability in the durability of individual components (SCARF, CAVALCANTE, 2010). We also explore scenarios with fixed states to account for the inherent randomness in maintenance opportunities.

By incorporating the concept of defaults into our model, we address the real-world complexities of maintenance decision-making, ensuring that our proposed policy is both practical and effective. This approach provides a detailed understanding of the trade-offs involved in maintenance planning, highlighting potential cost savings and reliability improvements through optimized inspection and replacement practices. Our comprehensive methodology aims to deliver a robust and flexible maintenance policy capable of meeting the challenges posed by defaults and enhancing the overall reliability of groundwater well-head systems.

Table 1. Notation

μ_X	The rate parameter of the defect arrival
μ_H	The rate parameter of the delay time
μ_Z	The rate parameter of opportunities
p	Probability of default
c_I	Cost of scheduled inspection
c_P	Cost of replacement of component
c_F	Cost of corrective maintenance action
c_O	Cost of opportunistic inspection
z	Arrival of opportunity
Decision Variables	
S	Onset of the window of opportunity
T	Time for a scheduled inspection.
Decision Criterion	
C_∞	Cost-rate

Source: Author (2024).

3.3 MODEL DEVELOPMENT

The method involves determining the probabilities of each potential replacement (renewal) event, referred to as scenarios. In this case, 20 scenarios are depicted in the figure, each associated with specific costs and life cycles. To ensure these events are mutually exclusive and collectively exhaustive, we verify that their total probabilities sum to 1.

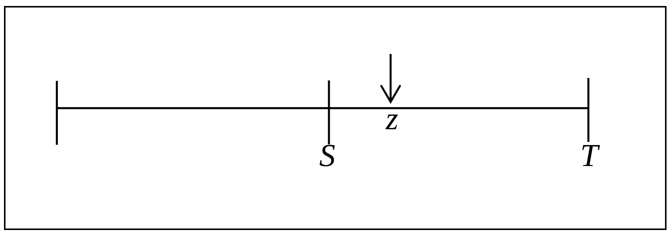
Figure 2 illustrates the proposed maintenance policy, which consists of two phases (opportunistic and scheduled inspection) and two decision variables: the onset of the window of opportunity (S) and the time for scheduled inspection (T). Maintenance actions, whether preventive or corrective, renew the system, ending the renewal cycle with each action.

Phase one includes the inspection period during the window of opportunity, with inspections carried out at the moment that an opportunity occurs. If a component shows defects during an opportunistic inspection, a preventive maintenance action is immediately performed.

These opportunistic inspections are conducted early in the equipment's lifespan to address components that may be vulnerable due to poor installation or variations in component quality.

In phase two, scheduled inspections are conducted at *T*. During this phase, maintainers can identify whether the operational state is good or defective, as defects are clearly visible at this point. When the system fails, corrective maintenance is performed as failure is immediately apparent in a critical system. Preventive replacement actions are carried out at *T*, following detection of defects (SCARF *et al.*, 2009, ADELE *et al.*, *2024*).

Figure 2 – Graphical representation of S,T maintenance policy



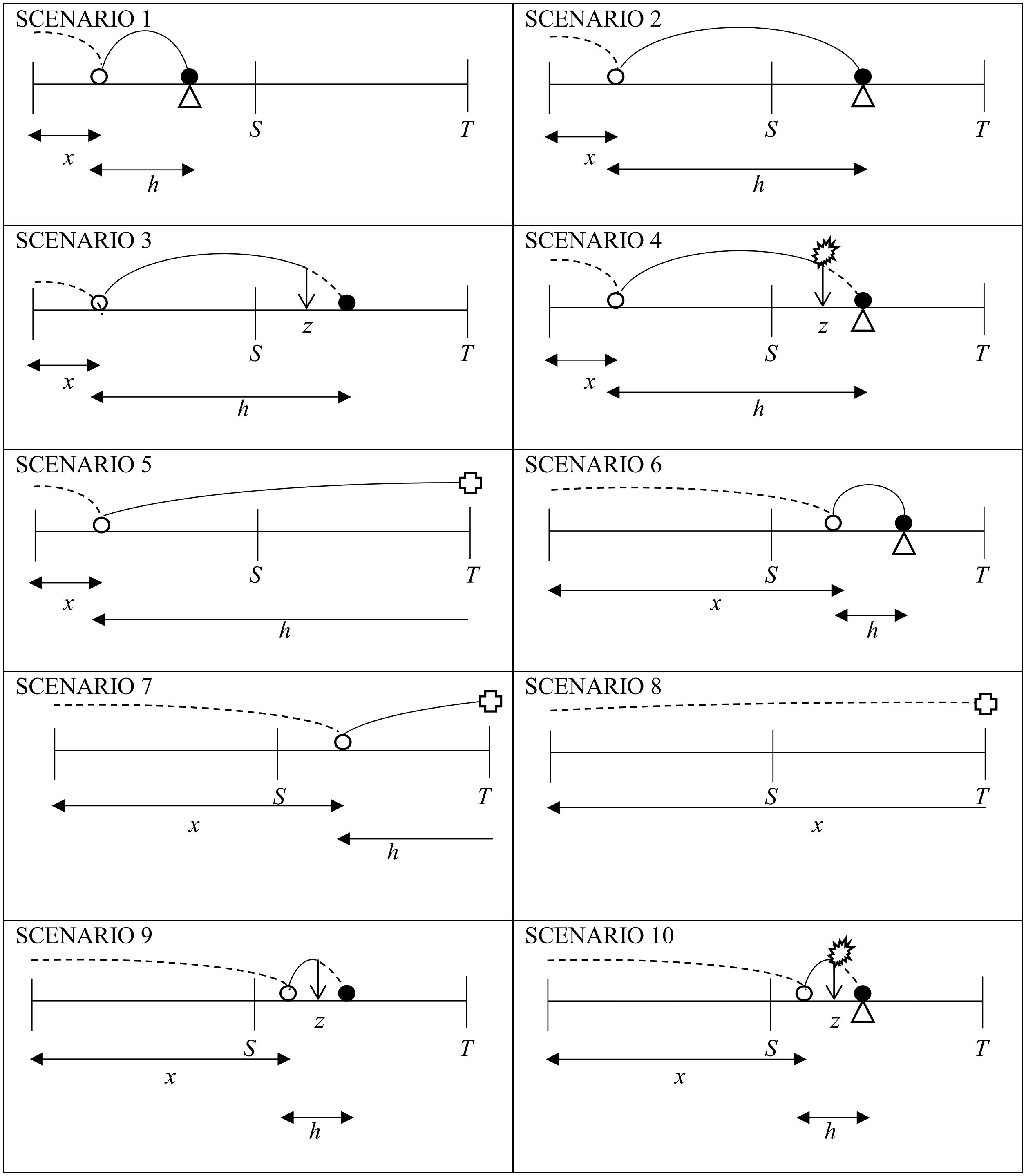
Source: *Author (2024).*

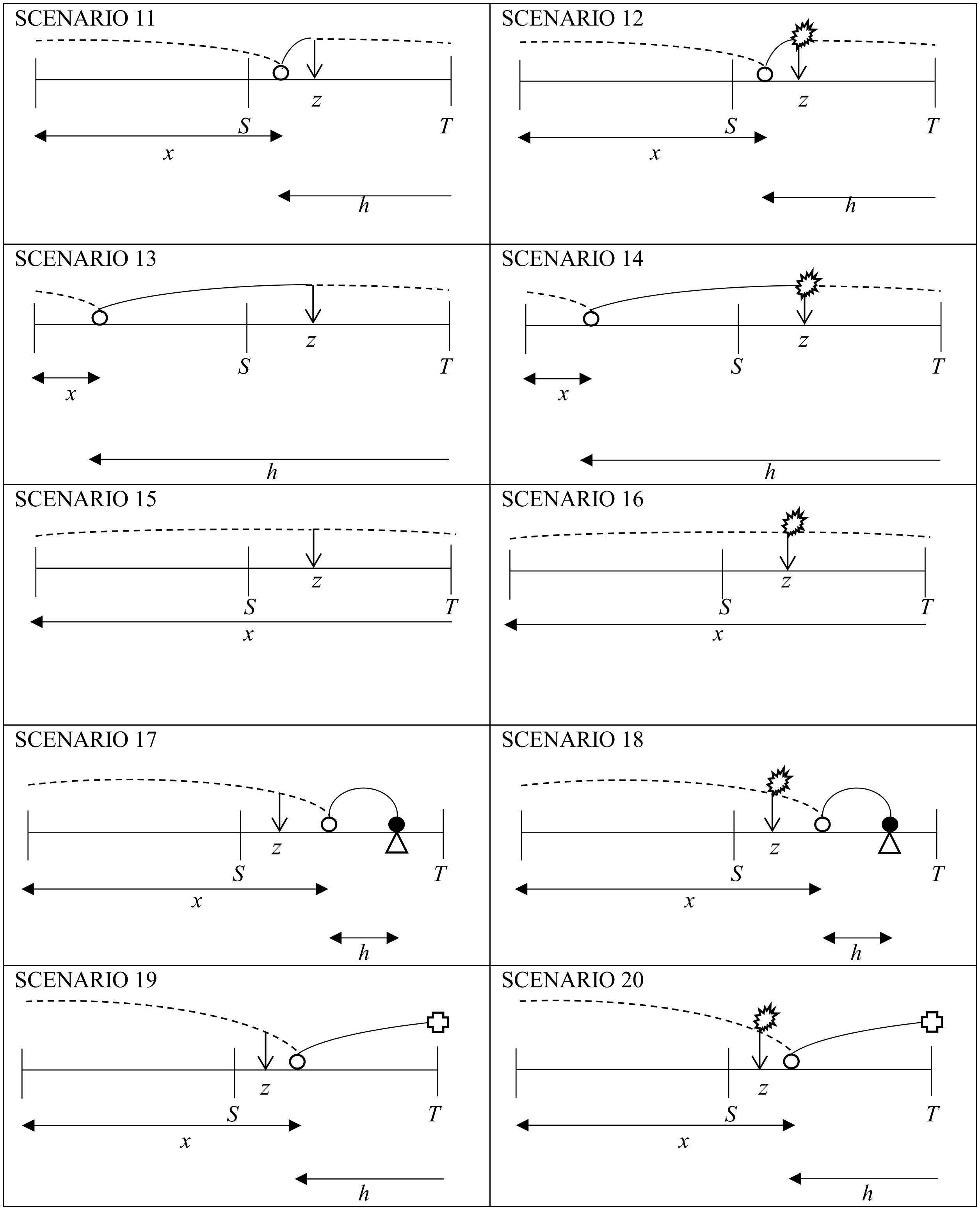
We consider the decision criteria as the cost-rate (C_∞), justified by the renewal-reward theorem (ALBERTI *et al.*, 2018). To compute the cost-rate, we identify all distinct renewal scenarios (see Table 2) and calculate the expected cost (E_{Cs}) and expected cycle length (E_{Ls}) for each scenario (s). Therefore, the cost-rate can be obtained through the following equation:

$$C_\infty\left(S,T\right)=\frac{\sum_{S=1}^{20}E_{Cs}}{\sum_{s=1}^{20}E_{Ls}} \tag{1}$$

We then determine the cost-optimal policy: those values of S and T that minimize $C_\infty\left(S,T\right)$ subject to $T\geq S$.

Table 2. Scenarios





Source: *Author (2024).*

Table 3. Symbols used in the Scenarios

Symbol	Meaning
○	Defect
●	Failure
✹	Default
✜	Preventive Maintenance (PM)
△	Corrective Maintenance (CM)
↓	Opportunity
├──┼──┤	Timeline

Source: *Author (2024).*

- Scenario 1

A defect followed by a failure emerges before set inspection threshold *S* of the proposed maintenance policy, resulting in a corrective maintenance.

The probability of occurrence of this renewal scenario is:

$$\mathrm{P}_1(S,T)=\int_0^S\int_0^{S-x} f_X(x)\,f_H(h)\,\mathrm{d}h\mathrm{d}x \tag{2}$$

The expected cost is:

$$C_1(S,T)=(c_F)\int_0^S\int_0^{S-x} f_X(x)\,f_H(h)\,\mathrm{d}h\mathrm{d}x \tag{3}$$

And the expected cycle length is:

$$L_1(S,T)=\int_0^S\int_0^{S-x} (x+h)\,f_X(x)\,f_H(h)\,\mathrm{d}h\mathrm{d}x \tag{4}$$

- Scenario 2

The defect also emerges before set inspection threshold *S*, and the failure occurs between *S* and *T*. In this case, there is no opportunity and corrective maintenance action is also carried out.

The probability of occurrence of this renewal scenario is:

$$\mathrm{P}_2(S,T)=\int_0^S\int_{S-x}^{T-x} f_X(x)\,f_H(h)\,e^{-\mu((x+h)-S)}\,\mathrm{d}h\mathrm{d}x \tag{5}$$

The expected cost is:

$$C_2(S,T) = (c_F)\int_0^S \int_{S-x}^{T-x} f_X(x) f_H(h) e^{-\mu((x+h)-S)} \mathrm{d}h\mathrm{d}x \qquad (6)$$

And the expected cycle length is:

$$L_2(S,T) = \int_0^S \int_{S-x}^{T-x} (x+h) f_X(x) f_H(h) e^{-\mu((x+h)-S)} \mathrm{d}h\mathrm{d}x \qquad (7)$$

- Scenario 3

Defect emerges before set inspection threshold *S*, but does not result in failure as a result of opportunity. In this case, there is no default and preventive replacement action is taken before the failure occurs.

The probability of occurrence of this renewal scenario is:

$$\mathrm{P}_3(S,T) = (1-p)\int_0^S \int_{S-x}^{T-x} \int_0^{(x+h)-S} f_X(x) f_H(h) f_Z(z) \mathrm{d}z\mathrm{d}h\mathrm{d}x \qquad (8)$$

The expected cost is:

$$C_3(S,T) = (1-p)(c_O + c_P)\int_0^S \int_{S-x}^{T-x} \int_0^{(x+h)-S} f_X(x) f_H(h) f_Z(z) \mathrm{d}z\mathrm{d}h\mathrm{d}x \qquad (9)$$

And the expected cycle length is:

$$L_3(S,T) = (1-p)\int_0^S \int_{S-x}^{T-x} \int_0^{(x+h)-S} (z+S) f_X(x) f_H(h) f_Z(z) \mathrm{d}z\mathrm{d}h\mathrm{d}x \qquad (10)$$

- Scenario 4

Defect emerges before set inspection threshold *S*, but despite the opportunity arrival in the system, failure occurs because of the occurrence of default. In this case, corrective maintenance action is taken.

The probability of occurrence of this renewal scenario is:

$$\mathrm{P}_4(S,T) = (p)\int_0^S \int_{S-x}^{T-x} \int_0^{(x+h)-S} f_X(x) f_H(h) f_Z(z) \mathrm{d}z\mathrm{d}h\mathrm{d}x \qquad (11)$$

The expected cost is:

$$C_4(S,T) = (p)(c_F)\int_0^S \int_{S-x}^{T-x} \int_0^{(x+h)-S} f_X(x) f_H(h) f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \qquad (12)$$

And the expected cycle length is:

$$L_4(S,T) = (p)\int_0^S \int_{S-x}^{T-x} \int_0^{(x+h)-S} (x+h) f_X(x) f_H(h) f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \qquad (13)$$

- Scenario 5

The defect also emerges before set inspection threshold *S*, but does not fail as the delay-time exceeds the remaining time until the time for scheduled inspection *T*. No opportunity, and preventive replacement is carried out on the component.

The probability of occurrence of this renewal scenario is:

$$\mathrm{P}_5(S,T) = \int_0^S \int_{T-x}^{\infty} f_X(x) f_H(h) e^{-\mu(T-S)}\mathrm{d}h\mathrm{d}x \qquad (14)$$

The expected cost is:

$$C_5(S,T) = (c_I + c_P)\int_0^S \int_{T-x}^{\infty} f_X(x) f_H(h) e^{-\mu(T-S)}\mathrm{d}h\mathrm{d}x \qquad (15)$$

And the expected cycle length is:

$$L_5(S,T) = \int_0^S \int_{T-x}^{\infty} (T) f_X(x) f_H(h) e^{-\mu(T-S)}\mathrm{d}h\mathrm{d}x \qquad (16)$$

- Scenario 6

The defect emerges after set inspection threshold *S*, resulting in failure between *S* and *T*. In this case, corrective maintenance action is also carried out because there was no opportunity.

The probability of occurrence of this renewal scenario is:

$$\mathrm{P}_6(S,T) = \int_S^T \int_0^{T-x} f_X(x) f_H(h) e^{-\mu((x+h)-S)}\mathrm{d}h\mathrm{d}x \qquad (17)$$

The expected cost is:

$$C_6(S,T) = (c_F)\int_S^T \int_0^{T-x} f_X(x) f_H(h) e^{-\mu((x+h)-S)}\mathrm{d}h\mathrm{d}x \qquad (18)$$

And the expected cycle length is:

$$L_6(S,T)=\int_S^T\int_0^{T-x}(x+h)f_X(x)f_H(h)e^{-\mu((x+h)-S)}\mathrm{d}h\mathrm{d}x \tag{19}$$

- Scenario 7

The defect also emerges after set inspection threshold *S*, but does not fail as the delay-time exceeds the remaining time until the time for scheduled inspection *T*. No opportunity. Thus, preventive replacement is carried out on the component.

The probability of occurrence of this renewal scenario is:

$$\mathrm{P}_7(S,T)=\int_S^T\int_{T-x}^{\infty}f_X(x)f_H(h)e^{-\mu(T-S)}\mathrm{d}h\mathrm{d}x \tag{20}$$

The expected cost is:

$$C_7(S,T)=(c_I+c_P)\int_S^T\int_{T-x}^{\infty}f_X(x)f_H(h)e^{-\mu(T-S)}\mathrm{d}h\mathrm{d}x \tag{21}$$

And the expected cycle length is:

$$L_7(S,T)=\int_S^T\int_{T-x}^{\infty}(T)f_X(x)f_H(h)e^{-\mu(T-S)}\mathrm{d}h\mathrm{d}x \tag{22}$$

- Scenario 8

The defect does not emerge throughout the time exceeding the scheduled inspection *T*. No opportunity. Since, no defect was detected, no preventive replacement is carried out on the component.

The probability of occurrence of this renewal scenario is:

$$\mathrm{P}_8(S,T)=\int_T^{\infty}f_X(x)e^{-\mu(T-S)}\mathrm{d}x \tag{23}$$

The expected cost is:

$$C_8(S,T)=(c_I)\int_T^{\infty}f_X(x)e^{-\mu(T-S)}\mathrm{d}x \tag{24}$$

And the expected cycle length is:

$$L_8(S,T)=\int_T^{\infty}(T)f_X(x)e^{-\mu(T-S)}\mathrm{d}x \tag{25}$$

➢ Scenario 9

The defect emerges after set inspection threshold *S*, but does not result in failure as a result of opportunity between *S* and the failure. In this case, there is no default and preventive replacement action is taken before the failure occurs.

The probability of occurrence of this renewal scenario is:

$$\mathrm{P}_9(S,T) = (1-p)\int_S^T \int_0^{T-x} \int_{x-S}^{(x+h)-S} f_X(x) f_H(h) f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \tag{26}$$

The expected cost is:

$$C_9(S,T) = (1-p)(c_O + c_P)\int_S^T \int_0^{T-x} \int_{x-S}^{(x+h)-S} f_X(x) f_H(h) f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \tag{27}$$

And the expected cycle length is:

$$L_9(S,T) = (1-p)\int_S^T \int_0^{T-x} \int_{x-S}^{(x+h)-S} (z+S) f_X(x) f_H(h) f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \tag{28}$$

➢ Scenario 10

The defect also emerges after set inspection threshold *S*, resulting in failure because of default in opportunity between *S* and the failure. In this case, corrective maintenance action is taken.

The probability of occurrence of this renewal scenario is:

$$\mathrm{P}_{10}(S,T) = (p)\int_S^T \int_0^{T-x} \int_{x-S}^{(x+h)-S} f_X(x) f_H(h) f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \tag{29}$$

The expected cost is:

$$C_{10}(S,T) = (p)(c_F)\int_S^T \int_0^{T-x} \int_{x-S}^{(x+h)-S} f_X(x) f_H(h) f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \tag{30}$$

And the expected cycle length is:

$$L_{10}(S,T) = (p)\int_S^T \int_0^{T-x} \int_{x-S}^{(x+h)-S} (x+h) f_X(x) f_H(h) f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \tag{31}$$

➢ Scenario 11

The defect emerges after set inspection threshold *S*, and it is identified by an opportunistic inspection. Thus, preventive replacement is carried out on the component.

The probability of occurrence of this renewal scenario is:

$$P_{11}(S,T)=(1-p)\int_{S}^{T}\int_{T-x}^{\infty}\int_{x-S}^{T-S} f_X(x)\,f_H(h)\,f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \tag{32}$$

The expected cost is:

$$C_{11}(S,T)=(1-p)(c_O+c_P)\int_{S}^{T}\int_{T-x}^{\infty}\int_{x-S}^{T-S} f_X(x)\,f_H(h)\,f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \tag{33}$$

And the expected cycle length is:

$$L_{11}(S,T)=(1-p)\int_{S}^{T}\int_{T-x}^{\infty}\int_{x-S}^{T-S} (z+S)\,f_X(x)\,f_H(h)\,f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \tag{34}$$

- Scenario 12

The defect arises after set inspection threshold *S*. Subsequently, an opportunity inspection appears, but does not identify the defect because default occurs. Even so, there is no failure because the time in the defective state exceeds the time for scheduled inspection *T*.

The probability of occurrence of this renewal scenario is:

$$P_{12}(S,T)=(p)\int_{S}^{T}\int_{T-x}^{\infty}\int_{x-S}^{T-S} f_X(x)\,f_H(h)\,f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \tag{35}$$

The expected cost is:

$$C_{12}(S,T)=(p)(c_I+c_P)\int_{S}^{T}\int_{T-x}^{\infty}\int_{x-S}^{T-S} f_X(x)\,f_H(h)\,f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \tag{36}$$

And the expected cycle length is:

$$L_{12}(S,T)=(p)\int_{S}^{T}\int_{T-x}^{\infty}\int_{x-S}^{T-S} (T)\,f_X(x)\,f_H(h)\,f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \tag{37}$$

- Scenario 13

Defect also appears before set inspection threshold *S*, but does not fail because it is identified by the opportunistic inspection. Thus, preventive replacement is carried out on the component.

The probability of occurrence of this renewal scenario is:

$$P_{13}(S,T)=(1-p)\int_{0}^{S}\int_{T-x}^{\infty}\int_{0}^{T-S} f_X(x)\,f_H(h)\,f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \tag{38}$$

The expected cost is:

$$C_{13}(S,T)=(1-p)(c_O+c_P)\int_0^S\int_{T-x}^{\infty}\int_0^{T-S} f_X(x)\,f_H(h)\,f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \tag{39}$$

And the expected cycle length is:

$$L_{13}(S,T)=(1-p)\int_0^S\int_{T-x}^{\infty}\int_0^{T-S}(z+S)\,f_X(x)\,f_H(h)\,f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \tag{40}$$

- Scenario 14

The defect appears before set inspection threshold *S*. Subsequently, an opportunity inspection appears, but does not identify the defect because default occurs. Even so, there is no failure because a preventive replacement occurs at the time for scheduled inspection *T*, upon identifying a defect. The probability of occurrence of this renewal scenario is:

$$\mathrm{P}_{14}(S,T)=(p)\int_0^S\int_{T-x}^{\infty}\int_0^{T-S} f_X(x)\,f_H(h)\,f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \tag{41}$$

The expected cost is:

$$C_{14}(S,T)=(p)(c_I+c_P)\int_0^S\int_{T-x}^{\infty}\int_0^{T-S} f_X(x)\,f_H(h)\,f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \tag{42}$$

And the expected cycle length is:

$$L_{14}(S,T)=(p)\int_0^S\int_{T-x}^{\infty}\int_0^{T-S}(T)\,f_X(x)\,f_H(h)\,f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \tag{43}$$

- Scenario 15

The defect does not emerge throughout the time scheduled inspection *T*. In this case, there is an opportunity but no preventive maintenance action is carried out on the component as no defect is identified.

The probability of occurrence of this renewal scenario is:

$$\mathrm{P}_{15}(S,T)=(1-p)\int_T^{\infty}\int_0^{T-S} f_X(x)\,f_Z(z)\mathrm{d}z\mathrm{d}x \tag{44}$$

The expected cost is:

$$C_{15}(S,T)=(1-p)(c_O)\int_T^{\infty}\int_0^{T-S} f_X(x)\,f_Z(z)\mathrm{d}z\mathrm{d}x \tag{45}$$

And the expected cycle length is:

$$L_{15}(S,T)=(1-p)\int_{T}^{\infty}\int_{0}^{T-S}(z+S)\,f_X(x)\,f_Z(z)\mathrm{d}z\mathrm{d}x \tag{46}$$

- Scenario 16

The defect does not emerge throughout the time until the scheduled inspection *T*. There is an opportunity but default occurs. But since defect is not identified until *T*, preventive maintenance action is not carried out on the component.

The probability of occurrence of this renewal scenario is:

$$\mathrm{P}_{16}(S,T)=(p)\int_{T}^{\infty}\int_{0}^{T-S}f_X(x)\,f_Z(z)\mathrm{d}z\mathrm{d}x \tag{47}$$

The expected cost is:

$$C_{16}(S,T)=(p)(c_I)\int_{T}^{\infty}\int_{0}^{T-S}f_X(x)\,f_Z(z)\mathrm{d}z\mathrm{d}x \tag{48}$$

And the expected cycle length is:

$$L_{16}(S,T)=(p)\int_{T}^{\infty}\int_{0}^{T-S}(T)\,f_X(x)\,f_Z(z)\mathrm{d}z\mathrm{d}x \tag{49}$$

- Scenario 17

The defect emerges after set inspection threshold *S* and after the opportunity arrival *Z*, resulting in failure between *Z* and *T*. In this case, corrective maintenance action is also carried out.

The probability of occurrence of this renewal scenario is:

$$\mathrm{P}_{17}(S,T)=(1-p)\int_{S}^{T}\int_{0}^{T-x}\int_{0}^{x-S}f_X(x)\,f_H(h)\,f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \tag{50}$$

The expected cost is:

$$C_{17}(S,T)=(1-p)(c_O+c_F)\int_{S}^{T}\int_{0}^{T-x}\int_{0}^{x-S}f_X(x)\,f_H(h)\,f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \tag{51}$$

And the expected cycle length is:

$$L_{17}(S,T)=(1-p)\int_{S}^{T}\int_{0}^{T-x}\int_{0}^{x-S}(x+h)\,f_X(x)\,f_H(h)\,f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \tag{52}$$

- Scenario 18

The defect also arises after set inspection threshold *S* and after the opportunity arrival *Z*, resulting in failure between *Z* and *T*. In this case there is also default in opportunity, but since failure occurred after the opportunistic inspection and before the scheduled inspection, corrective maintenance action is carried out.

The probability of occurrence of this renewal scenario is:

$$\mathrm{P}_{18}(S,T) = (p)\int_{S}^{T}\int_{0}^{T-x}\int_{0}^{x-S} f_X(x) f_H(h) f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \tag{53}$$

The expected cost is:

$$C_{18}(S,T) = (p)(c_F)\int_{S}^{T}\int_{0}^{T-x}\int_{0}^{x-S} f_X(x) f_H(h) f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \tag{54}$$

And the expected cycle length is:

$$L_{18}(S,T) = (p)\int_{S}^{T}\int_{0}^{T-x}\int_{0}^{x-S} (x+h) f_X(x) f_H(h) f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \tag{55}$$

- Scenario 19

Defect emerges after set inspection threshold *S* and after the opportunity arrival *Z*, but does not fail because the delay-time reached the time for scheduled inspection *T*. Thus, preventive replacement is carried out on the component.

The probability of occurrence of this renewal scenario is:

$$\mathrm{P}_{19}(S,T) = (1-p)\int_{S}^{T}\int_{T-x}^{\infty}\int_{0}^{x-S} f_X(x) f_H(h) f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \tag{56}$$

The expected cost is:

$$C_{19}(S,T) = (1-p)(c_O + c_I + c_P)\int_{S}^{T}\int_{T-x}^{\infty}\int_{0}^{x-S} f_X(x) f_H(h) f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \tag{57}$$

And the expected cycle length is:

$$L_{19}(S,T) = (1-p)\int_{S}^{T}\int_{T-x}^{\infty}\int_{0}^{x-S} (T) f_X(x) f_H(h) f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \tag{58}$$

- Scenario 20

Defect also appears after set inspection threshold *S* and after the opportunity arrival *Z*, but does not fail because the delay-time reached the scheduled inspection *T*. In this case there is also default in opportunity, but since failure does not occur until after *T*, preventive replacement is carried out on the component.

The probability of occurrence of this renewal scenario is:

$$\mathrm{P}_{20}(S,T)=(p)\int_{S}^{T}\int_{T-x}^{\infty}\int_{0}^{x-S} f_X(x)\,f_H(h)\,f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \tag{59}$$

The expected cost is:

$$C_{20}(S,T)=(p)(c_I+c_P)\int_{S}^{T}\int_{T-x}^{\infty}\int_{0}^{x-S} f_X(x)\,f_H(h)\,f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \tag{60}$$

And the expected cycle length is:

$$L_{20}(S,T)=(p)\int_{S}^{T}\int_{T-x}^{\infty}\int_{0}^{x-S} (T)\,f_X(x)\,f_H(h)\,f_Z(z)\mathrm{d}z\mathrm{d}h\mathrm{d}x \tag{61}$$

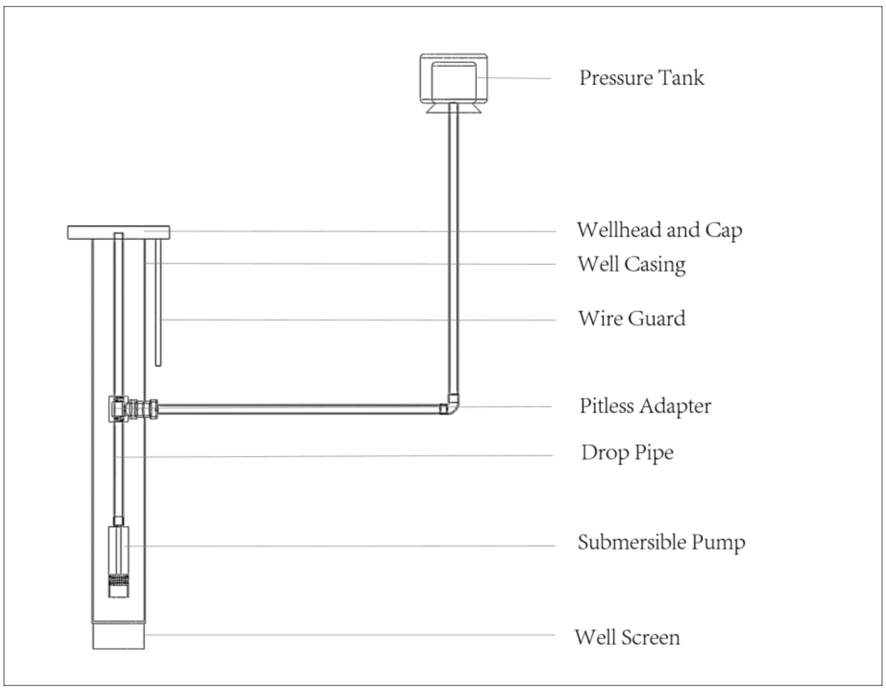
4 NUMERICAL STUDY AND DISCUSSION

This chapter presents a numerical application conducted in a context that closely mirrors real-world conditions. In the following section, the final outcomes are analyzed, especially in response to variations in input parameters, to evaluate the model's robustness through sensitivity analysis.

4.1 APPLICATION OF THE MODEL

In this numerical study, the model's application is demonstrated in the context of a groundwater distribution system, focusing on the critical role of well-heads as depicted in figure 3.

Figure 3 – Illustration of the Groundwater well-head



Source: Author (2024)

In semi-arid and arid regions, groundwater extraction is crucial for meeting water demands, with deep wells serving as vital components of the water supply system. These wells, equipped with large submersible pumps, are often situated in remote areas, making their maintenance both challenging and costly. The well-heads, which house these pumps, require regular inspections and maintenance to ensure continuous operation and prevent costly failures. This study examines maintenance strategies for these well-heads, with a specific focus on the benefits of opportunistic inspections and addressing the challenges posed by defaults—defined here as the inability to carry out a pre-planned or pre-scheduled maintenance activity.

Typically, well-head equipment is designed for a lifespan of around 30 years, but the most common issue is a reduction in pumping capacity due to sediment buildup, leading to pump failure. Other critical failure points include the pump motor, turbine assembly, and control panel. Given the remote locations of many well-heads, the costs associated with transporting personnel, tools, and spare parts to the site are significant. This study explores the implementation of opportunistic inspections, where maintenance is performed on nearby well-heads during scheduled visits to optimize resource use and reduce operational costs.

However, a key contribution of this study is addressing the issue of defaults. In maintenance planning, a default occurs when a scheduled maintenance activity cannot be executed, often due to logistical challenges, lack of resources, or unforeseen circumstances. This study not only models the timing and frequency of inspections but also incorporates strategies to mitigate the impact of defaults. By accounting for the likelihood of defaults, the study provides a more resilient maintenance strategy that ensures critical maintenance tasks are completed, even in the face of unexpected challenges.

The purpose of these inspections is threefold: to prevent disruptions in water supply, reduce energy consumption by avoiding the operation of degraded pumps, and comply with regulatory requirements. The study's model balances the risks of over-inspection, which leads to unnecessary costs, against under-inspection, which could result in equipment failure and service interruptions. By incorporating subjective estimates from experienced engineers, the study captures the variability in maintenance conditions while maintaining the robustness of the decision-making process.

Moreover, the study suggests that by broadening the definition of neighboring wells and ensuring maintenance crews carry a wider range of spare parts, the effectiveness of opportunistic maintenance can be significantly enhanced. This approach not only reduces direct maintenance costs but also addresses the challenge of defaults by providing flexibility in maintenance execution.

The estimates for the model parameters are obtained from a case study focusing on the maintenance of remote groundwater well-heads, as detailed by Alotaibi *et al*. 2023. Table 4 provides the base case parameters and the possible range of each parameter, determined through expert evaluations.

Table 4 – Base Case Parameters

Base Case	μ_X	μ_H	μ_Z	c_P	c_I	c_O	c_F	p
Value	2	1	1	1	0.5	0.1	5	0.2
Range	-	0.5 - 2	0.5 - 2	-	-	0 – 0.3	5 – 10	0 – 0.8

Source: Adapted from Alotaibi et al. 2023

From the table above, c_I, c_O, c_F, are all dependent on c_P as the base unit, meaning they are proportional to the value of c_P in monetary terms, with each expressed in arbitrary monetary units. The units of μ_X, μ_H and μ_Z, however, are in time^{-1}, while p is unitless, as it is a probability.

4.2 RECOMMENDED MAINTENANCE POLICY

The base case parameters are outlined in Table 4, along with a range of values each parameter can assume, based on expert analyses. Additionally, Table 5 presents the results of cost rate optimization for the lower and upper bound values from the specified range (other parameters as base case). Maintenance policy optimization was conducted in Python utilizing SciPy and NumPy libraries, incorporating expressions for all conceivable scenarios. The inspection interval is regulated by the state and can extend up to 2 years. For the base case, the optimum policy is S * = 0.396 year and T * = 2.000 years with a cost-rate of 3.215 monetary units per year.

Table 5 – Optimal policy for base case parameter values (Lower & Upper bound). S and T values are given in years (time unit), and the cost-rate is given in monetary units per year.

Base case		Range	For lower bound {S *, T *}	Cost-rate	For upper bound {S *, T *}	Cost-rate
μ_X	2	–	–	–	–	–
μ_H	1	0.5 – 2	{1.227, 2.000}	2.123	{0.300, 0.536}	4.526
μ_Z	1	0.5 – 2	{0.314, 2.000}	3.249	{0.502, 2.000}	3.184
c_P	1	–	–	–	–	–
c_I	0.5	–	–	–	–	–
c_O	0.1	0 – 0.3	{0.304, 2.000}	3.176	{0.744, 2.000}	3.281
c_F	5	5 – 10	{0.396, 2.000}	3.215	{0.206, 0.387}	5.064
ρ	0.2	0 – 0.8	{0.386, 2.000}	3.186	{0.501, 1.600}	3.286

Source: Author (2024).

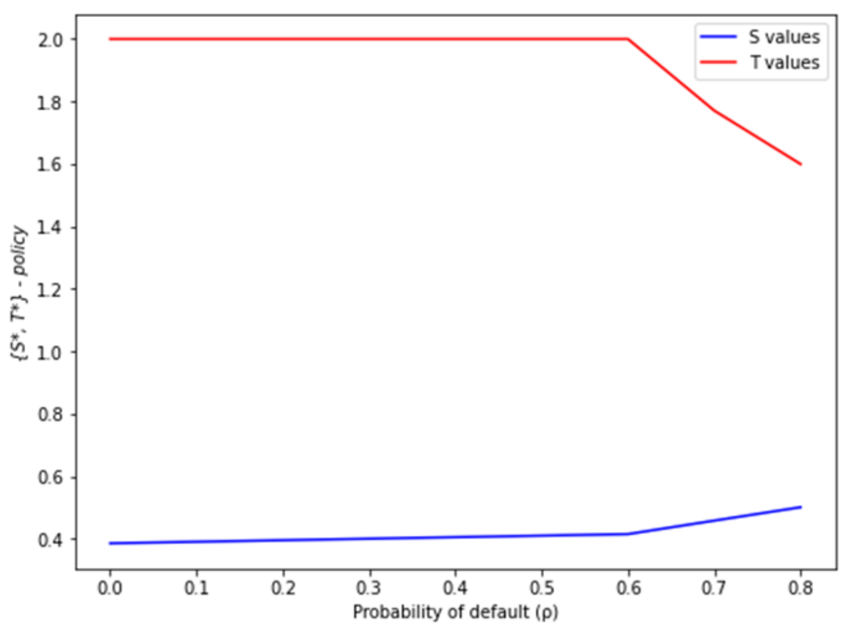
4.3 ANALYSIS AND DISCUSSION

Table 5 demonstrates the robustness of the maintenance model, aligning well with the expected outcomes of the proposed policy. As inspection or replacement costs increase, the cost rate rises, whereas increasing the frequency of inspection opportunities lowers the cost rate, underscoring the importance of utilizing such opportunities. A longer delay-time also results in a reduced cost rate, showing the effectiveness of the optimal policy when the time of the transition between defective to failed is extended.

Additionally, as opportunity costs decrease, the opportunity window widens, allowing for greater utilization of emerging opportunities. A key observation is that the inspection interval shortens as corrective replacement costs rise. The cost rate also increases with higher default probabilities.

Graph 1 and 2 provide further insights, displaying the optimal policy and its corresponding cost rates for different default probabilities.

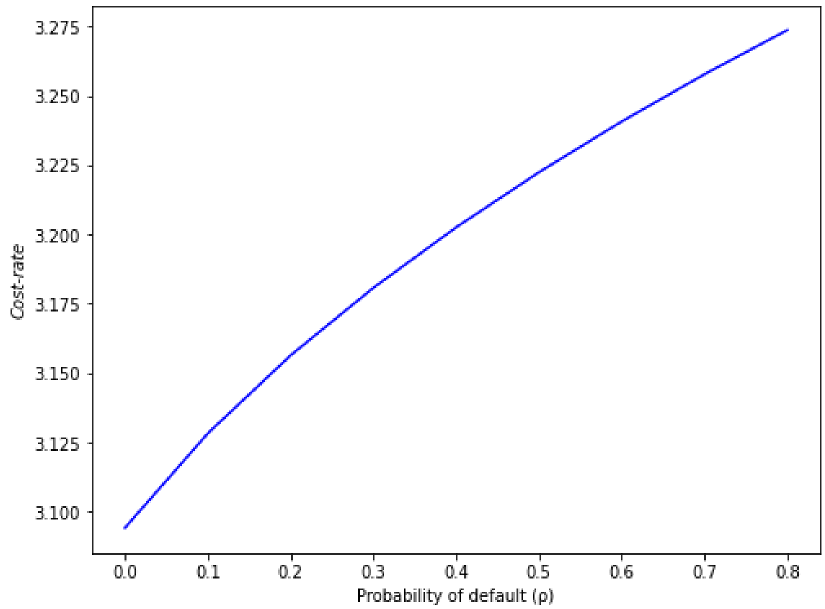
Graph 1 – Optimal (S^*, T^*) – policy versus probability of default (ρ).



Source: Author (2024).

Building on the results presented in Graph 1, it is evident that the optimal maintenance policy adapts efficiently to varying system parameters. This adaptability reflects the model's ability to maintain cost-effectiveness across different scenarios, ensuring that critical maintenance decisions are informed by both cost and operational factors. Moreover, the interplay between inspection intervals and default probabilities highlights the delicate balance required to minimize total costs while mitigating risks.

Graph 2 – Minimal cost-rate versus probability of default (ρ).



Source: Author (2024).

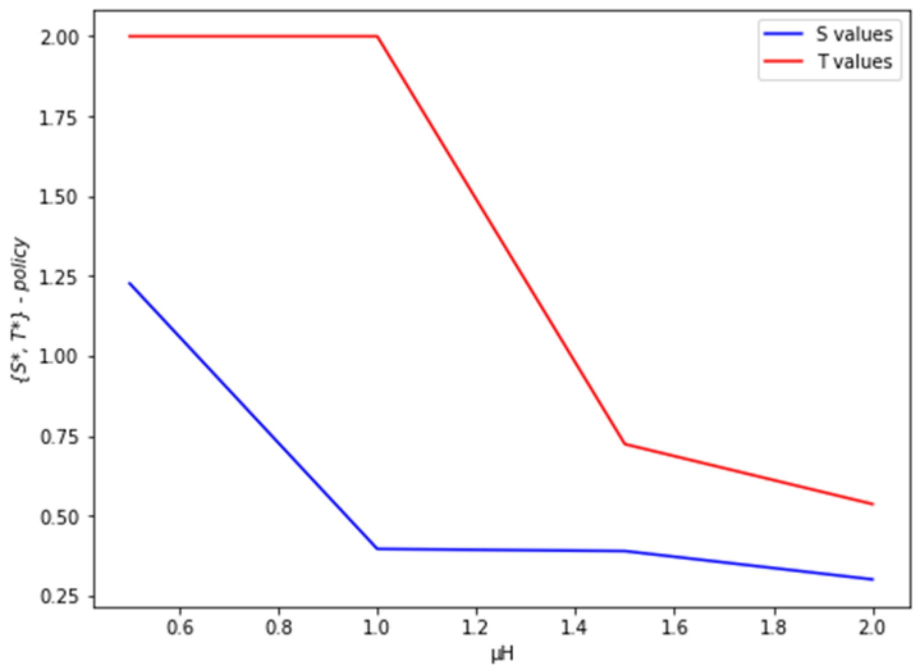
Graph 2 illustrates a positive correlation between default probability and cost rate. As the default probability increases, the cost rate also rises, reflecting the heightened maintenance expenses associated with the inability to perform necessary actions. This relationship emphasizes the importance of proactive maintenance strategies in managing costs, particularly in groundwater systems where maintaining operational integrity is critical. By minimizing defaults, operators can better control maintenance expenditures and ensure more efficient resource allocation.

Graph 3 is an illustration for the relationship between μ_H and the S, T policy values. Both policy values display a downward trend as μ_H increases. Initially, the T values remain constant for lower values of μ_H, but after a certain point, they sharply decline, indicating a significant adjustment in policy as μ_H reaches higher thresholds. On the other hand, the S values decrease more gradually throughout the range of μ_H, although they stabilize after an initial decline.

This behavior suggests that as μ_H increases, delay time reduces, indicating possibilities of fewer interventions, possibly reflecting a more susceptible system to failure. The steeper drop in

T indicates that the timing of inspections or maintenance opportunities may need to be adjusted more aggressively compared to the scope of actions represented by S. Understanding these trends helps refine the maintenance policies by showing how different system parameters like μ_H affect both decisions variables, enabling a more cost-effective and efficient approach to system management.

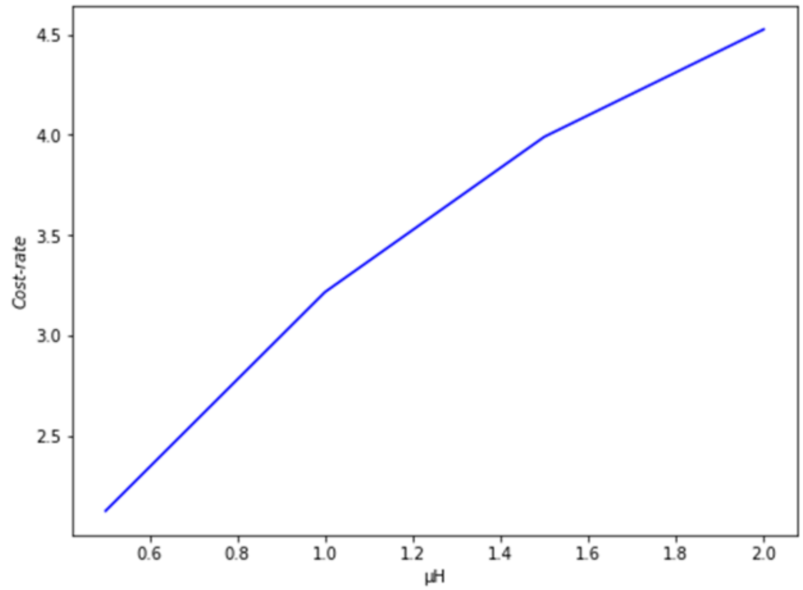
Graph 3 – Optimal (S *, T *) – policy versus μ_H



Source: Author (2024).

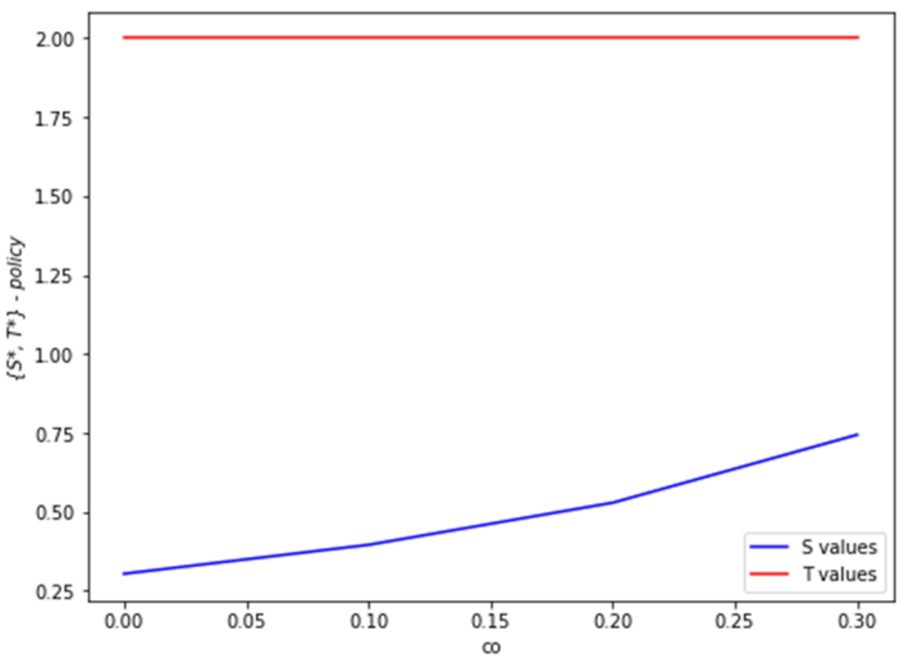
Graph 4 demonstrates a linear positive relationship between μ_H and the cost rate. As μ_H increases, the cost rate steadily rises, indicating that higher values of μ_H, as a result reduced delay time lead to increased maintenance costs. This trend suggests that the system becomes more expensive to maintain as μ_H increases, likely reflecting the growing complexity or inefficiency of the system under those conditions. The graph highlights the importance of managing μ_H effectively to minimize cost impacts and optimize the overall maintenance strategy. The consistent upward trend points to the need for careful calibration of maintenance policies to balance cost against system performance.

Graph 4 – Minimal cost-rate versus μ_H



Source: *Author (2024).*

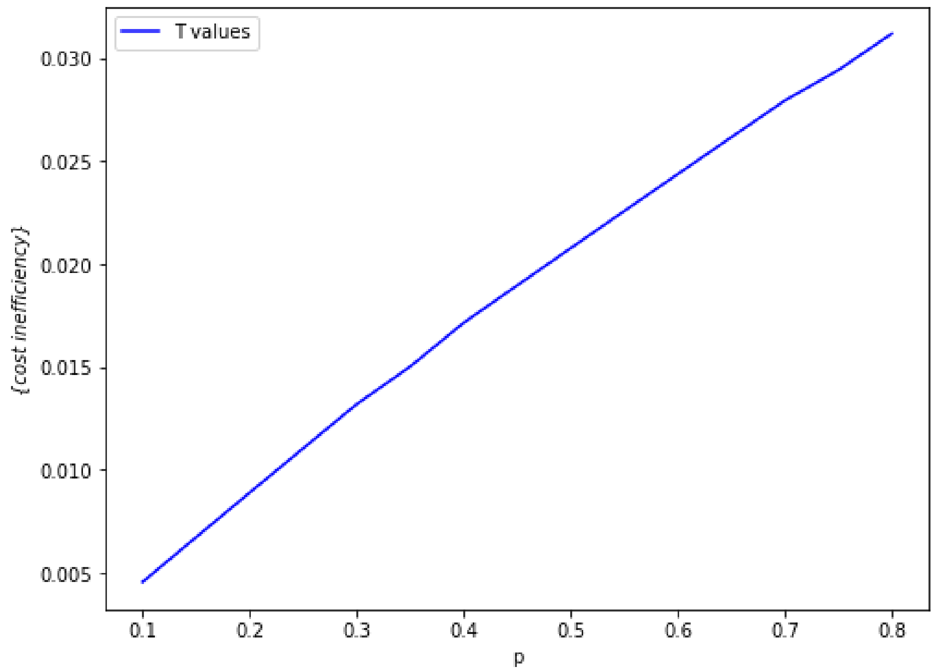
Graph 5 – Optimal ($S*, T*$) – policy versus Opportunity Cost c_O



Source: *Author (2024)*

Graph 5 illustrates the relationship between opportunity cost (c_O) and the corresponding optimal policy values (*S* and *T*). As opportunity cost increases, *S* values gradually increase, reflecting the tendency for maintenance actions to become less spaced out as the cost associated with taking advantage of emerging opportunities increases. In contrast, T values remain constant, under the restriction of inspection regulations. This graph reinforces the idea that increasing opportunity costs primarily affect inspection strategy but do not significantly alter replacement.

Graph 6 – Cost Inefficiency versus Probability of default (ρ)



Source: *Author (2024)*

Dismissing the defaults, as Alotaibi *et al.* (2023), with other base case parameters unchanged, the optimal policy is $S^* = 0.386$ and $T^* = 2.000$ resulting in a cost-rate of 3.186, as seen in Table 5. But comparing this cost-rate with the presence of default as seen in Graph 6. It is evident that as the probability of default increases, the cost-rate also increases, which in turns increases the cost inefficiency of the model. The cost inefficiency is calculated as: $1-\frac{3.186}{C_\infty(0.386, 2.000)}$. For instance, if we do not take default into consideration, we incur a cost inefficiency of up to 3%. This value of inefficiency appears minute but not negligible. The restricted value of T as a result of the groundwater system regulations also has an impact on this analysis but there is tendency to have significant cost inefficiency if we do not consider default in systems without this constraint. Hence, we cannot take this as negligible because in some cases even 3% inefficiency means a lot.

5 CONCLUSION

The aim of this dissertation has been to develop and optimize maintenance policies for critical groundwater systems, focusing on groundwater well-heads and submersible pumps. Although, the model can be generally applied to systems subject to default. Through the use of optimization modeling and sensitivity analysis, we explored the effects of varying key parameters such as default probability, inspection costs, replacement costs, delay times, and inspection frequency on overall system performance and cost-effectiveness. The analysis carried out in this work provides valuable insights into how these parameters interact and influence the operational efficiency and financial sustainability of maintenance policies.

The integration of default probabilities, which represents the inability to carry out necessary maintenance actions due to external factors, proved to be one of the most critical components of the model. By incorporating the likelihood of defaults into the opportunistic inspection model, we were able to account for real-world uncertainties, providing a more robust and adaptable maintenance framework. The results show a clear positive correlation between increasing default probabilities and rising cost rates. This underlines the necessity for proactive strategies that minimize the risk of defaults by prioritizing regular inspections and maintaining flexibility in scheduling maintenance activities. The more we reduce the likelihood of defaults, the more stable and predictable the system becomes, leading to lower long-term costs.

Another key finding is the inverse relationship between delay-time and the cost rate. Allowing longer delays before defects are detected results in reduced cost rates, which suggests that under certain conditions, defects may be detected later without significantly compromising the system. This flexibility enables maintenance managers to optimize inspection schedules, reduce the frequency of interventions, and minimize costs, especially in scenarios where the risk of immediate failure is low. However, while extended delay times can reduce costs, they must be carefully managed to ensure that defects are caught early enough to prevent catastrophic failures.

The sensitivity analysis carried out has further validated the robustness of the proposed maintenance model. As inspection and replacement costs increase, the cost rate predictably rises, highlighting the need for efficient cost-management strategies. On the other hand, higher inspection frequencies were found to lower the cost rate, demonstrating the value of seizing available inspection opportunities to maintain system integrity. These insights indicate that a well-balanced approach, combining frequent inspections and cost-effective repair strategies, is essential for minimizing total operational costs.

The results also highlight an important relationship between opportunity costs and the system's opportunity window. As opportunity costs decrease, the window for leveraging maintenance opportunities expands, allowing for more extensive utilization of emerging inspection and repair chances. This dynamic plays a crucial role in optimizing the timing and frequency of inspections. The policy response, specifically the reduction in inspection intervals as corrective replacement becomes more expensive, is particularly relevant for high-cost environments where preventive maintenance is preferable to costly corrective actions. Proactively reducing inspection intervals when replacement costs rise leads to a more controlled and predictable maintenance process.

In considering limitations and future directions, prospective research could explore additional complexities such as different geographic areas and factor in more environmental considerations, multi-component systems or integrating real-time data analytics for predictive maintenance. However, the current findings offer a strong foundation for further advancements in maintenance optimization, contributing to more sustainable and resilient infrastructure management practices.

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