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Modified-opportunistic inspection and the case of remote, groundwater well-heads

Naif M. Alotaibi [a], Philip Scarf [b,*], Cristiano A.V. Cavalcante [c], Rodrigo S. Lopes [d], André Luiz de Oliveira e Silva [e], Augusto J.S. Rodrigues [c], Salem A. Alyami [f]

[a] Department of Mathematics and Statistics, Imam Mohammad Ibn Saud Islamic University, Riyadh, Kingdom of Saudi Arabia
[b] Cardiff Business School, Cardiff University, CF10 3AT, UK, and RANDOM, Research Group on Risk and Decision Analysis in Operations and Maintenance, Universidade Federal de Pernambuco, Recife, PE CEP:50740-550, Brazil.
[c] RANDOM, Research Group on Risk and Decision Analysis in Operations and Maintenance, and Department of Industrial Engineering, Universidade Federal de Pernambuco, Recife, PE CEP:50740-550, Brazil
[d] Department of Mechanical and Production Engineering, Federal University of São João del Rei–UFSJ, São João del Rei, Minas Gerais 36307-352, Brazil
[e] Instituto Federal de Pernambuco, Campus Ipojuca, Brazil
[f] College of Science, Imam Mohammad Ibn Saud Islamic University, Riyadh, Saudi Arabia

A R T I C L E I N F O

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A B S T R A C T

We develop a model of a maintenance policy in which inspections are partly opportunistic and partly scheduled. Opportunities for inspection occur at random, and the system is inspected at such an opportunity only if the system is aged at least *S*. Further, once the system reaches age *T*, an emergency inspection is performed. The purpose of inspection is to determine whether the system is in the defective state, which acts as a warning stage prior to failure. The policy represents a reality in which flexible inspections prioritise production or missions or convenience, subject to statutory or safety regulations. The model is a generalization of the delay time model. Inspection of pumps at groundwater well-heads, which are geographically remote, motivates the model. Maintenance interventions at other nearby installations are opportunities. Policy outcomes (cost-rate, mean time between operational failures) are studied numerically for a range of values of the parameters of the model. The model is useful for practice because it quantifies the benefit and disbenefit of flexibility in the inspection policy. We show that in some circumstances making better use of opportunities can simultaneously reduce cost and increase reliability.

1. Introduction

Remoteness is a key factor in the maintenance of critical systems for water supply, energy production, and telecommunications in many countries. This remoteness means that the transportation of resources (personnel, equipment, spares) is time-consuming and costly. For example, groundwater well-heads are geographically remote and critical equipment located there (pumps, valves, switches) require regular maintenance checks [41]. Consequently, flexible planning of maintenance interventions is desirable, but it must also accommodate statutory or safety regulations that specify a maximum allowable time between inspections of such systems. Telecommunications networks [16] and power systems [23] in sparsely populated areas with poor transportation links face the same issue. Further, the installation of such technologies is increasingly penetrating remote regions [12,51], in consequence of rural development policy [29,62]. Therefore, the demand for maintenance for these systems will continue to grow, and the development of engineering services solutions (maintenance, spare-parts, personnel) for geographically dispersed micro-facilities is a pressing issue. Thus, studying the cost and reliability of policies that are flexible and feasible is important (e.g. [25,74]).

In this paper, we develop a new model of an opportunistic inspection policy that is partly flexible and partly fixed. The model is a generalization of the delay time model [17]. The state of the system is described by a semi-Markov process with three states: good, defective or failed. The system operates when it is in the good or defective states. The system does not operate in the failed state, which is immediately revealed by, for example, loss of water supply. A failed system requires immediate

* Corresponding author.
E-mail address: scarfp@cardiff.ac.uk (P. Scarf).

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replacement; this is our definition of a critical, non-repairable system. The defective state is a warning state prior to failure, and a defect is revealed only by inspection. Sojourns in the good and defective states are random variables. At a positive inspection (defect found) the system is replaced. Events that are external to the system provide opportunities for inspection, and in our model opportunities arise according to a Poisson process with rate λ. For well-heads in remote locations, these events are typically visits by maintainers to neighbouring systems, whence personnel and equipment may be relatively close but time and spare-parts may be limited.

The policy that we model is not purely opportunistic. It is a modified-opportunistic policy in which the time since the last inspection or replacement of the system determines whether an opportunity is used or not: an opportunity is used for inspection if and only if this time is at least S; and when this time reaches T the system is inspected. Thus, the system waits at least S but not more than T to be inspected. Inspection at time T is termed an emergency inspection. In this way, the policy differs from the delay time model because the inspection interval is random while in the delay time model the inspection interval (typically denoted by Δ) is a constant. We use the term "modified" in the same sense that Berg and Epstein [7] used to modify block-replacement. Dekker and Plasmeijer [22] use the same modification of age-replacement of a two-state system (good or failed). The cost of an emergency inspection is much more than the cost of an opportunistic inspection, and the cost of replacement on failure (corrective replacement) is much more than the cost of replacement at a positive inspection (preventive replacement), regardless of whether the inspection was opportunistic or an emergency. We assume that replacement renews the system and that a negative inspection (no defect found) has no influence on the system state or the sojourn in the good state, noting that an inspection is negative if and only if the system is good. We use the terms "$\{S,T\}$-opportunistic inspection" and "$\{S,T\}$-policy" interchangeably with the term "modified-opportunistic inspection".

The $\{S,T\}$-policy has a number of established policies as special cases. Inspection is periodic when $S = T$. This is the classic delay-time model [17]. When $S = 0$ and $T\to\infty$, we obtain the pure opportunistic (random) inspection policy of Scarf et al. [54]. When $\lambda = 0$ and $T\to\infty$, there is no inspection, and replacement is carried if and only if the system is failed (failure-based maintenance). Opportunistic inspection in the delay-time framework was first studied by Christer and Wang [19], and has been extended by others (e.g. [10,27,48,56,73,76]). Jiang [30] also considers the notion of a flexible inspection plan, but inspections are not opportunistic. On the other hand, random inspection of stand-by systems [39,43,80,81] or protection systems [14] is a different model because such systems can persist in the failed state; this is the characteristic of a stand-by or protection system (as opposed to a critical system), wherein the purpose of inspection is to determine whether the system is failed or not. The hard and soft-failure modeling framework of Taghipour and Banjevic [61] is also different. Indeed, many models with random inspections have been studied in this dual failure-mode framework (e.g. [28,49,69,78,79]). Inspections are also used to determine the performance of multi-state systems and random inspections have been modeled in this context (e.g. [50,75]). Waiting until S to use opportunities shares some of the characteristics of postponement [9,63]. Nonetheless, the model developed in our paper is novel.

Works on opportunistic maintenance policies, considering opportunistic maintenance as a topic that includes opportunistic inspection as a subset, are increasingly appearing in the literature. Typically, these consider particular industries, e.g. aerospace [31,66], manufacturing [58], railways (e.g. [6,34]), wind energy [35,37,42,72], or configurations, e.g. two units [11,67,82], auxiliary, standby units [57], multi-component systems [45,65,68], or concepts, e.g. grouping of maintenance activities [40,64]. Some of these post-date the recent review of maintenance optimization models in De Jonge and Scarf [20]. Most closely related to our work is Zhang and Yang [77], which uses a window-type policy but for opportunistic replacement of a unit that has been identified as defective. Nonetheless, our perspective is different to these works. We aim to provide quantitative decision-support for the maintainer of a fleet of systems that is geographically dispersed (e.g. [24,38,44,46]). We suppose that the maintainer seeks a flexible maintenance plan that meets either statutory/safety regulations or an operational reliability requirement [55]. We compare the cost-benefit of our new policy relative to periodic inspection, pure opportunistic inspection (random inspections), and failure-based replacement. We do this for a range of plausible cases (scenarios), quantified by the unit costs of inspections and replacements, and the parameters of the distributions of the sojourns in the good and defective states. Data for the parameters in the base-case come from the groundwater well case-study. We aim to use a comprehensive set of cases and parameter values and model assumptions that cover a wide range of plausible realities.

In summary, the contribution of the paper lies in:

- The development of a new model for which published opportunistic inspection models are special cases. The new model is motivated by a real problem—groundwater well-head equipment.
- Crucially, we think, the new model of inspection provides a neat solution to a practical problem in maintenance management that is more realistic—closer to the reality—than the solutions provided by existing models, particularly for geographically dispersed systems.
- In this way, this paper and our solution bridges the gap between theoretical developments in academia and industry needs. In respect of this gap, we present the model and the results in the paper in a way that is accessible to the engineering community.
- Finally, and importantly, as the demand grows for e.g. energy and telecommunications in remote regions, our maintenance planning solution is provident.

The structure of the paper is as follows. Next, we define our model and present the assumptions and notation. We then derive the cost-rate (long run cost per unit time) and the operational reliability (mean time between operational failures), our decision criteria, in two cases: for an exponential sojourn in the good state (Section 3.1), and for fixed sojourns in the good and defective states (Section 3.2). We discuss by do not solve the finite-horizon decision problem in Section 3.3. The case study is presented in Section 4.1 and the extended numerical study follows that in Section 4.2. The paper finishes with a discussion in Section 5.

2. Mathematical model of modified-opportunistic inspection

Conceptually, we regard the system as a component that when located in a socket performs an operational function [4], and that the system is one part of system or fleet of systems wherein opportunities are generated.

The system can be in one of three states: good (G), defective (D), and failed (F). The system operates in the good and defective states and does not operate when failed. The failed state is immediately revealed. This is our definition of a critical system. The state D is revealed only by inspection. When a defect is found (positive inspection), replacement is immediate and instantaneous. We call a replacement at a positive inspection a preventive replacement. On failure, replacement is also immediate and instantaneous. Replacements are renewals of the system.

The sojourn in state G is a random variable X with distribution F, survival function $\bar{F}$, and density function f. The sojourn in state D is a random variable H with distribution G, survival function $\bar{G}$, and density function g. X and H are statistically independent.

The sojourns between opportunities are exponentially distributed with mean $1/\lambda$, a constant, so that opportunities arise as a Poisson process with rate λ.

The inspection policy is such that the system is inspected (provided it survives): at an opportunity if the time since last inspection or replacement is at least S; at time T since the last inspection or replacement if no opportunity arises beforehand. The types of inspection (at S or at T) differ in their cost only (costs are defined below). Inspections are perfect, so that there are no misclassifications (false positives or false negatives) or defect introductions [8], no postponement or defaulting [3,33,71]. Spare parts are assumed always available at an inspection. The assumptions about availability of spares and no defaulting are natural because necessarily an opportunity cannot exist if there are no resources (spare parts or time) for replacement if inspection demands it.

Randomness of opportunities is justified when maintenance is somewhat reactive, so that maintenance of a system is triggered by a production stop or maintenance of another co-dependant system [60]. Nonetheless, opportunities can be periodic in other circumstances [15].

The unit costs are as follows: c_{O} is the cost of an opportunistic inspection; c_{I} is the cost of an (emergency) inspection at T; c_{P} is the cost of a preventive replacement; c_{F} is the cost of failure (corrective) replacement.

Our decision criterion is the long-run cost per unit time, or cost-rate for short, in a renewal-reward formulation of the model. We also calculate the mean time between operational failures in order to quantify the reliability of the system under the maintenance policy.

Principally, our analysis below assumes the sojourn in state G is exponentially distributed. This allows for a tractable analysis because a negative inspection is a renewal. This assumption is justified when the sojourns (lifetimes) of components are heterogeneous, either because among a fleet of the systems age and operating conditions vary or because an individual system may be weak or strong so that its lifetime is a mixture [53]. We also consider the case of fixed sojourns, at the other extreme, noting that there still exists randomness because opportunities are random.

3. Derivation of the cost-rate

We start by determining the distribution of the time from renewal to the next notional inspection, which we denote by Z. This inspection is notional because the system may or may not survive to reach it. If the latter (failure), then there is no inspection in the renewal cycle. Thus, this next notional inspection may be the scheduled, emergency inspection (at T), or an opportunistic one at a random time, or may not occur at all because failure intervenes. Necessarily $Z > S$ because opportunities that arise before S are ignored. Then, Z has an improper exponential distribution with density

$$f_Z(z) = \begin{cases} 0, & z \le S \\ \lambda e^{-\lambda(z-S)}, & S < z < T \\ e^{-\lambda(T-S)}, & z = T. \end{cases} \tag{1}$$

This is because opportunities arise according to a Poisson process with rate λ. Therefore, the excess time, $Z - S$, beyond S to the next opportunity is exponentially distributed (by the lack of memory property) provided $Z < T$. Further, $Z = T$ with probability $\exp\{-\lambda(T - S)\}$, because a non-opportunistic inspection occurs at T if no opportunity arises in $[S, T)$.

3.1. Exponential sojourn in the good state

In this section, we shall suppose that the sojourn in the good state is exponentially distributed. Then, a negative inspection (system in state G—no defect found) at an opportunity is a renewal point due to the lack of memory property of the exponential distribution. We denote the length of a renewal cycle by V and the total cost in a renewal cycle by U.

Note, in the classic delay-time model [17], sojourns in both the good and defective states are exponential, but nonetheless there exists a finite optimum inspection interval (subject to conditions about unit costs of inspection and failure). This is because, even though a defect arises at random, inspection is cost-effective because failure is not immediate. Indeed, it is the nature of the sojourn in the defective state that largely determines the extent to which inspection is effective.

We first condition on the event $Z = z$, that is, the next inspection occurs at time z. Then, we have

$$E(V|z) = \phi_0 + \phi(z),$$

where

$$\phi_0 = \int_0^S \int_0^{S-x} (x+h)\mathrm{d}G(h)\mathrm{d}F(x), \tag{2}$$

which does not depend on z, and

$$\phi(z) = \int_0^S \int_{S-x}^{z-x} (x+h)\mathrm{d}G(h)\mathrm{d}F(x) + \int_S^z \int_0^{z-x} (x+h)\mathrm{d}G(h)\mathrm{d}F(x) + z \times \int_0^z \bar{G}(z-x)\mathrm{d}F(x) + z\bar{F}(z). \tag{3}$$

which does depend on z. Here, we use $\mathrm{d}G(h)$ and $\mathrm{d}F(x)$ as shorthand for $g(h)\mathrm{d}h$ and $f(x)\mathrm{d}x$. The double integral in Eq. (2) corresponds to failure before S (case 1 in Fig. 1). The first term in Eq. (3) corresponds to a defect before S and subsequent failure after S but before z (case 2, Fig. 1). Further terms then correspond to: a defect after S and subsequent failure before z (case 3, Fig. 1); a defect arising and surviving to z (case 4, Fig. 1); no defect arising before z (case 5, Fig. 1).

Unconditionally, with the distribution of Z given by Eq. (1), we have

$$E(V) = \phi_0 + \int_S^T \phi(z)\lambda e^{-\lambda(z-S)}\mathrm{d}z + \phi(T)e^{-\lambda(T-S)}. \tag{4}$$

Cases 1, 2 and 3 (Fig. 1) are failures so that the associated unit cost is c_{F}. Case 4 is a positive inspection (system in state D) with cost that depends on z. If $z < T$ then the unit cost is $c_{\mathrm{P}} + c_{\mathrm{O}}$ (preventive replacement plus opportunistic inspection). If $z = T$ then the cost is $c_{\mathrm{P}} + c_{\mathrm{I}}$ (preventive replacement plus non-opportunistic inspection). Case 5 is a negative inspection (system in state G) with cost c_{O} when $z < T$ and c_{I} when $z = T$. Then, similarly to Eq. (4), we have

$$E(U) = \psi_0 + \int_S^T \psi(z)\lambda e^{-\lambda(z-S)}\mathrm{d}z + \psi(T)e^{-\lambda(T-S)}$$

where

$$\psi_0 = c_{\mathrm{F}} \int_0^S \int_0^{S-x} \mathrm{d}G(h)\mathrm{d}F(x),$$

and

$$\psi(z) = c_{\mathrm{F}} \int_0^S \int_{S-x}^{z-x} \mathrm{d}G(h)\mathrm{d}F(x) + c_{\mathrm{F}} \int_S^z \int_0^{z-x} \mathrm{d}G(h)\mathrm{d}F(x) + (c_{\mathrm{P}} + c_{\mathrm{O}}) \int_0^z \bar{G}(z-x)\mathrm{d}F(x) + c_{\mathrm{O}}\bar{F}(z),$$

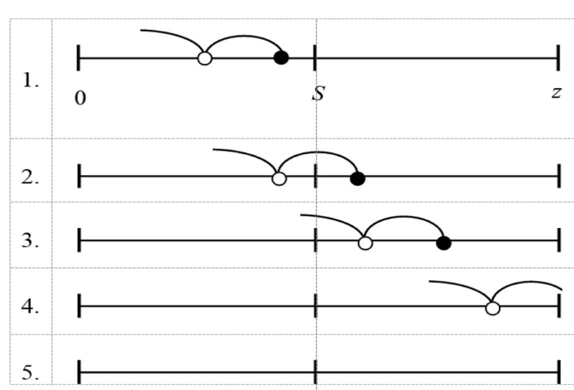

Fig. 1. Exhaustive and disjoint cases, conditional on next available inspection at time z. Defect arrival ○ and subsequent failure ●.

and

$$\psi(T) = c_F \int_0^S \int_{S-x}^{T-x} dG(h)dF(x) + c_F \int_S^T \int_0^{T-x} dG(h)dF(x) + (c_P + c_I)\int_0^T \bar{G}(T-x)dF(x) + c_I\bar{F}(T).$$

Then, our optimization criterion is the cost-rate, $Q(S,\ T) = E(U)/E(V)$.

We can also determine the mean time between operational failures (MTBOF). This is just $E(V)/p_F$ [55], where p_F is the probability that a renewal cycle ends in failure:

$$p_F = \int_0^S \int_0^{S-x} dG(h)dF(x) + \int_S^T \left\{ \int_0^S \int_{S-x}^{z-x} dG(h)dF(x) + \int_S^z \int_0^{z-x} dG(h)dF(x) \right\} \lambda e^{-\lambda(z-S)}dz + \left\{ \int_0^S \int_{S-x}^{T-x} dG(h)dF(x) + \int_S^T \int_0^{T-x} dG(h)dF(x) \right\} e^{-\lambda(T-S)}.$$

The three terms in this expression correspond to failure before S, failure in $[S,T]$ but before the first opportunity conditional on at least one opportunity, and failure in $[S,T]$ conditional on no opportunities arising, respectively.

Note, in the special case when $T\to\infty$, we have

$$E(V) = \int_0^S \int_0^{S-x} (x+h)dG(h)dF(x) + \int_S^\infty \phi(z)\lambda e^{-\lambda(z-S)}dz,$$

and

$$E(U) = c_F \int_0^S \int_0^{S-x} dG(h)dF(x) + \int_S^\infty \psi(z)\lambda e^{-\lambda(z-S)}dz,$$

and

$$p_F = \int_0^S \int_0^{S-x} dG(h)dF(x) + \int_S^\infty \left\{ \int_0^S \int_{S-x}^{z-x} dG(h)dF(x) + \int_S^z \int_0^{z-x} dG(h)dF(x) \right\} \lambda e^{-\lambda(z-S)}dz,$$

and further when $S = 0$ we get pure opportunistic inspection with

$$E(V) = \int_0^\infty \left\{ \int_0^z \int_0^{z-x} (x+h)dG(h)dF(x) + z \int_0^z \bar{G}(z-x)dF(x) + z\bar{F}(z) \right\} \lambda e^{-\lambda z}dz,$$

and

$$E(U) = \int_0^\infty \left\{ c_F \int_0^z \int_0^{z-x} dG(h)dF(x) + (c_P + c_O)\int_0^z \bar{G}(z-x)dF(x) + c_O\bar{F}(z) \right\} \lambda e^{-\lambda z}dz,$$

and

$$p_F = \int_0^\infty \int_0^z \int_0^{z-x} \lambda e^{-\lambda z} dG(h)dF(x)dz.$$

3.2. Non-exponential sojourns

The formulae above apply when G, the distribution of the delay-time, is not exponential. However, when F, the distribution of the time in the good state, is not exponential, a negative inspection (no defect found) is not a renewal point and the formulae do not apply. Instead, one has to allow for any number of negative inspections prior to any renewal event (positive inspection, failure). These negative inspections can be at opportunities or at an emergency inspection. We think this case is intractable. Nonetheless, some general insights could be gained via simulation, but this would be a different study.

However, a much simpler case is both tractable and informative. This is when both X and H are deterministic (fixed). We can think of this as the other end of the spectrum for sojourns. In reality, sojourns are neither purely random (exponential) nor deterministic, and so studying these two ends of the spectrum will be informative. Note, in this special case, inspections are not required to reveal the state of the system because this is always known. Instead, inspections are opportunities to replace the system before it fails.

Now if $X = x$ and $H = h$ fixed, then one might obviously set $S = T = x + h$ so that an emergency inspection is scheduled just-in-time. However, if $c_O < c_I$ one might prefer to take an opportunity to inspect before $x + h$ but certainly not before x. On the other hand, emergency inspection at $x + h$ would utilise the system fully. So, one can consider the cost-rate over the range $x \le S < T = x + h$. Note, we assume here that if inspection and failure occur at the same instant, inspection precedes failure. This implies that for $x \le S < T = x + h$ there are no failures ($p_F = 0$) and the MTBOF is not finite, and likewise for periodic inspection but not opportunistic inspection ($S = 0, T = \infty$).

The system is replaced at a positive inspection that occurs either at an opportunity or at T. In the former case, $V = z$ (the time of the first opportunity) and $U = c_O + c_P$, and in the latter $V = T = x + h$ and $U = c_I + c_P$. It follows that

$$E(U) = (c_O + c_P)\int_S^T \lambda e^{-\lambda(z-S)}dz + (c_I + c_P)e^{-\lambda(T-S)} = c_P + c_O + (c_I - c_O)e^{-\lambda(T-S)}, \tag{5}$$

and

$$E(V) = \int_S^T \lambda z e^{-\lambda(z-S)}dz + Te^{-\lambda(T-S)} = S + \left(1 - e^{-\lambda(T-S)}\right)\Big/\lambda. \tag{6}$$

Notice Eq. (5) is valid when $c_O < c_I$, otherwise one would not inspect opportunistically. Also, we can see that $E(V)\to T$ as $\lambda\to 0$ (no opportunities) and $E(V)\to S$ as $\lambda\to\infty$ (infinitely frequent opportunities).

For a periodic inspection policy with fixed sojourns, the optimum policy inspects just-in-time (at $\Delta = x + h$), so that the cost-rate is $(c_I + c_P)/(x + h)$.

For the pure opportunistic policy, similarly to Eqs. (5) and (6), we have that

$$E(U) = (c_O + c_P)\left(1 - e^{-\lambda h}\right) + c_F e^{-\lambda h} + \frac{x}{\mu_Z}c_O, \tag{7}$$

and

$$E(V) = x + \left(1 - e^{-\lambda h}\right)/\lambda.$$

In Eq. (7), the first term corresponds to a positive inspection at an opportunity, the second to failure, and the third is the expected cost of additional opportunistic inspections while the system is in state G.

3.3. Finite-horizon opportunistic inspection

We can conceptualize opportunistic inspection with a finite planning horizon. Let us suppose that the finite planning horizon extends from the decision point until the time at which the functionality of the system is no longer required. Then, for a purely opportunistic inspection policy, decision points naturally arise at opportunities and not elsewhere. In this case, suppose an opportunity arises (at time $t = 0$). The maintainer must decide whether to inspect the system at the opportunity or not. At this decision-point, let the time since last inspection or replacement be τ and let the time from now until the end of the horizon be L. Then, the maintainer should compare the expected total cost over $[0,L]$, C_L, under the two alternatives: inspect at the opportunity (Y); do not inspect at the opportunity (N).

If the decision is Y, then if the inspection is positive (defect found), the system is subsequently G and aged 0 (because it is replaced), or if the inspection is negative (no defect found), the system is G and aged at least τ. If the decision is N (ignore opportunity), then system is either G or D and aged at least τ. Regarding the costs under the two alternatives, $C_L|\mathrm{Y}$ and $C_L|\mathrm{N}$, when X is exponentially distributed, the decision point is a renewal point and calculation of the costs would proceed similarly to that in Scarf et al. [54]. However, when X is not exponentially distributed, $C_L|\mathrm{N}$ appears to be intractable. This is because future negative inspections are not renewals. We might posit that only a small number of future inspections might arise (because the horizon is finite and presumably short, otherwise the decision maker would use an infinite horizon) and we could condition on the outcomes of these inspections. This would allow us to calculate an approximation to $C_L|\mathrm{N}$, but this would be conditional on τ, the system age at the decision point. Then, to calculate $C_L|\mathrm{N}$ unconditionally, we would have to integrate over all possible histories (of the state of the system) for which the system age at the decision point is τ. This is intractable. Furthermore, a simulation approach to find $C_L|\mathrm{N}$ looks difficult.

Modifying this policy, by introducing the possibility of an emergency inspection, presents a further difficulty because every instant is then a decision point. That is, continuously, the maintainer must decide whether or not to perform an emergency inspection. There would be no notion of an age-limit for emergency inspection as in the infinite-horizon model because at every instant t, the best choice (among Y and N) depends on τ and L. There is also no notion of S, the age-threshold for using an opportunity, because using an opportunity for inspection or otherwise also depends on τ and L. Nonetheless, at each instant, the cost calculations would proceed as above.

In practice, if statutory regulation determines T, then the finite-horizon case is irrelevant for the modified policy because postponement of an emergency inspection to the point of functional obsolescence would not be permitted. If, on the other hand, T is chosen by the maintainer, then it would be useful to determine some heuristics for inspection planning as a system nears the point of functional obsolescence. However, this is beyond the scope of the current paper.

4. Results

We present the results in four parts. We begin with the description of the case study that motivates the model. We then present a limited set of results for this specific case. We then study the behaviour of the policy more generally, for a wider range of the parameter values, firstly for exponential sojourns in the good and defective states (random failure model) and then secondly for fixed sojourns (deterministic failure model). In all cases, opportunities are arising at random.

The purpose of studying these two restricted cases is to demonstrate behaviour across the spectrum of uncertainty about the lifetime of the system. Note, when sojourns are exponential, in the classic delay time model there exists a finite optimum inspection interval (subject to conditions on the unit costs), so the cost-rate in our policy is not indifferent to S or T. Further, when sojourns are fixed, an inspection is not revealing the state of the system (because this is known); instead, inspection is an opportunity to replace the system before it fails, and since inspections arise at random a missed opportunity could be costly.

4.1. Case study description

Groundwater is an important resource [1], and extraction from deep wells is increasing [52]. Deep wells require large pumps and pumps require maintenance [41], and the well-heads where pumps are located are often geographically remote [2]. Maintenance resources are often stretched and new, better management practices are sought [21]. The case study in this paper is about maintenance of such pumps for water extraction from deep wells in a large, remote, semi-arid region.

The location and exact details of the pumps are anonymised. The design-life of well-head equipment is typically 30 years. The most frequent failure mode is the loss of pumping capacity, typically due to pump failure as a result of build-up of solids in the intake. Other failure modes arise in components such as the pump motor, "turbine" assembly (Fig. 2), and control panel (not shown). A typical well is 300m deep, with a dynamic water level (height water must be pumped) of 60m and a submersible pump ($\sim$ 7000 USD) delivering 1500m^3 per day.

A large part of maintenance is reactive (corrective maintenance on failure) although inspection, to establish both the state of the equipment and the quality of the water output, is state-regulated. The period between planned inspections varies according to local regulations, although typically it is one or two years. Water quality can interfere with the ageing of the equipment, e.g. through nitrate contamination, and furthermore the greater is the age of the well-head, the greater is the chance of equipment being subject to severe conditions. There is also interdependence between wells, so that a new well may change the characteristics of water in a neighbouring well [13].

Since well heads are in remote locations, the transportation of personnel, special equipment, such as cranes and winches, and spare parts is costly. Therefore, it is desirable to inspect well-heads opportunistically. The purpose of the case study was to quantify the benefit of opportunistic inspection and to identify a target for the rate of occurrence of opportunities. The latter was important because the maintainer has some control over this rate: for example, a wider definition of neighbour and the routine transportation of a broader and larger set of spares would increase the rate. Conversely, for example, when the maintainer visits well-head A with only a spare pump for A and the spare is not used (negative inspection), then there is no opportunity to replace a pump at a neighbouring well-head B if the pumps at A and B are different. The maintainer can also increase the chance to do

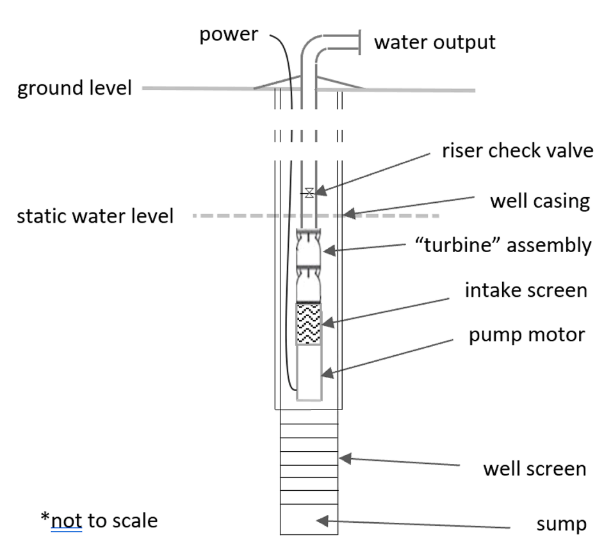

Fig. 2. Components in a typical well.

opportunistic maintenance by having more slack in the transportation and personnel schedule.

The purpose of inspection itself is to prevent interruption of water supply, to reduce electricity consumption (operation of degraded pumps increases costs), and to meet statutory requirements. Therefore, we sought to model opportunities to carry out inspections, as long as the time since the last inspection is not too large (T in our model) or the time since last inspection is not so small as to incur unnecessary costs from over-inspection (S in our model).

We obtained subjective estimates of the parameters in the model (Table 1) by consulting engineers who manage the maintenance of the pumps. Subjective estimation in reliability analysis has a long tradition, see for example Singpurwalla and Song [59] and Küçüker and Yet [32], so we consider such an approach to be justified. Also, it has been argued that maintenance decisions are robust to variability in estimates of model parameters [5,26]. Of the cost parameters, some were well known to the engineers, e.g. costs of spares and transportation, although these varied depending on location and equipment specification of the well-head. Lifetime parameters (of sojourns) were not well known. We simplified the analysis so that we study a typical pump at a typical location, in arbitrary unit of cost. The unit of time is one year. We use the cost of a replacement of a pump, including parts and labour, as the unit of cost. The cost of transportation is approximately half a unit; this is the cost of taking equipment and personnel to and from the well-head, and includes the cost of personnel (wages). We equate this cost with the cost of inspection since once at the well-head an inspection uses negligible resource. Failure incurs costs for all three (transport, wages, spares) plus an additional "penalty cost" [18] that is difficult to quantify.

Mean sojourns were difficult to quantify, so we try to present an analysis that accounts for this uncertainty through sensitivity analysis. For brevity, the results presented in Section 4.2 illustrate the case-study analysis rather than present comprehensive analyses of scenarios. A fuller sensitivity analysis follows in Section 4.3. for a more general context.

The inspection interval was state-regulated. Therefore, we fix T. Then the policy is a special case of the general $\{S,T\}$-policy presented in Section 3.

4.2. Case study results

Here we simply indicate what would be a good time threshold for using an opportunity (S) when the maximum interval between inspections (T) is regulated (fixed). Fig. 3 shows the cost-rate and MTBOF for different values of the cost of opportunistic inspection and the mean time between opportunities. The results here can be interpreted in various ways and our aim at this stage is to demonstrate how the analysis can be used for decision support. A fully discussion of the behaviour of the policy follows in the next two sub-sections.

In simple terms, one can see what is an optimal S and how the minimum cost-rate depends on the frequency and cost of opportunities. A less obvious interpretation is as follows. Suppose the maintainer seeks to increase the frequency of opportunities by carrying more spares and introducing more slack in the transportation schedule. Suppose halving the mean time between opportunities (from $\mu_z = 1$ to $\mu_Z = 0.5$) doubles the cost of opportunistic inspection (from $c_O = 0.1$ to $c_O = 0.2$) then one can see that the cost-rate does not increase if S is held at 0.2 but the MTBOF does. So, one can increase the reliability at no additional cost overall. Or, by optimising S in both cases, the cost-rate can be reduced and the reliability increased, but to a smaller extent. This is persuasive argument for influencing the behaviour of a maintainer who might naturally neglect opportunities.

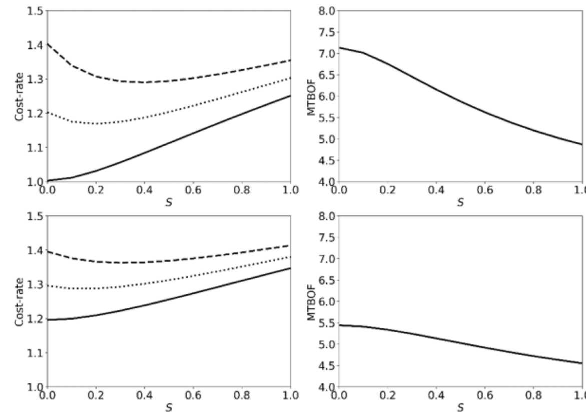

Fig. 3. For modified-opportunistic inspection, cost-rate (left) and mean time between operational failures (right) as a function of S for fixed $T = 2$. $\mu_Z = 0.5$ (top), $\mu_Z = 1$ (bottom); $c_O = 0$ (solid line), $c_O = 0.1$ (dotted line), and $c_O = 0.2$ (dashed line). Exponential sojourns. Other parameter values: $\mu_X = 2$, $\mu_H = 1$, $c_I = 0.5$, $c_P = 1$, $c_F = 5$.

4.3. Numerical study with exponential sojourns

For analysis of general properties of the policy, we use values that are to an extent motivated by the well-head case-study. Thus, we use $\mu_X = 2$ and $\mu_H = 1$ in an arbitrary unit of time, and consider a range of values of the rate of opportunities: relatively more frequent than defects ($\mu_Z = 0.5$), the same frequency as defects ($\mu_Z = 1$), and relatively less frequently than defects ($\mu_Z = 2$). For the unit costs, we set $c_P = 1$, and $c_I = 0.5$. We consider a range of values of c_F and of c_O.

Moderate values of c_O and μ_Z define the base case (Table 2). In Table 2 in particular, we compare the cost-rate of the modified-opportunistic policy with other policies that are special cases.

A number of interesting observations can be made. Firstly, when the cost of an opportunistic inspection is zero, S^* is zero, as expected. If opportunities are frequent (case 1), emergency inspections are not required ($T \to \infty$), but as the frequency of opportunities decreases it becomes optimal to do more expensive emergency inspections when required. Secondly, emergency inspections are performed when the age of the system is similar to its sojourn in the good state. Thirdly, the $\{S,T\}$-policy (modified-opportunistic inspection) is always cheaper than the comparator policies for these parameter values. This point is further demonstrated in Fig. 4 (right-hand plots). Note, the optimum comparator policies of course do not vary with μ_Z and c_O. Also, in the periodic

Table 1
Model parameters; costs in an arbitrary unit; time in years.

	value	range	comment
c_P	1	–	cost of replacing a pump (parts plus wages); well known; the unit of cost
c_I	0.5	–	cost of transportation; well known; includes personnel time (wages)
c_O	0.1	0 – 0.3	cost of an opportunity; transportation and labour; not well known
c_{pen}	3.5	3.5 – 8.5	penalty cost of a failure (e.g. damage or loss of water supply); not well known
c_F	5	5 – 10	$c_F = c_I + c_P + c_{pen}$
μ_X	2	–	mean time in good state; not well known
μ_H	1	0.5 – 2	mean time in defective state (delay time); not well known
μ_Z	1	0.5 – 2	mean time between opportunities; controllable to some extent
T	2	1 – 2	inspection interval; fixed by statutory regulation

Table 2
Optimal policy for exponential sojourns for various values of $\mu_Z = 1/\lambda$ (mean time between opportunities), and c_O (cost of inspection at an opportunity). Other parameter values: $\mu_X = 2$, $\mu_H = 1$, $c_I = 0.5$, $c_F = 5$, $c_P = 1$. μ_{OF} is the MTBOF. *base case.

			modified-opportunistic inspection			opportunistic inspection			Periodic inspection			replacement on failure	
case	μ_Z	c_O	S^*	T^*	cost-rate	μ_{OF}	cost-rate	μ_{OF}	Δ^*	cost-rate	μ_{OF}	cost-rate	μ_{OF}
1	0.5	0	0	∞	1.000	7.00	1.000	7.0	1.386	1.500	5.0	1.667	3.0
2	0.5	0.1	0.194	∞	1.167	6.65	1.200	7.0	1.386	1.500	5.0	1.667	3.0
3	0.5	0.2	0.388	∞	1.288	6.07	1.400	7.0	1.386	1.500	5.0	1.667	3.0
4	0.5	0.3	0.593	∞	1.382	5.53	1.600	7.0	1.386	1.500	5.0	1.667	3.0
5	1	0	0	2.171	1.195	5.35	1.200	5.0	1.386	1.500	5.0	1.667	3.0
6	1	0.1	0.150	2.126	1.287	5.31	1.300	5.0	1.386	1.500	5.0	1.667	3.0
*7	1	0.2	0.316	2.004	1.363	5.22	1.400	5.0	1.386	1.500	5.0	1.667	3.0
8	1	0.3	0.507	1.832	1.425	5.13	1.500	5.0	1.386	1.500	5.0	1.667	3.0
9	2	0	0	1.677	1.336	5.06	1.375	4.0	1.386	1.500	5.0	1.667	3.0
10	2	0.1	0.128	1.666	1.383	5.06	1.425	4.0	1.386	1.500	5.0	1.667	3.0
11	2	0.2	0.278	1.632	1.424	5.05	1.475	4.0	1.386	1.500	5.0	1.667	3.0
12	2	0.3	0.462	1.576	1.459	5.03	1.525	4.0	1.386	1.500	5.0	1.667	3.0

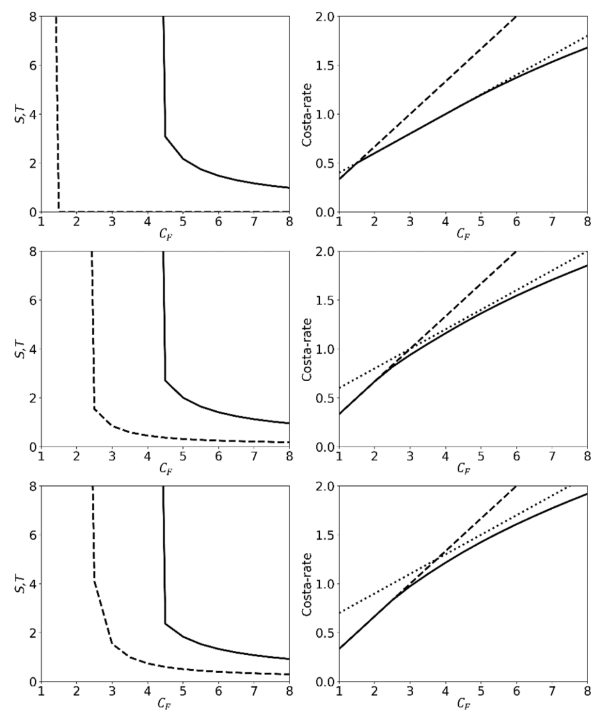

Fig. 4. Optimal policy as a function of cost of failure, c_F, for $c_O = 0$(top row), $c_O = 0.2$ (middle) and $c_O = 0.3$ (bottom). Left column: optimal values of decision variables for modified-opportunistic policy, S^* (dashed) and T^* (solid). Right column: optimum cost-rates for modified-opportunistic inspection (solid line), opportunistic inspection (dotted line), and replacement on failure (dashed line). Other parameter values as base case: $\mu_X = 2$, $\mu_H = 1$, $\mu_Z = 1$, $c_I = 0.5$, $c_P = 1$. Sojourns are exponentially distributed.

inspection policy, inspections are always costed as emergency inspections.

Fig. 4 also shows that there is a range of values of the cost of failure c_F for which the modified-opportunistic inspection is sensible. Broadly, if $c_F < 4$, then emergency inspection is not required, and if $c_F < 2$ inspection, opportunistic or emergency, is not required.

Fig. 5 is a similar policy comparison but now the mean time between opportunities varies. The more frequent the opportunities, the more desirable is the flexibility to miss opportunities (action of S) and the less is the need for emergency inspections (at T). The relative cost-saving of modified-opportunistic inspection over periodic inspection is practically significant—of the order of 20% for moderate values of the cost of failure and opportunity frequency (Fig. 6).

Fig. 7 provides a comprehensive policy comparison for a range of values of the parameters associated with opportunities (cost and rate).

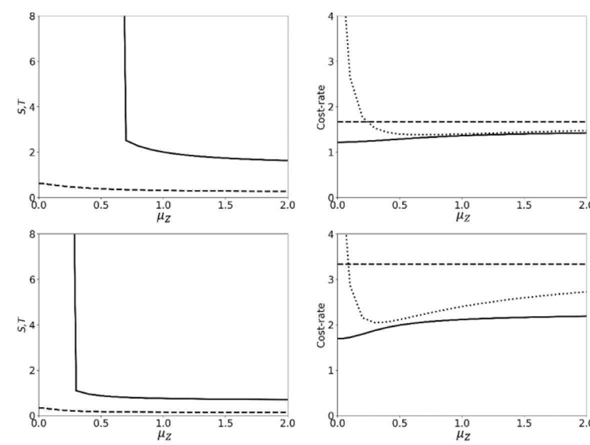

Fig. 5. Optimal policy as a function of mean time between opportunities, μ_Z, for $c_F = 5$ (top row) and $c_F = 10$ (bottom). Left column: optimal values of decision variables for modified-opportunistic policy, S^* (dashed) and T^* (solid). Right column: optimum cost-rates for modified-opportunistic inspection (solid line), opportunistic inspection (dotted line), and replacement on failure (dashed line). Other parameter values as base case: $\mu_X = 2$, $\mu_H = 1$, $c_O = 0.2$, $c_I = 0.5$, $c_P = 1$.

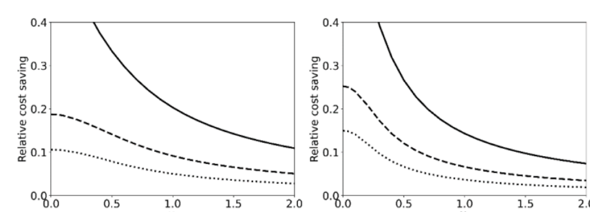

Fig. 6. Cost-saving of modified-opportunistic inspection over periodic inspection, $\{C^*(\mu_Z = \infty) - C^*(\mu_Z)\}/C^*(\mu_Z = \infty)$, as a function of mean time between opportunities, μ_Z. Note, $C^*(\mu_Z = \infty) = C^*(\Delta)$. $c_F = 5$ (left), $c_F = 10$ (right). $c_O = 0$ (solid line), $c_O = 0.2$ (dashed line), and $c_O = 0.3$ (dotted line). Other parameters as base case: $\mu_X = 2$, $\mu_H = 1$, $c_I = 0.5$, $c_P = 1$.

Modified-opportunistic inspection always has a lower cost than opportunistic inspection. Logically, this must be so. The practical significance of the cost divergence is the important factor, and we can see that there is little divergence when opportunities are relatively infrequent (large μ_Z). When the cost of opportunistic inspection is zero, the cost-rates of the two policies almost coincide (column 1). We can see that when the cost of opportunistic inspection is non-zero, opportunistic inspection can be costly if opportunities are frequent (small μ_Z). In this case, the modification (inspect only if the system age is at least S) is a sensible

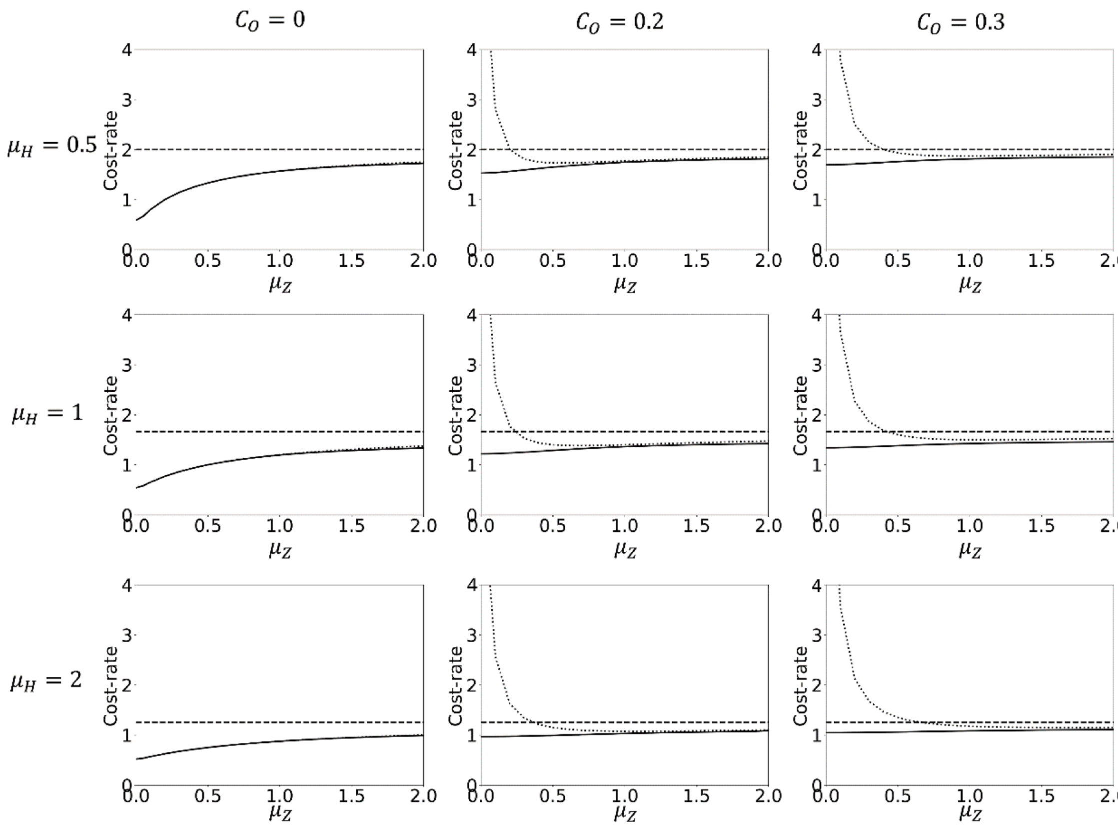

Fig. 7. Optimal cost-rate as a function of mean time between opportunities, μ_Z, for various values of the mean delay-time, μ_H, and the cost of inspection at an opportunity, c_O. Modified-opportunistic inspection (solid line), opportunistic inspection (dotted line), and replacement on failure (dashed line). Other parameter values as base case: $\mu_X = 2$, $c_I = 0.5$, $c_P = 1$, $c_F = 5$.

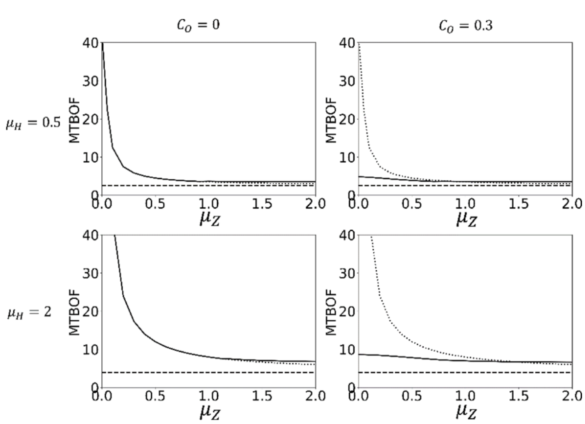

Fig. 8. MTBOF as a function of mean time between opportunities, μ_Z, for extreme cases of the mean delay-time, μ_H, and the cost of inspection at an opportunity, c_O. Modified-opportunistic inspection (solid line), opportunistic inspection (dotted line), and replacement on failure (dashed line). Other parameter values as base case: $\mu_X = 2$, $c_I = 0.5$, $c_P = 1$, $c_F = 5$.

action. Thus, some randomness in the inspection policy is sensible, within the limits that S and T provide, but following a purely random inspection policy could be very costly. On the other hand, a policy preferred on a cost basis would not be preferred on the basis of reliability (mean time between operational failures, MTBOF), see Fig. 8. Thus, when the cost of opportunistic inspection is non-zero, cost and reliability must be traded-off.

Table 3
Optimal policy for fixed sojourns ($x = 2$, $h = 1$) and fixed T ($T = x + h$) for various values of $\mu_Z = 1/\lambda$ (mean time between opportunities), and c_O (cost of inspection at an opportunity). Other parameter values: $c_I = 0.5$, $c_F = 5$, $c_P = 1$. *base case.

case	μ_Z	c_O	S^*	modified-opportunistic inspection cost-rate	periodic inspection cost-rate	opportunistic inspection cost-rate
1	0.5	0	2.390	0.418	0.500	0.634
2	0.5	0.1	2.484	0.443	0.500	0.834
3	0.5	0.2	2.585	0.464	0.500	1.034
4	0.5	0.3	2.698	0.482	0.500	1.234
5	1	0	2.247	0.445	0.500	0.939
6	1	0.1	2.377	0.463	0.500	1.039
*7	1	0.2	2.513	0.478	0.500	1.139
8	1	0.3	2.657	0.489	0.500	1.239
9	2	0	2.142	0.467	0.500	1.229
10	2	0.1	2.301	0.478	0.500	1.279
11	2	0.2	2.463	0.487	0.500	1.329
12	2	0.3	2.631	0.494	0.500	1.379

4.4. Numerical study with fixed sojourns

For this study, we consider the same cases (Table 1). For the modified-opportunistic inspection policy T is chosen so that emergency inspection is "just in time" ($T = x + h$) and the policy has a single decision variable S. For the comparator policy, period inspection, inspections are also scheduled "just in time" ($\Delta = x + h$). We only study the cost-rate as the MTBOF is not finite for both modified-opportunistic inspection and periodic inspection.

Broadly, we observe (Table 3) for the cases studied that the $\{S,T\}$-policy (modified-opportunistic inspection) has a much lower cost than

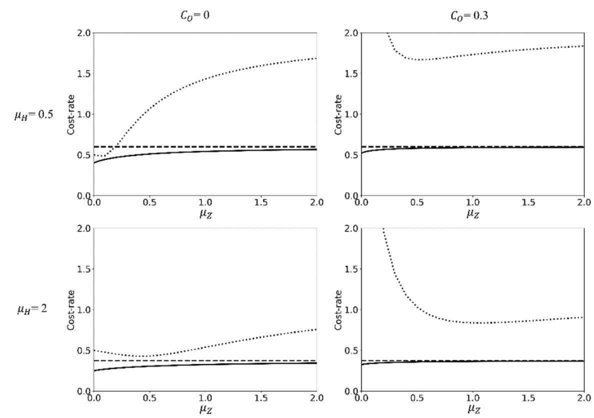

Fig. 9. Optimal cost-rate as a function of mean time between opportunities, μ_Z, for extreme cases of μ_H and c_O. Modified-opportunistic inspection (solid line), opportunistic inspection (dotted line), and periodic inspection (dashed line). Other parameter values as base case: $\mu_X = 2$, $c_I = 0.5$, $c_P = 1$, $c_F = 5$.

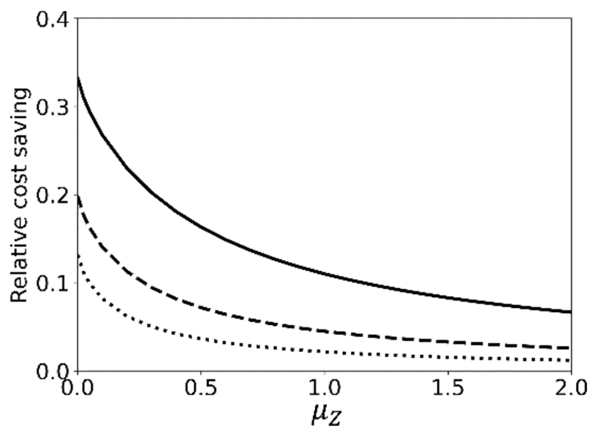

Fig. 10. Cost-saving of modified-opportunistic inspection over periodic inspection as a function of mean time between opportunities, μ_Z. $c_O = 0$ (solid line), $c_O = 0.2$ (dashed line), and $c_O = 0.3$ (dotted line). Other parameters as base case: $\mu_X = 2$, $\mu_H = 1$, $c_I = 0.5$, $c_P = 1$, $c_F = 5$.

opportunistic inspection. The cost difference varies with the parameter values (Fig. 9). Thus, we can tentatively conclude that the more predictable is the lifetime of the system the more beneficial it is to control the times between inspection. This conclusion is reinforced when we compare the modified policy with periodic inspection (Fig. 10), using the same comparison when lifetimes are uncertain (Fig. 6) as a point of reference. That is, modified-opportunistic is preferable to periodic inspection to a greater extent when lifetimes are uncertain than when they are not.

5. Discussion

We develop a new model for planning inspections of a critical, non-repairable system in which opportunities for inspection arise at random. These opportunities are used in a flexible way. If they too frequent they are filtered. If they are too infrequent, planned inspection is triggered. The model generalises the classic delay-time model of inspection maintenance and a pure opportunistic inspection policy.

The policy is motivated by a case study of inspection of pumps for groundwater extraction. These systems are geographically remote. Transportation cost is high, and a visit to one asset is an opportunity, if resources permit, to visit other neighbouring assets. The model is simple to implement and therefore has the potential to provide cost-savings for maintainers of such systems. The model has potential for application to other fleets of systems (e.g. power generating and telecommunication systems) in which inspection is opportunistic because production or missions, say, have priority over maintenance.

For the parameter values we study, the proposed policy (the $\{S,T\}$-policy) has significant cost-saving potential relative to both the pure opportunistic and the periodic inspection policies. Furthermore, for the maintainer of the well-heads in the case-study, the analysis provides a quantified, rational basis for changing policy regarding opportunistic inspections, transportation of spares for neighbouring well-heads, and the introduction of more slack into the transportation schedule. With the latter, the notion here is that if visits were longer, fewer would be needed while still meeting regulatory requirements. Furthermore, an upper limit for the time between inspections is generally a good thing. On the other hand, if operational reliability is the priority of the system maintainer, then there is little to be gained from ignoring early opportunities.

The expressions for the cost-rate and mean time between operational failures that we develop are not completely general. This is a limitation of our study. Nonetheless, we consider best-case (known lifetime) and worst-case (exponential lifetime) scenarios so that our conclusions are robust.

A further limitation is that inspections are solely age-based. The model does not account for the operational history of the system. Such an approach would be relevant when a system operates in a dynamic environment [36,70]. While operational history (relating to e.g. shocks, heterogeneous usage, etc.), if available, might be combined, using a suitable method of information fusion (e.g. [47]), to specify an "effective age" measure, such a measure would distort the time scale at which opportunities arise. Then, opportunities might be modeled with a Poisson process that is homogeneous on the age scale and non-homogeneous on the effective-age scale, by using the history of the system to modify the intensity dynamically. Then, $\{S,T\}$ would be updated as the history of the system develops. This would make an interesting study, although we suspect a simulation approach would be required.

We study a one-component system. There is scope to extend the model to multi-component systems. This would add an additional dimension to the decision-problem regarding which components to inspect at an opportunity. This would be interesting to develop in future work. Simulation could be used to study the case of a non-exponential sojourn in the good state. The model might be extended to handle inspection classification errors (false negatives and false positives), minimal repairs, and postponement of replacement in the event that an inspection is positive but no resources (time, spares) are immediately available for replacement. There is also scope to develop a similar model for inspection of a stand-by (protection) system with two states (good, failed) and failure only revealed on-demand or at inspection. Finally, it would be interesting to study a finite-horizon version of the model and to develop heuristics for inspection planning when a system is close to functionally obsolete.

Data statement

The data presented in this article were calculated using code written in python. This code calculates the cost-rate and the mean time between operational failures (MTBOF) using the expressions presented in the paper. A demonstrator of the code can be accessed here: https://share.streamlit.io/randomprototype/st_policy/main/STPolicy.py. With this code, the reader can verify the results presented and explore new cases.

CRediT authorship contribution statement

Naif M. Alotaibi: Funding acquisition, Writing – original draft. **Philip Scarf:** Conceptualization, Project administration, Writing – review & editing. **Cristiano A.V. Cavalcante:** Formal analysis, Investigation, Methodology, Writing – original draft. **Rodrigo S. Lopes:** Formal analysis, Investigation. **André Luiz de Oliveira e Silva:** Data curation, Investigation. **Augusto J.S. Rodrigues:** Formal analysis, Methodology, Software. **Salem A. Alyami:** Formal analysis, Validation, Investigation.

Declaration of Competing Interest

As corresponding author I can confirm there has been no conflict of interest in preparation of the manuscript "Modified-opportunistic inspection and the case of remote, groundwater well-heads".

Data availability

A link to code to generate data is provided

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References

[1] Algaydi BA, Subyani AM, Hamza MH. Investigation of groundwater potential zones in hard rock terrain, Wadi Na'man, Saudi Arabia. Groundwater 2019;57:940–50.
[2] Aliyu M, Hassan G, Said SA, Siddiqui MU, Alawami AT, Elamin IM. A review of solar-powered water pumping systems. Renew Sustain Energy Rev 2018;87:61–76.
[3] Alotaibi NM, Cavalcante CAV, Lopes RS, Scarf PA. Preventive replacement with defaulting. IMA J Manag Math 2020;31:491–504.
[4] Ascher H, Feingold H. Repairable systems reliability. Marcel Dekker; 1984.
[5] Baker RD, Scarf PA. Can models fitted to small data samples lead to maintenance policies with near-optimum cost? IMA J Math Appl Bus Ind 1995;6:3–12.
[6] Bakhtiary A, Mohammadzadeh S, Zakeri JA, Kasraei A. Multiobjective optimization of ballasted track maintenance scheduling. J Transp Eng Part A 2022;148(1):04021099.
[7] Berg M, Epstein B. A modified block replacement policy. Nav Res Logist 1976;23:15–24.
[8] Berrade MD, Cavalcante CAV, Scarf PA. Modelling imperfect inspection over a finite horizon. Reliab Eng Syst Saf 2013;111:18–29.
[9] Berrade MD, Scarf PA, Cavalcante CAV. A study of postponed replacement in a delay time model. Reliab Eng Syst Saf 2017;168:70–9.
[10] Berrade MD, Scarf PA, Cavalcante CA. Conditional inspection and maintenance of a system with two interacting components. Eur J Oper Res 2018;268:533–44.
[11] Uit Het Broek MAJ, Teunter RH, de Jonge B, Veldman J. Joint condition-based maintenance and load-sharing optimization for two-unit systems with economic dependency. Eur J Oper Res 2021;295:1119–31.
[12] Butchers J, Williamson S, Booker J, Tran A, Karki PB, Gautam B. Understanding sustainable operation of micro-hydropower: a field study in Nepal. Energy Sustain Dev 2020;57:12–21.
[13] Cabral JJSP, Santos SM, Filho IDSP. Bombeamento intensivo de agua subterrânea e riscos de subsidência do solo. Rev Bras Recur Hídr 2006;11:147–57.
[14] Cai X, Shen J, Shen L. Reliability evaluation and maintenance planning for systems with load-sharing auxiliary components. IEEE Trans Reliab 2022. https://doi.org/10.1109/TR.2022.3215792 (in press).
[15] Cavalcante CAV, Lopes RS, Scarf PA. Inspection and replacement policy with a fixed periodic schedule. Reliab Eng Syst Saf 2021;208:107402.
[16] Chaoub A, Giordani M, Lall B, Bhatia V, Kliks A, Mendes L, Rabie K, Saarnisaari H, Singhal A, Zhang N, Dixit S, Zorzi M. 6G for bridging the digital divide: wireless connectivity to remote areas. IEEE Wirel Commun 2022;29:160–8.
[17] Christer A. Developments in delay time analysis for modelling plant maintenance. J Oper Res Soc 1999;50:1120–37.
[18] Christer AH, Scarf PA. A robust replacement model with applications to medical equipment. J Oper Res Soc 1994;45:261–75.
[19] Christer AH, Wang W. A delay-time-based maintenance model of a multi-component system. IMA J Manage Math 1995;6:205–22.
[20] De Jonge B, Scarf PA. A review on maintenance optimization. Eur J Oper Res 2020;285:805–24.
[21] Pereira LS, Morais DC. Multicriteria decision model to establish maintenance priorities for wells in a groundwater system. Water Resour Manae 2020;34:377–92.
[22] Dekker R, Plasmeijer RP. Multi-parameter maintenance optimisation via the marginal cost approach. J Oper Res Soc 2001;52:188–97.
[23] Dos Santos Pereira GM, Weigert GR, Macedo PL, Alves e Silva K, Salas CSS, Maurício de Matos Gonçalves A, Selvo do Nascimento HH. Quasi-dynamic operation and maintenance plan for photovoltaic systems in remote areas: the framework of Pantanal-MS. Renew Energy 2022;181:404–16.
[24] Drent C, Olde Keizer M, van Houtum GJ. Dynamic dispatching and repositioning policies for fast-response service networks. Eur J Oper Res 2020;285:583–98.
[25] Elodie R, Berenguer C, Bouvard K, Tedie H, Lesobre R. Joint dynamic scheduling of missions and maintenance for a commercial heavy vehicle: value of on-line information. IFAC-PapersOnLine 2018;51(24):837–42.
[26] Fouladirad M, Paroissin C, Grall A. Sensitivity of optimal replacement policies to lifetime parameter estimates. Eur J Oper Res 2018;266:963–75.
[27] Garambaki AHS, Thaduri A, Seneviratne A, Kumar U. Opportunistic inspection planning for railway e-maintenance. IFAC PapersOnLine 2016;49(28):197–202.
[28] Hajipour Y, Taghipour S. Non-periodic inspection optimization of multi-component and k-out-of-m systems. Reliab Eng Syst Saf 2016;156:228–43.
[29] Jayachandran M, Ranjith Kumar Gatla RK, Rao KP, Rao GS, Mohammed S, Milyani AH, Azhari AA, Kalaiarasy C, Geetha S. Challenges in achieving sustainable development goal 7: affordable and clean energy in light of nascent technologies. Sustain Energy Technol Assess 2022;53:102692.
[30] Jiang R. An efficient modified-periodic inspection scheme for a one-component system. IMA J Manage Math 2017;28:373–86.
[31] Jin P, Chen Z, Li R, Li Y, Cai G. Opportunistic preventive maintenance scheduling for multi-unit reusable rocket engine system based on the variable maintenance task window method. Aerosp Sci Technol 2022;121:107346.
[32] Küçüker FU, Yet B. Reliability prediction for aircraft fleet operators: a Bayesian network model that combines supplier estimates, maintenance data and expert judgement. J Oper Res Soc 2022. https://doi.org/10.1080/01605682.2022.2129486 *(in press)*.
[33] Levitin G, Xing L, Huang HZ. Cost effective scheduling of imperfect inspections in systems with hidden failures and rescue possibility. Appl Math Model 2019;68:662–74.
[34] Liu G, Chen S, Jin H, Liu S. Optimum opportunistic maintenance schedule incorporating delay time theory with imperfect maintenance. Reliab Eng Syst Saf 2021;213:107688.
[35] Liu Q, Li Z, Xia T, Hsieh M, Li J. Integrated structural dependence and stochastic dependence for opportunistic maintenance of wind turbines by considering carbon emissions. Energies 2022;15(2):625.
[36] Luo C, Shen L, Xu A. Modelling and estimation of system reliability under dynamic operating environments and lifetime ordering constraints. Reliab Eng Syst Saf 2022;218:108136.
[37] Ma Y, Zhang W, Branke J. Multi-objective optimisation of multifaceted maintenance strategies for wind farms. J Oper Res Soc 2022. https://doi.org/10.1080/01605682.2022.2085066.
[38] Manco P, Rinaldi M, Caterino M, Fera M, Macchiaroli R. Maintenance management for geographically distributed assets: a criticality-based approach. Reliab Eng Syst Saf 2022;218:108148.
[39] McCall JJ. Operating characteristics of opportunistic replacement and inspection policies. Manag Sci 1963;10:85–97.
[40] Mena R, Viveros P, Zio E, Campos S. An optimization framework for opportunistic planning of preventive maintenance activities. Reliab Eng Syst Saf 2021;215:107801.
[41] Mora M, Vera J, Rocamora C, Abadia R. Energy efficiency and maintenance costs of pumping systems for groundwater extraction. Water Resour Manag 2013;27:4395–408.
[42] Li M, Jiang X, Negenborn RR. Opportunistic maintenance for offshore wind farms with multiple-component age-based preventive dispatch. Ocean Eng 2021;231:109062.
[43] Nakagawa T. Random maintenance policies. London: Springer; 2014.
[44] Nguyen HSH, Do P, Vu HC, Iung B. Dynamic maintenance grouping and routing for geographically dispersed production systems. Reliab Eng Syst Saf 2019;185:392–404.
[45] Oakley JL, Wilson KJ, Philipson P. A condition-based maintenance policy for continuously monitored multi-component systems with economic and stochastic dependence. Reliab Eng Syst Saf 2022;222:108321.
[46] Phan DT, Zhu Y. Multi-stage optimization for periodic inspection planning of geo-distributed infrastructure systems. Eur J Oper Res 2015;245:797–804.
[47] Qin J. Preposterior analysis considering uncertainties and dependencies of information relevant to structural performance. ASCE-ASME J Risk Uncertain Eng Syst Part A Civ Eng 2022;8:04021085.
[48] Qiu Q, Cui L. Reliability modelling based on dependent two-stage virtual age processes. J Syst Eng Electron 2021;32:711–21.
[49] Qiu Q, Cui L, Kong D. Availability and maintenance modeling for a two-component system with dependent failures over a finite time horizon. Proc Inst Mech Eng Part O J Risk Reliab 2019;233:200–10.
[50] Ruiz-Castro JE, Dawabsha M. A multi-state warm standby system with preventive maintenance, loss of units and an indeterminate multiple number of repairpersons. Comput Ind Eng 2020;142:106348.
[51] Sanjel N, Baral B. Modelling and analysis of decentralized energy systems with photovoltaic, micro-hydro, battery and diesel technology for remote areas of Nepal. Clean Energy 2021;5:690–703.
[52] Sayre SS, Taraz V. Groundwater depletion in India: social losses from costly well deepening. J Environ Econ Manage 2019;93:85–100.
[53] Scarf PA, Cavalcante CAV. Hybrid block replacement and inspection policies for a multi-component system with heterogeneous component lives. Eur J Oper Res 2010;206:384–94.

[54] Scarf PA, Cavalcante CAV, Lopes RS. Delay-time modelling of a critical system subject to random inspections. Eur J Oper Res 2019;278:772–82.
[55] Scarf P, Dwight R, Al-Musrati A. On reliability criteria and the implied cost of failure for a maintained comp-onent. Reliab Eng Syst Saf 2005;89:199–207.
[56] Seyedhosseini SM, Moakedi H, Shahanaghi K. Imperfect inspection optimization for a two-component system subject to hidden and two-stage revealed failures over a finite time horizon. Reliab Eng Syst Saf 2018;174:141–56.
[57] Shen J, Zhang Y, Ma Y, Lin C. A novel opportunistic maintenance strategy for systems with dependent main and auxiliary components. IMA J Manage Math 2021;32:69–90.
[58] Shen Y, Zhang X, Shi L. Joint optimization of production and maintenance for a serial–parallel hybrid two-stage production system. Reliab Eng Syst Saf 2022;226:108600.
[59] Singpurwalla ND, Song MS. Reliability analysis using Weibull lifetime data and expert opinion. IEEE Trans Reliab 1988;37:340–7.
[60] Sinisterra WQ, Cavalcante CAV. An integrated model of production scheduling and inspection planning for resumable jobs. Int J Prod Econ 2020;227:107668.
[61] Taghipour S, Banjevic D. Optimum inspection interval for a system under periodic and opportunistic inspections. IIE Trans 2012;44:932–48.
[62] *United Nations* (2019) Sustainable development goal 7: ensure access to affordable, reliable, sustainable and modern energy for all. https://sdgs.un.org/goals/goal7 (accessed 11/10/2022).
[63] Van Oosterom CD, Elwany AH, Çelebi D, van Houtum GJ. Optimal policies for a delay time model with postponed replacement. Eur J Oper Res 2014;232:186–97.
[64] Viveros P, Pantoja NC, Kristjanpoller F, Mena R. reportability tool design: assessing grouping schemes for strategic decision making in maintenance planning from a stochastic perspective. Appl Sci 2022;12(11):5386.
[65] Vu HC, Do P, Fouladirad M, Grall A. Dynamic opportunistic maintenance planning for multi-component redundant systems with various types of opportunities. Reliab Eng Syst Saf 2020;198:106854.
[66] Witteman M, Deng Q, Santos BF. A bin packing approach to solve the aircraft maintenance task allocation problem. Eur J Oper Res 2021;294:365–76.
[67] Wang J, Miao Y, Yi Y, Huang D. An imperfect age-based and condition-based opportunistic maintenance model for a two-unit series system. Comput Ind Eng 2021;160:107583.
[68] Wu T, Yang L, Ma X, Zhang Z, Zhao Y. Dynamic maintenance strategy with iteratively updated group information. Reliab Eng Syst Saf 2020;197:106820.
[69] Xiao H, Yan Y, Kou G, Wu S. Optimal inspection policy for a single-unit system considering two failure modes and production wait time. IEEE Trans Reliab 2023;72:395–407.
[70] Xu A, Zhou S, Tang Y. A unified model for system reliability evaluation under dynamic operating conditions. IEEE Trans Reliab 2021;70:65–72.
[71] Yang L, Ma X, Zhai Q, Zhao Y. A delay time model for a mission-based system subject to periodic and random inspection and postponed replacement. Reliab Eng Syst Saf 2016;150:96–104.
[72] Yang L, Li G, Zhang Z, Ma X, Zhao Y. Operations and maintenance optimization of wind turbines integrating wind and aging information. IEEE Trans Sustain Energy 2021;12:211–21.
[73] Yang L, Zhao Y, Ma X, Qiu Q. An optimal inspection and replacement policy for a two-unit system. Proc Inst Mech Eng Part O J Risk Reliab 2018;232:766–76.
[74] Yildrim M, Gebraeel N, Sun X. Integrated predictive analytics and optimization for opportunistic maintenance and operations in wind farms. IEEE Trans Power Syst 2017;32:4319–28.
[75] Yue D, Gao Q. A geometric process model for deteriorating operating system with periodic and random inspections. Qual Technol Quant Manag 2017;14:269–79.
[76] Zhang J. Reliability evaluation and opportunistic maintenance policy based on a novel delay time model. Qual Reliab Eng Int 2019;35:978–94.
[77] Zhang Z, Yang L. State-based opportunistic maintenance with multifunctional maintenance windows. IEEE Trans Reliab 2021;70:1481–94.
[78] Zhang J, Zhao X, Song Y, Qiu Q. Joint optimization of condition-based maintenance and spares inventory for a series–parallel system with two failure modes. Comput Ind Eng 2022;168:108094.
[79] Zhao L, Chen M, Zhou D. General (N, T, τ) opportunistic maintenance for multicomponent systems with evident and hidden failures. IEEE Trans Reliab 2016;65:1298–313.
[80] Zhao X, Nakagawa T. Optimal periodic and random inspections with first, last and overtime policies. Int J Syst Sci 2015;46:1648–60.
[81] Zhao X, Zheng Q, Jia X, Qian C, Mizutani S, Chen M. Periodic and sequential inspection policies with mission failure probabilities. Qual Reliab Eng Int 2022;38:1539–57.
[82] Zheng R, Zhou Y. A dynamic inspection and replacement policy for a two-unit production system subject to interdependence. Appl Math Model 2022;103:221–37.