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Optimizing shock-based replacement and inspection policy in standby systems exposed to multi-source shocks

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Abstract

The standby sparing technique is widely applied in diverse industries to reduce system downtime. This paper models a new class of standby sparing systems operating in a random environment, modeled by two independent shock processes from different sources affecting distinct sets of components during the mission. The operating and standby components may be replaced or refilled based on their status and the number of shocks experienced, which are observable through periodic inspections. The shock-based inspection and component replacement/addition policy (SBP) is defined in a parametric form, and an optimization problem is formulated to find the SBP that minimizes the expected cost of task accomplishment (ECTA). The objective function of the formulated optimization problem is evaluated using a fast numerical procedure based on system state transitions. The optimal SBP is determined using brute force enumeration over the possible values of integer policy parameters. A detailed case study using a sensor system is performed to examine the effects of key cost and shock parameters on the ECTA and optimization results, offering managerial insights. A comparison between the proposed SBP and an existing time-based policy demonstrates the advantage of the proposed policy in reducing overall ECTA.

Keywords: standby system, replacement, component refill, periodic inspection, multi-source shock, mission cost

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Acronyms

(*Note: the same acronym used for singular and plural*)

cdf	cumulative distribution function
CRP	component replacement policy
CMS	common shock
ECTA	expected cost of task accomplishment
HPP	homogeneous Poisson process
OPM	operation mode
OPS	operational shock
pmf	probability mass function
SBP	shock-based inspection and component replacement/addition policy
STM	standby mode
TBP	time-based inspection and component replacement/addition policy

Notation

T	total required mission time
τ	duration of the inter-inspection interval
N	number of inspections carried out during the mission
m_n,k_n	number of shocks impacting operating, standby components immediately after inspection n
h_n	number of components available in the STM immediately after inspection n
m_n,k_n,h_n	system state immediately after inspection n
$p_n(m, k, h)$	probability that the system is in state m, k, h following the nth inspection action
M	number of shocks impacting operating component triggering its replacement
H,K	number of shocks impacting operating, standby components triggering the standby component replacement
Λ, λ	arrival rate of CMS, OPS process
$P(t,i,\rho)$	probability of i shocks occurring in $[0, t)$ given the shock rate of ρ
$v(i)$	conditional probability of a component surviving the ith shock given that it has survived all previous shocks
$V(n)$	probability that a component survives n shocks
Ω	survival probability of a component upon the first shock
ω	shock resistance deterioration parameter
Z	maximum number of shocks that can be survived by a component with a non-negligible probability
$U(k\|z)$	conditional probability of a component surviving $(z+k)$ shocks conditioned on having survived z shocks
$F(k\|z)$	conditional probability that a component fails in the event of the $k+z$th shock conditioned on it having survived z shocks
$\pi(t, i, j,)\mathrm{d}t$	probability that j CMS and i OPS occur during time t and the last of these shocks occurs in $[t,t+\mathrm{d}t)$
A_S, A_O	cost of placing a new component into STM, OPM (B_S=A_S, B_O=A_O for all inspections except the dummy $(N+1)$th one)
A_{SO}	cost of placing a component in STM into OPM
C_I	cost of performing a single inspection ($B_I = C_I$ for all inspections except the dummy $(N+1)$th one).
C_F	cost of a component failure
c_D	per unit time cost incurred by system downtime
c_O, c_S	per unit time costs incurred by keeping a component in the OPM, STM
E_n	ECTA accumulated between the $(n-1)$th inspection and the nth inspection
E_a	expected activation cost or cost incurred by placing a component in STM, OPM, or STM-OPM transfer
E_d	expected cost of downtime
E_i	total cost of inspections
E_o	expected operation cost
E_f	expected cost incurred by failures of system components
E	total ECTA ($E = E_a+E_d+E_i+E_o+E_f$)
μ_i	occurrence probability of case i of state transition
w_i, d_i	conditional expected cost of operation, system downtime between inspections for case i of state transition
$1(x)$	logical function (indicator) returning 1 if x is TRUE, and 0 if x is FALSE

1. Introduction

The standby sparing technique is commonly adopted in diverse industries to reduce system downtime [1–3]. For example, backup generators are usually utilized in power systems [4], redundant virtual machines are often created for critical services in cloud computing [5], backup servers are typical in data centers [6], and extra sensors are typically deployed in critical applications like surveillance [7]. In general, a standby sparing system contains one or multiple components that are online and operating and additional components that wait in the STM. In the event of an online component malfunctioning, an available standby component is activated to take over the system function, avoiding or minimizing the system downtime [8, 9].

Modeling and optimizing standby systems have remained a hot research topic in the reliability community for several decades. Various methods have been developed for evaluating the reliability of standby systems. Examples include, but are not limited to, combinatorial methods based on models like universal generating functions [10] and different forms of decision diagrams (binary [11], multi-valued [12]), and state space models based on Markov processes [13] or Petri nets [14]. Other examples include the approximate models based on central limit theorem [15], Monte Carlo simulations [16], and event transition-based algorithms [17]. Some extended behaviors or characteristics have also been addressed for standby systems. For example, standby systems performing diverse tasks in multiple, consecutive phases with different environmental conditions were modeled in [18, 19]. Standby systems undergoing inspections for detecting component statuses were considered in [20, 21]. Standby systems coupled with the checkpointing technique to reduce

system recovery time upon failures were studied in [22]. Standby systems subject to condition-based mission aborting to survive asset were investigated in [23, 24]. Standby systems with preventive maintenance for online components were modeled in [25, 26]. Other features addressed include different levels of loading characterized by distinct component performance and failure time distributions [27], imperfect fault recovery mechanism incurring extensive damage [28, 29], periodic and nonperiodic switching mechanisms for alternating standby and online components [30, 31], priority in use for system components [32, 33], sudden failures and degradation of spare units [34], resource constraints [35], and random external shocks [36–39]. In the models mentioned above, a standby component is assumed to stay in the same mode before being activated to take over system operation. Several recent models considered STM transfers based on a pre-defined schedule [40–43] or triggered by certain condition [44–46]; through transferring a standby component from lower to higher readiness level before being activated, the system reliability can be improved. Another recent model in [47] considered an inspected standby system operating in random shock environments and undergoing periodic inspections to determine refilling for operating and standby components in addition to the STM to operating mode transfer upon the operating component failure. In the model of [47], it was assumed that the number of shocks experienced by the operating and standby components before inspections are not observable and component refilling is determined based on the component statuses and on the number of inspections experienced (or time elapsed). Such a time-based policy may not be effective as it fails to consider the shock status.

In many real systems, the shocks affecting system components can be detected and counted. For example, in data processing systems, the shocks (e.g. hacker attacks) are usually indicated by software analyzing the data traffic and processor loading anomalies [48]. In aerial vehicles, the shocks (e.g. electromagnetic impulses) are detected by electronic equipment [49]. In sensor networks, the shocks (e.g. extreme weather impacts) are detected by simple temperature, humidity and wind sensors [50]. Using the information about the shocks can improve the inspection and replacement policy and reduce the mission cost [51].

This paper contributes by modeling standby systems subject to an SBP. Unlike [47], we assume that the shocks can be detected and counted and analyze the effect of shock counting on the optimization of system metrics. Under the suggested system model, the following specific contributions are made:

(1) Consider simultaneously two types of shocks, including OPSs deteriorating only the operating component and CMSs affecting both operating and standby components. The shocks are observable during periodic inspections and the information about the number of shocks experienced is utilized for determining component replacement/addition.
(2) Represent the SBP in a parametric form and suggest a new numerical procedure of evaluating the ECTA for arbitrary SBP.
(3) Formulate and solve the SBP optimization problem to minimize the ECTA.
(4) Conduct a case study of a standby sensor system to show that the SBP using information about the shocks allows achieving ECTA reduction, as compared to the time-based policy of [47].
(5) Conduct sensitivity analysis of key cost parameters and shock rates using the case study, revealing their impacts on the ECTA and optimal SBP obtained.

The remainder of the paper is structured as follows: In section 2, we present the standby system as well as SBP and formulate the ECTA optimization problem. In section 3, the ECTA is derived and the numerical procedure for evaluating the ECTA is presented. In section 4, we conduct the sensor system case study. In section 5, we present conclusions and outline research issues to solve in the future.

2. System model and optimization problem formulation

The system must operate during mission time T to accomplish the mission task. At the start of the mission, one component is put in the OPM and only one system component can operate at any time.

To reduce system downtime, extra components are put into an STM during the mission. Only one component can stay in the STM at any time. In the event of the operating component failing, a standby component (if available) immediately takes over the mission task through the STM-OPM transfer.

The system is exposed to multi-source shocks characterized by different, independent HPP. Specifically, the operating component is impacted by an HPP of OPS; operating and standby components are both impacted by another HPP of CMS. The OPS HPP and CMS HPP have arrival rates λ and Λ, respectively. The shock resistance of the components deteriorates as the number of shocks increases, resulting in a higher probability of component failure.

2.1. The inspection and replacement policy

The system is inspected periodically during the execution of the mission task. N inspections can be carried out with the inter-inspection interval being $\tau = T/(N+1)$ time units. In the first stage of the inspection, a decision about adding/replacing the operating component is made. If the inspection reveals that no component operates, a new component is put into the OPM. If the inspection reveals that the operating component has experienced $m \geqslant M$ shocks, this component is replaced with a new one. Then the decision about adding/replacing the standby component is made. If the component residing in the OPM has experienced $m \geqslant H$ ($H \leqslant M$) shocks and no components reside in the STM, a new component is put to the STM to back up the operating component. If the inspection reveals that the operating component has experienced at least H shocks and the component residing in STM has experienced $k \geqslant K$

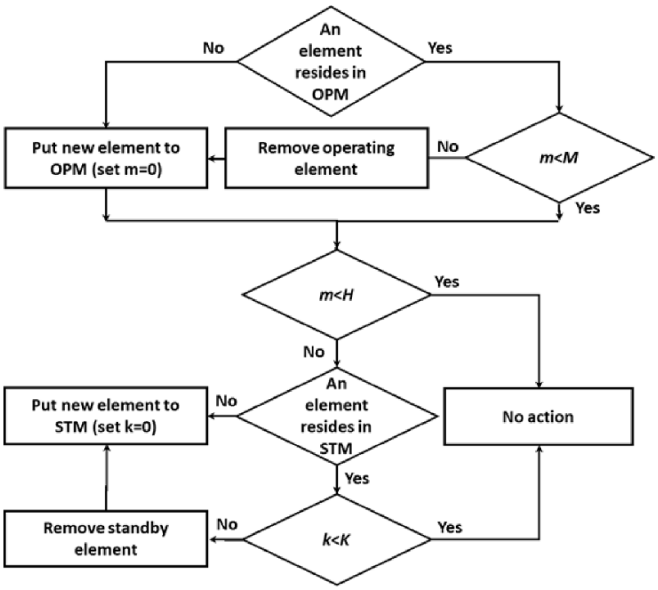


Figure 1. Components replacement policy (m and k are the numbers of shocks experienced before the inspection by operating and standby components, respectively).

shocks, the standby component is substituted with a new one. The CRP is illustrated in figure 1.

The same rule is applied at the beginning of the mission (referred to as inspection 0). This means that one component is always put in operation, and another component is put to STM if $H = 0$.

Three integer parameters M, H and K determine the replacement policy. Observe that when $M = H = K = 0$, new components are put into OPM and STM in each inspection. When $M = H > 0$, no component resides in the STM during the mission because if $m \geqslant M$ the operating component is replaced and the number of shocks it experienced becomes $m = 0 < H$.

2.2. Optimization problem formulation

Let A_S and A_O ($A_S < A_O$) represent the costs incurred by placing a new component into STM and OPM, respectively, and A_{SO} represent the cost of automatic STM to OPM transfer. Let c_S and c_O ($c_S < c_O$) represent the per unit time cost incurred by keeping a component in STM and OPM, respectively. Let c_D represent the per unit time cost incurred by system downtime. Let C_F represent the cost of a component failure. Let C_I represent the cost of a single inspection.

Increasing the values of M and K reduces the cost of placing new components to OPM and STM, but increases the expected downtime of the system. Increasing the number of inspections N carried out during the mission can reduce system downtime, but increases the total inspection cost as well as component activation and operation costs. The optimal inspection and component replacement/addition policy N, H, M, K should balance these conflicting effects and minimize the ECTA. The ECTA, denoted by $E(N, H, M, K)$, consists of costs incurred by inspections, component failures, component activation and mode transition, system downtime, and keeping components in STM and OPM. Hence, it is pivotal to solve the optimization problem formulated in (1),

$$\text{Minimize } E(N,H,M,K). \tag{1}$$

2.3. Assumptions

The model has the following assumptions:

(1) Mode transfer time and inspection time are negligible, and inspections cause no downtime.
(2) The inspection perfectly detects the failures of components and the number of shocks hitting the components.
(3) Internal deteriorations of the components are not considered due to relatively short mission time. Component failures are caused solely by external shocks. This assumption is commonly adopted in literature where the system operates in a harsh environment and the operation time (i.e. time between scheduled maintenance) is relatively short [52–54].
(4) A supply of components is always available to refill or replace the component in the OPM or STM during inspection time.
(5) All components are statistically identical.

3. ECTA evaluation methodology

3.1. Shock-dependent failure probability of component

Let $v(i)$ denote the conditional probability that a component survives the ith shock given that it survived all previous shocks with $v(0) \equiv 1$ by definition. Let Ω denote the probability that a component survives the first shock. A common model for determining $v(i)$ is [55]

$$v(i) = \Omega\omega(i) \text{ for } i > 0 \tag{2}$$

$\omega(i)$ in (2) denotes shock resistance deterioration parameter (a decreasing function of its argument with $\omega(1) = 1$). Thus, the component survival probability upon every shock decreases as the number of survived shocks occurring increases. For instance, $\omega(i) = \omega^{i-1}$, $0 < \omega < 1$. Then, (3) can be used to compute the probability of a component surviving z shocks.

$$V(z) = \prod_{i=0}^{z} v(i) = \Omega^z \omega^{\frac{z(z-1)}{2}}. \tag{3}$$

Equation (4) gives the conditional probability of a component surviving $(z + k)$ shocks conditioned on having survived z shocks. Expression (5) gives the probability of a component failing upon the zth shock.

$$U(k|z) = V(z+k)/V(z) = \prod_{i=z+1}^{z+k} v(i) \tag{4}$$

$$V(z-1)\cdot(1-v(z)). \tag{5}$$

Equation (6) gives the conditional probability of a component failing upon the occurrence of the $(k+z)$th shock conditioned on having survived z of them.

$$F(k|z)=\begin{cases}\frac{V(z+k-1)(1-v(z+k))}{V(z)} & \text{if } k>0,\\ 0 & \text{if } k=0.\end{cases} \tag{6}$$

With Ω and ω, we can determine the number of shocks (Z) for which the component failure probability in (5) can be negligible (i.e. for a predetermined small value ε and for any $z>Z$, $V(z-1)<\varepsilon$). Hence, in numerical computations, for $z+k>Z$, $F(k|z)=0$ can be assumed.

3.2. Probabilities of shocks occurring

As the occurrence of shocks obeys an HPP, the occurrence probability of i shocks during t under arrival rate ρ, denoted by $P(t,i,\rho)$ is computed as

$$P(t,i,\rho)=\mathrm{e}^{-\rho t}\frac{(\rho t)^i}{i!}. \tag{7}$$

The occurrence probability of the jth shock in interval $[t,t+\mathrm{d}t)$ from some event is $P(t,j-1,\rho)\,\rho\mathrm{d}t$, where $\mathrm{d}t$ is infinitesimal.

For a component exposed to two independent processes of CMS and OPS, respectively, with arrival rates Λ and λ, the probability that j CMS and i OPS take place during t since some event, and the last one happens in $[t,t+\mathrm{d}t)$ can be evaluated as

$$\begin{aligned}\pi(t,i,j)\,dt=&(1(j>0)\cdot P(t,j-1,\Lambda)\cdot P(t,i,\lambda)\cdot\Lambda\\&+1(i>0)\cdot P(t,j,\Lambda)\cdot P(t,i-1,\lambda)\cdot\lambda)\,\mathrm{d}t.\end{aligned} \tag{8}$$

Expression (9) gives the conditional probability of a component that is exposed only to CMS failing between the $(n-1)$th inspection and the nth inspection after undergoing j shocks in-between inspections, conditioned on having survived z shocks before the inspection $(n-1)$.

$$F(j|z)\int_0^{\tau}P(t,j-1,\Lambda)\,\Lambda\mathrm{d}t. \tag{9}$$

Expression (10) gives the conditional probability of a component that is exposed to both CMS and OPS failing between the $(n-1)$th inspection and the nth inspection after undergoing j CMS and i OPS in-between inspections, conditioned on having survived z shocks before inspection $(n-1)$.

$$F(j+i|z)\int_0^{\tau}\pi(t,i,j)\,\mathrm{d}t. \tag{10}$$

3.3. Transitions of system states

The system state immediately following the nth inspection can be represented by three integer variables: the total number of shocks so far impacting specific components in OPM

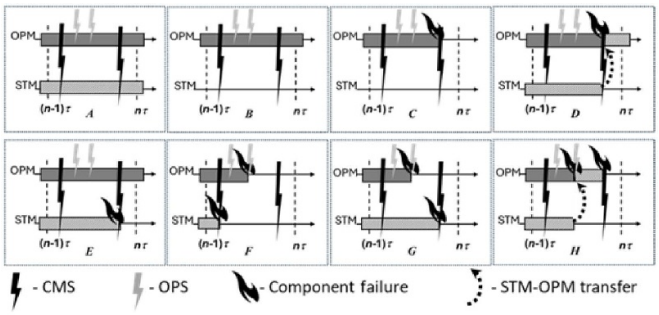


Figure 2. Eight possible system state transition cases.

$m_n\in\{0,1,\ldots,Z\}$ and in STM $k_n\in\{0,1,\ldots,Z\}$, and the number of system components that are available in STM $h_n\in\{0,1\}$. Note that $k_n\leqslant m_n$ since the online operating component is impacted by both CMS and OPS whereas the standby component is impacted by only CMS; in the case of the online operating component malfunctioning, the standby component transfers to the OPM immediately.

Define $p_n(m_n,k_n,h_n)$ as the probability of the system occupying a specific state following inspection n. At the start of the mission (referred to as inspection 0), $m_0=k_0=0$ and $h_0=1(H=0)$. Thus, by definition,

$$p_0(m_0,k_0,h_0)=\begin{cases}1 \text{ if } m_0=k_0=0,\ h_0=1\,(H=0);\\ 0 \text{ otherwise.}\end{cases} \tag{11}$$

the ECTA at the beginning of the mission is $E_0=0$.

Next, we give a recursive derivation of the conditional probabilities of eight different state transition cases, which take place between instants immediately after the $(n-1)$th inspection and the nth inspection, conditioned on the system being in state $(m_{n-1},k_{n-1},h_{n-1})$ following inspection $(n-1)$ (illustrated in figure 2, where CMS and OPS are, respectively, represented using black and grey lightnings). The ECTA E_n between these times is also derived. The last dummy inspection $(N+1)$ is defined corresponding to the mission termination, upon which no cost of inspection is incurred, and no more components are activated. An indicator function $1(n\leqslant N)$ is used to model this fact, which returns zero for the last dummy inspection. Instead of the component activation and inspection costs A_{O}, A_{S} and C_I, we use the costs $B_{\mathrm{O}}=A_{\mathrm{O}}\cdot1(n\leqslant N)$, $B_{\mathrm{S}}=A_{\mathrm{S}}\cdot1(n\leqslant N)$ and $B_{\mathrm{I}}=C_{\mathrm{I}}\cdot1(n\leqslant N)$.

Case 1: $h_{n-1}=1$; neither standby nor operating component fails between inspections (figure 2(A)).

Assume that exactly i CMS and j OPS take place with probability $P(\tau,i,\Lambda)\cdot P(\tau,j,\lambda)$ during the last interval of inter-inspection. The conditional probability of the operating component surviving $(i+j)$ shocks between the $(n-1)$th inspection and the nth inspection, conditioned on it having survived m_{n-1} shocks before inspection $(n-1)$ is $U(i+j|m_{n-1})$. The conditional probability of the standby component surviving i shocks between the $(n-1)$th inspection and the nth inspection, conditioned on it having survived k_{n-1} shocks before inspection $(n-1)$ is $U(i|k_{n-1})$.

The system's state immediately following inspection n is $(m_{n-1}+i+j,k_{n-1}+i,1)$ with probability

$$p_{n-1}(m_{n-1},k_{n-1},1)\cdot\mu_1(i,j,m_{n-1},k_{n-1}),$$
$$\text{where } \mu_1(i,j,m_{n-1},k_{n-1})=P(\tau,i,\Lambda)\cdot P(\tau,j,\lambda)\cdot U(i+j|m_{n-1})\cdot U(i|k_{n-1}), \quad (12)$$

which produces a negligible value in the event of $m_{n-1}+i+j>Z$.

According to the CRP, the inspection transfers the system to state $(m_n,k_n,1)$, where

$$m_n=(m_{n-1}+i+j)\,1(m_{n-1}+i+j<M),$$
$$k_n=(k_{n-1}+i)\,(1-1(m_n\geqslant H)\cdot 1(k_{n-1}+i\geqslant K)). \quad (13)$$

No failures have happened and no system downtime is incurred between inspections $(n-1)$ and n. Both operating and standby components are switched on during the whole inter-inspection interval τ. The condition of the operating component replacement is $1(m_{n\text{-}1}+i+j\geqslant M)$, the condition of standby component replacement is $1(m_n\geqslant H)\times 1(k_{n-1}+i\geqslant K)$. Therefore, the ECTA update is

$$E_n=E_{n-1}+[B_I+1(m_{n-1}+i+j\geqslant M)\cdot B_O+1(m_n\geqslant H)\cdot 1(k_{n-1}+i\geqslant K)\cdot B_S+(c_S+c_O)\tau]\cdot p_{n-1}(m_{n-1},k_{n-1},1)\,\mu_1(i,j,m_{n-1},k_{n-1}) \quad (14)$$

Case 2: $h_{n-1}=0$; the online operating component does not fail between inspections (figure 2(B)).

If exactly i CMS and j OPS take place during the final inter-inspection time interval, the state of the system right before inspection n is $(m_{n-1}+i+j,0,0)$ with probability

$$p_{n-1}(m_{n-1},0,0)\,\mu_2(i,\,j,\,m_{n-1}), \quad (15)$$

where $\mu_2(i,j,m_{n-1})=P(\tau,i,\Lambda)\cdot P(\tau,j,\lambda)\cdot U(i+j|m_{n-1})$, which has a negligible value in the case of $m_{n-1}+i+j>Z$.

According to the CRP, the inspection transfers the system to state $(m_n,\,0,\,h_n)$, where

$$m_n=(m_{n-1}+i+j)\,1(m_{n-1}+i+j<M),h_n=1(m_n\geqslant H). \quad (16)$$

Between two inspections, no failures have happened and no system downtime is incurred and thus added. Only the online operating component functions during the whole inter-inspection interval τ. The condition of operating component replacement is $1(m_{n-1}+i+j\geqslant M)$, the condition of standby component addition is $1(m_n\geqslant H)$. Therefore, the ECTA update is

$$E_n=E_{n-1}+[B_I+1(m_{n-1}+i+j\geqslant M)B_O+1(m_n\geqslant H)B_S+c_O\tau]\cdot p_{n-1}(m_{n-1},k_{n-1},0)\cdot\mu_2(i,\,j,\,m_{n-1}) \quad (17)$$

Case 3: $h_{n-1}=0$; the online operating component fails between inspections (figure 2(C)).

Assume that the online operating component is failed in $[t,t+\mathrm{d}t)$ $(t<\tau)$, after undergoing i CMS and j OPS. Upon inspection n, a new component is put into the OPM and a new component is put into the STM if $m_n\geqslant H$. The state of the system right before inspection n is (0, 0, 0) with probability

$$p_{n-1}(m_{n-1},0,0)\,\mu_3(i,j,m_{n-1}),$$
$$\text{where } \mu_3(i,j,m_{n-1})=F(i+j|m_{n-1})\int_0^\tau\pi(t,i,j)\,\mathrm{d}t \quad (18)$$

which takes a negligible value in the case of $m_{n-1}+i+j>Z$.

As after inspection $m_n=k_n=0$, according to the CRP, the inspection transfers the system to state (0, 0, $1(m_n\geqslant H)$), where $1(m_n\geqslant H)=1(H=0)$ for $m_n=0$.

The operating component functions during t and its failure in $[t,t+\mathrm{d}t)$ incurs system downtime of τ–t. Hence, the expected cost of operation between inspections is

$$w_3(i,j,m_{n-1})\,p_{n-1}(m_{n-1},k_{n-1},0),$$
$$\text{where } w_3(i,j,m_{n-1})=c_OF(i+j|m_{n-1})\int_0^\tau t\pi(t,i,j)\,\mathrm{d}t \quad (19)$$

and the expected cost of system downtime is

$$d_3(i,j)\cdot p_{n-1}(m_{n-1},k_{n-1},0),$$
$$\text{where } d_3(i,j,m_{n-1})=c_D\cdot F(i+j|m_{n-1})\int_0^\tau(\tau-t)\,\pi(t,i,j)\,\mathrm{d}t. \quad (20)$$

One component fails between the inspections and one component is put into the OPM upon inspection. Hence, the ECTA update is

$$E_n=E_{n-1}+p_{n-1}(m_{n-1},k_{n-1},0)\cdot[w_3(i,\,j,\,m_{n-1})+d_3(i,\,j,\,m_{n-1})+(B_O+1(H=0)B_S+B_I+C_F)\,\mu_3(i,j,m_{n-1})]. \quad (21)$$

Case 4: $h_{n-1}=1$; only one operating component becomes failed between inspections (figure 2(D)).

Once the online operating component is failed in $[t,t+\mathrm{d}t)$, the standby component takes over the mission task immediately and survives all the shocks till inspection n.

In the case of exactly i CMS and j OPS occurring before failure, and l CMS and q OPS occurring between failure and inspection n, the online operating component is failed upon shock $(i+j)$ and another component undergoes and survives i CMS in STM and additional $(l+q)$ shocks in OPM between inspections. The state of the system right before inspection n is $(k_{n-1}+i+l+q,0,0)$ with probability

$$p_{n-1}(m_{n-1},k_{n-1},0)\,\mu_4(i,\,j,\,l,q,m_{n-1},k_{n-1}),$$
$$\text{where } \mu_4(i,j,l,q,m_{n-1},k_{n-1})=U(i+l+q|k_{n-1})\cdot F(j+i|m_{n-1})\cdot\int_0^\tau P(\tau-t,l,\Lambda)\cdot P(\tau-t,q,\lambda)\cdot\pi(t,i,j)\,\mathrm{d}t, \quad (22)$$

which takes a negligible value in the case of $i+l+q+k_{n-1} > Z$ or $j+i+m_{n-1} > Z$.

According to the CRP, the inspection transfers the system to state (m_n, 0, h_n), where

$$m_n = (k_{n-1}+i+l+q)\cdot 1\,(k_{n-1}+i+l+q<M),$$
$$h_n = 1\,(m_n \geqslant H).$$

If the online operating component becomes failed in the interval [t,t + dt), both standby and operating components function during time t, and then only the online operating component functions during time ($\tau-t$). For this case, the cost of operation can be obtained as ($c_O + c_S$) $\cdot t + c_O(\tau-t) = c_O\tau + c_S t$. The expected cost of system operation between inspections is

$$w_4\,(i,j,l,q,m_{n-1},k_{n-1})\cdot p\,(m_{n-1},k_{n-1},1),$$
$$\text{where } w_4\,(i,j,l,q,m_{n-1},k_{n-1}) = U(i+l+q|k_{n-1})$$
$$\cdot F(j+i|m_{n-1})\cdot\int_0^\tau (c_O\tau+c_S t)\,P(\tau-t,l,\Lambda)$$
$$\cdot P(\tau-t,q,\lambda)\cdot\pi\,(t,i,j)\,\mathrm{d}t. \tag{23}$$

One component is failed, one component transfers from STM to OPM, and no system downtime is added between inspections. The condition of operating component replacement is $1(k_{n-1}+i+l+q \geqslant M)$, the condition of standby component addition is $1(H \leqslant k_{n-1}+i+l+q<M)$. Hence, the ECTA update is

$$E_n = E_{n-1} + p_{n-1}\,(m_{n-1},k_{n-1},1)\cdot[w_4\,(i,j,\ l,\ q,m_{n-1},k_{n-1})$$
$$+ (A_{SO}+B_O\cdot 1\,(k_{n-1}+i+l\ +q\geqslant M)+B_S$$
$$\cdot 1\,(m_n\geqslant H)+C_F+B_I)\cdot\mu_4(i,j,\ l,\ q,m_{n-1},\ k_{n-1})] \tag{24}$$

Case 5: $h_{n-1} = 1$; only the standby component is failed between inspections (figure 2(E)).

Assume that the standby component becomes failed in [t,t + dt) upon the occurrence of the ith CMS since the previous inspection action, and the online operating component survives i CMS before time t and j CMS after time t and l OPS during time τ between inspections. The state of the system right before inspection n is ($m_{n-1}+i+l+q$,0,0) with probability

$$p_{n-1}\,(m_{n-1},k_{n-1},0)\cdot\mu_5\,(i,\ j,\ l,m_{n-1},k_{n-1}),$$
$$\text{where } \mu_5\,(i,j,l,m_{n-1},k_{n-1}) = U(i+j+l|m_{n-1})\cdot F(i|k_{n-1})$$
$$\cdot P(\tau,l,\lambda)\cdot\int_0^\tau \Lambda P(t,i-1,\Lambda)\cdot P(\tau-t,j,\Lambda)\,\mathrm{d}t, \tag{25}$$

which produces negligible values in the event of $(i+j+l+m_{n-1}) > Z$.

According to the CRP, the inspection transfers the system to state (m_n, 0, h_n), where

$$m_n = (m_{n-1}+i+l+q)\cdot 1\,(m_{n-1}+i+l+q<M),$$
$$h_n = 1\,(m_n\geqslant H).$$

If the standby component is failed in interval [t,t + dt), it functions during time t. The online operating component functions during the whole inter-inspection time. The cost of operation is obtained as $(c_O + c_S)\cdot t + c_O\cdot(\tau-t) = c_O\tau + c_S t$. The expected cost of operation of the standby component between inspections is

$$w_5\,(i,j,\ l,\ m_{n-1},k_{n-1})\,p_{n-1}\,(m_{n-1},k_{n-1},1),$$
$$\text{where } w_5\,(i,j,\ l,m_{n-1},k_{n-1}) = U(i+j+l|m_{n-1})\cdot F(i|k_{n-1})$$
$$\cdot P(\tau,l,\lambda)\cdot c_S\int_0^\tau t\Lambda P(t,i-1,\Lambda)\cdot P(\tau-t,j,\Lambda)\,\mathrm{d}t. \tag{26}$$

One component is failed, and no system downtime is incurred and thus added in-between two inspections. The condition of operating component replacement is $1(m_{n-1}+i+l+q\geqslant M)$, the condition of standby component addition is $1(H\leqslant m_{n-1}+i+l+q<M)$. Hence, the ECTA update is

$$E_n = E_{n-1} + p_{n-1}\,(m_{n-1},\ k_{n-1},1)$$
$$\cdot[w_5(i,j,\ l,m_{n-1},k_{n-1}) + (c_O\tau + C_F + B_I$$
$$+ B_O\cdot 1\,(m_{n-1}+i+l+q\geqslant M)$$
$$+ B_S\cdot 1\,(m_n\geqslant H))\cdot\mu_5(i,j,\ l,m_{n-1},k_{n-1})] \tag{27}$$

Case 6: $h_{n-1} = 1$; both components become failed between inspections, and the standby component is failed earlier (figure 2(F)).

Assume that the standby component becomes failed in [t,t + dt) upon the occurrence of the ith CMS from the previous inspection ($i>0$), j OPS take place in interval [0,t), the online operating component is failed in [γ, γ + $d\gamma$) ($\gamma > t$) after undergoing additional l CMS and q OPS in [t,γ) (where $l+q>0$).

The state of the system right before inspection n is (0, 0, 0) with probability

$$p_{n-1}\,(m_{n-1},k_{n-1},0)\cdot\mu_6\,(i,\ j,l,q,m_{n-1},k_{n-1}),$$
$$\text{where } \mu_6\,(i,j,\ l,\ q,m_{n-1},k_{n-1}) = F(i+j+l+q|m_{n-1})\cdot F(i|k_{n-1})$$
$$\cdot\int_0^\tau \Lambda P(t,i-1,\Lambda)\cdot P(t,j,\lambda)\int_t^\tau \pi\,(\gamma-t,l,q)\,\mathrm{d}\gamma\mathrm{d}t \tag{28}$$

which produces a negligible value in the event of $(i+j+l+q+m_{n-1}) > Z$.

According to the CRP, the inspection transfers the system to state (0, 0, $1(H=0)$) upon placing a new component into the OPM and, if $H=0$, placing a new component into the STM.

Between inspections, the online operating component functions during time γ, and the standby component works during time t. Thus, the expected operation cost can be obtained as

$$w_6\,(i,j,\ l,\ q,m_{n-1},k_{n-1})\ p_{n-1}\,(m_{n-1},k_{n-1},1),$$
$$\text{where } w_6\,(i,j,\ l,\ q,m_{n-1},k_{n-1}) = F(i+j+l+q|m_{n-1})$$
$$\cdot F(i|k_{n-1})\cdot\int_0^\tau \Lambda P(t,i-1,\Lambda)\cdot P(t,j,\lambda)\int_t^\tau (c_S t + c_O\gamma)$$
$$\cdot\pi\,(\gamma-t,l,q)\,\mathrm{d}\gamma\mathrm{d}t. \tag{29}$$

If the online operating component becomes failed in $[\gamma, +d\gamma)$, the downtime in-between inspection is $(\tau-\gamma)$. The expected cost of downtime is

$$d_6(i,j,\ l,\ q,\ m_{n-1},k_{n-1})p_{n-1}(m_{n-1},k_{n-1},1),$$
$$\text{where } d_6(i,j,\ l,\ q,m_{n-1},k_{n-1})$$
$$= c_{\mathrm{D}}\cdot F(i+j+l+q|m_{n-1})\cdot F(i|k_{n-1})\cdot\int_0^{\tau}\Lambda P(t,i-1,\Lambda)$$
$$\times P(t,j,\lambda)\int_t^{\tau}(\tau-\gamma)\cdot\pi(\gamma-t,l,q)\,\mathrm{d}\gamma\mathrm{d}t. \quad (30)$$

Two components are failed between inspections, a new component is put into the OPM. Hence, the ECTA update is

$$E_n = E_{n-1}+p_{n-1}(m_{n-1},\ k_{n-1},1)\cdot[w_6(i,j,\ l,\ q,m_{n-1},\ k_{n-1})$$
$$+d_6(i,j,\ l,\ q,m_{n-1},k_{n-1})+(B_O+1(H=0)B_S$$
$$+2C_F+B_I)\cdot\mu_6(i,j,\ l,\ q,m_{n-1},k_{n-1})]. \quad (31)$$

Case 7: $h_{n\text{-}1} = 1$; both components are failed simultaneously between inspections (figure 2(G)).

Assume that the components are failed in $[t,t+\mathrm{d}t)$ upon the occurrence of the ith CMS from the previous inspection $(i>0)$, and j OPS take place in interval $[0,t)$. The state of the system right before inspection n is (0, 0, 0) with probability

$$p_{n-1}(m_{n-1},k_{n-1},0)\,\mu_7(i,j,l,m_{n-1},k_{n-1}),$$
$$\text{where } \mu_7(i,j\ ,m_{n-1},k_{n-1}) = F(i+j|m_{n-1})\cdot F(i|k_{n-1})$$
$$\cdot\int_0^{\tau}\Lambda P(t,i-1,\Lambda)\cdot P(t,j,\lambda)\,\mathrm{d}t, \quad (32)$$

which produces negligible values in the event of $i+j+m_{n-1}>Z$.

According to the CRP, the inspection transfers the system to state (0, 0, $1(H=0)$) upon unconditionally placing a new component into the OPM and, if $H=0$, placing a new component into the STM.

Between inspections, both components function during time t. Hence, the expected cost of operation is

$$w_7(i,j,m_{n-1},k_{n-1})\cdot p_{n-1}(m_{n-1},\ k_{n-1},1),$$
$$\text{where } w_7(i,j,m_{n-1},k_{n-1}) = (c_S+c_O)\cdot F(i+j|m_{n-1})$$
$$\cdot F(i|k_{n-1})\int_0^{\tau}t\Lambda P(t,i-1,\Lambda)\cdot P(t,j,\lambda)\,\mathrm{d}t. \quad (33)$$

The expected cost of downtime is

$$d_7(i,j,\ m_{n-1},k_{n-1})p_{n-1}(m_{n-1},k_{n-1},1),$$
$$\text{where } d_7(i,j,\ m_{n-1},k_{n-1}) = c_D\cdot F(i+j|m_{n-1})$$
$$\cdot F(i|k_{n-1})\int_0^{\tau}(\tau-t)\,\Lambda P(t,i-1,\Lambda)\cdot P(t,j,\lambda)\,\mathrm{d}t. \quad (34)$$

Two components become failed between inspections, and a new component is put into OPM. Hence, we have the ECTA update as

$$E_n = E_{n-1}+p_{n-1}(m_{n-1},k_{n-1},1)$$
$$\cdot[w_7(i,j,m_{n-1},k_{n-1})+d_7(i,j,m_{n-1},k_{n-1})$$
$$+(B_{\mathrm{O}}+1(H=0)B_{\mathrm{S}}+2C_{\mathrm{F}}+B_{\mathrm{I}})\,\mu_7(i,j,m_{n-1},k_{n-1})]. \quad (35)$$

Case 8: $h_{n-1} = 1$; both components are failed between inspections, and the online operating component is failed earlier (figure 2(H)).

Assume that the online operating component becomes failed in $[t,t+\mathrm{d}t)$ from the previous inspection, the standby component transfers to OPM and becomes failed in $[\gamma, \gamma+d\gamma)$. Assume also that i CMS and j OPS $(i+j>0)$ take place in $[0,t)$, l CMS and q OPS take place in $[t,\gamma)$ $(l+q>0)$. For this case, the initially, online operating component is failed once it experiences shock $(i+j)$ since the prior inspection, and the standby component is failed once it experiences shock $(i+l+q)$ since the prior inspection (after undergoing i shocks in STM, and then $l+q$ shocks in OPM).

The state of the system right before inspection n is (0, 0, 0) with probability

$$p_{n-1}(m_{n-1},k_{n-1},0)\,\mu_8(i,\ j,l,q,m_{n-1},k_{n-1}),$$
$$\text{where } \mu_8(i,j,l,q,m_{n-1},k_{n-1}) = F(i+j|m_{n-1})$$
$$\cdot F(i+l+q|k_{n-1})\cdot\int_0^{\tau}\pi(t,i,j)\int_t^{\tau}\pi(\gamma-t,l,q)\,\mathrm{d}\gamma\mathrm{d}t, \quad (36)$$

which produces negligible values in the event of $(i+j+m_{n-1})>Z$ or $(i+l+q+k_{n-1})>Z$.

According to the CRP, the inspection transfers the system to state (0, 0, $1(H=0)$) upon unconditionally placing a new component into the OPM and, if $H=0$, placing a new component into the STM.

Between inspections, both components function during time t, and then only the online operating component functions during time $(\gamma-t)$, leading to a cost of operation of $(\gamma c_{\mathrm{O}}+tc_{\mathrm{S}})$. Thus, the expected cost of operation is

$$w_8(i,j,\ l,\ q,m_{n-1},k_{n-1})p_{n-1}(m_{n-1},k_{n-1},1),$$
$$\text{where } w_8(i,j,\ l,\ q,m_{n-1},k_{n-1}) = F(i+j|m_{n-1})$$
$$\cdot F(i+l+q|k_{n-1})\cdot\int_0^{\tau}\pi(t,i,j)\int_t^{\tau}(c_St+c_O\gamma)$$
$$\cdot\pi(\gamma-t,l,q)\,d\gamma\mathrm{d}t. \quad (37)$$

The system downtime between inspection is $(\tau-\gamma)$. The expected cost of downtime is

$$d_8(i,j,l,q,m_{n-1},k_{n-1})p_{n-1}(m_{n-1},k_{n-1},1),$$
$$\text{where } d_8(i,j,\ l,\ q,m_{n-1},k_{n-1}) = c_DF(i+j|m_{n-1})$$
$$F(i+l+q|k_{n-1})\cdot\int_0^{\tau}\pi(t,i,j)\int_t^{\tau}(\tau-\gamma)\,\pi(\gamma-t,l,q)\,d\gamma\mathrm{d}t. \quad (38)$$

Two components are failed between inspections, a new component is put into OPM, and if $H = 0$, a new component is put into STM, and one component transits from the STM to the OPM. Hence, we have the ECTA update as

$$\begin{aligned} E_n = E_{n-1} + p_{n-1}(m_{n-1},k_{n-1},1)[&w_8(i,j,\ l,\ q,m_{n-1},k_{n-1}) \\ &+ d_8(i,j,\ l,\ q,m_{n-1},k_{n-1}) \\ &+ (B_O + 1(H=0)B_S + A_{SO} + 2C_F + B_I) \\ &\times \mu_8(i,j,\ l,\ q,m_{n-1},k_{n-1})]. \end{aligned} \tag{39}$$

3.4. ECTA evaluation procedure

All the state transition cases for distinct values of *i, j, l* and *q* are disjoint or mutually exclusive. Therefore, the probability of a system state after inspection *n*, that is, $p_n(m_n,k_n,h_n)$ can be computed by adding the product of probabilities $p_{n-1}(m_{n-1},k_{n-1},k_{n-1})$ of system states, from which the system can transfer to state m_n,k_n,h_n, with the corresponding state transition probabilities. The inter-inspection ECTA under every state transition is also added to determine the overall ECTA.

Based on derivations presented in section 3.3, we present a procedure, which consecutively determines the probabilities of all the possible states of the system m_n,k_n,h_n based upon the probabilities of system states m_{n-1},k_{n-1},k_{n-1}, the probabilities of state transitions, as well as inspection rules, and calculates the ECTA. Consider any inspection *n*. The procedure first sets all system state probabilities as zero. Then, for any system state m_{n-1},k_{n-1},k_{n-1} and any state transition cases, the procedure updates the occurrence probability of the state, to which the system can transfer upon inspection *n* for any CMS and OPS combination that can take place between inspections. Two $Z \times Z \times 2$ arrays of state probabilities for $p_{n-1}(m_{n-1},k_{n-1},k_{n-1})$ and $p_n(m_n,k_n,h_n)$ need to be stored in the memory during the evaluation.

In the procedure below, α and β represent the number of shocks impacting the online operating component and the standby component immediately before inspection, respectively, δ represents the number of shocks impacting the component residing in the OPM mode immediately after the inspection, π, σ and φ are indicators of component replacement/addition conditions. θ is the indicator that a standby component should be added/replaced after the inspection even when in the OPM the component experiences no shocks (i.e. when $H = 0$).

Because values of μ_i, w_i, and d_i ($i = 1,\ldots,8$) can be determined before the procedure is run for any CMS and OPS combination, the procedure has computational complexity $O(Z^4)$. As *i, j, l*, and *q* may range from 0 to *Z,* and double integration is involved in (28)–(30) and in (36)–(38), determining values of μ_i, w_i and d_i for each *i, j, l* and *q* has a computational complexity of $O(Z^4 dt^{-2})$, where dt is referred to as the time discretization factor.

Having the presented procedure for obtaining the value of the ECTA for arbitrary *N, H, M* and *K*, the optimization problem of (1) can be solved using either brute force enumeration of the parameters *N, H, M* and *K* or any algorithm for integer optimization.

ECTA evaluation procedure for arbitrary N, H, M and K.

1	For $m = 0, \ldots, Z$: For $k = 0, \ldots, m$: For $h = 0, 1$: initialize $p_0(m, k, h) = 0$;
2	Initialize $p_0(0, 0, 0) = 1$; $E = 0$; $\theta = 1(H = 0)$;
3	For $n = 1, \ldots, N + 1$:
4	$B_O = A_O 1(n \leqslant N)$; $B_S = A_S 1(n \leqslant N)$; $B_I = C_I 1(n \leqslant N)$;
5	For $m = 0, \ldots, Z$: For $k = 0, \ldots, Z$: For $h = 0, 1$: initialize $p_n(m, k, h) = 0$;
6	For $m = 0, \ldots, Z$: For $k = 0, \ldots, Z$:
7	$Y_1 = p_{n-1}(m, k, 1)$; $Y_0 = p_{n-1}(m, k, 0)$;
8	For $i = 0,\ldots, (Z\text{-}m)$ For $j = 0, \ldots, (Z - m - i)$:
9	$\alpha = m + i + j$; $\pi = 1(\alpha \geqslant M)$; $\delta = \alpha(1\text{-}\pi)$; $\sigma = 1(\delta \geqslant H)$; $\beta = k + i$; $\varphi = 1(\beta \geqslant K)$;
10	Add $Y_1\mu_1(i, j, m, k)$ to $p_n(\delta, \beta(1-\sigma\varphi)),1)$;
11	Add $Y_0\mu_2(i, j, m)$ to $p_n(\delta,0,\sigma)$;
12	Add $Y_0\mu_3(i,j,m) + Y_1\mu_7(i, j, m, k)$ to $p_n(0, 0, \theta)$;
13	Add $Y_1[((c_S + c_O)\tau + B_I + \pi B_O + \varphi\sigma B_S)\mu_1(i, j, m, k) + w_7(i, j, m, k) + d_7(i, j, m, k) + (B_O + \theta B_S + 2\ C_F + B_I)\mu_7(i,j,m,k)] + Y_0[(c_O\tau + B_I + \pi B_O + \sigma B_S)\mu_2(i, j, m) + w_3(i, j, m) + d_3(i, j, m) + (B_O + \theta B_S + C_F + B_I)\mu_3(i, j, m)]$ to E;
14	For $l = 0, \ldots, (Z-m-i-j)$:
15	$\alpha = (m + i + j + l)$; $\pi = 1(\alpha \geqslant M)$; $\delta = \alpha(1-\pi)$; $\sigma = 1(\delta \geqslant H)$;
16	Add $Y_1\mu_5(i, j, l, m, k)$ to $p_n(\delta,0,\sigma)$;
17	Add $Y_1[w_5(i, j, l, m, k) + (c_O\tau + \pi B_O + \sigma B_S + C_F + B_I)\mu_5(i, j, l, m, k)]$ to E;
18	For $q = 0,\ldots, (Z-k-i-l)$:
19	$\alpha = k + i + l + q$; $\pi = 1(\alpha \geqslant M)$; $\delta = \alpha(1-\pi)$; $\sigma = 1(\delta \geqslant H)$;
20	Add $Y_1\mu_4(i, j, l, q, m, k)$ to $p_n(\delta,0,\sigma)$;
21	Add $Y_1(\mu_6(i, j, l, q, m, k) + \mu_8(i, j, l, q, m, k))$ to $p_n(0, 0, \theta)$;
22	Add $Y_1[w_4(i, j, l, q, m, k) + (A_{SO} + \pi B_O + \sigma B_S + C_F + B_I)\mu_4(i, j, l, q, m, k)]$ to E;
23	Add $Y_1[w_6(i,j,l,q,m,k) + d_6(i, j, l, q, m, k) + w_8(i, j, l, q, m, k) + d_8(i, j, l, q, m, k) + (B_O + \theta B_S + 2C_F + B_I)(\mu_6(i, j, l, q, m, k) + \mu_8(i, j, l, q, m, k)) + A_{SO}\mu_8(i, j, l, q, m, k)]$ to E.

4. Case study

To compare the SBP proposed in this work with the TBP of [47], we use the same example as in [47]. In this example, we consider a sensor system that autonomously acquires and transfers environment data to a network server. A standby sensor is used, which is not connected to the network while in the STM. Both the operating sensor and the standby sensor are impacted by extreme weather conditions (i.e. CMS) modeled by an HPP with rate of $\Lambda = 0.1$, which may deteriorate and even fail these sensors. The operating sensor can also be impacted by OPS in the form of voltage surges with a rate of $\lambda = 0.2$, caused by its link to the network. The values of CMS and OPS shock rates can be determined from weather condition records, and data detected by the voltage monitoring equipment, respectively. The deterioration of sensors due to shocks is modeled by (2) and (3), where $\Omega = 0.78$, $\omega = 0.53$. Under this shock model, the sensor's survival probability is negligible when the number of shocks exceeds $Z = 7$ (particularly, $V(8) < 10^{-5}$).

The mission time of data collection is 100 days. The cost of data loss per day is $c_{\mathrm{D}} = 2$, the per day operation cost of sensor is $c_{\mathrm{O}} = 0.2$, and the per day standby cost is $c_{\mathrm{S}} = 0.002$. The cost of a single inspection is $C_{\mathrm{I}} = 2.25$. The cost of sensor failure is $C_{\mathrm{F}} = 9$. The costs of placing a sensor in STM and OPM are $A_{\mathrm{S}} = 0.4$ and $A_{\mathrm{O}} = 1$, respectively. The cost of activating and connecting to the network of standby sensor is $A_{\mathrm{SO}} = 0.2$. The problem addressed is to determine the number of inspections ($N \geqslant 1$) and sensor replacement policy parameters M, H, K that minimize the ECTA.

4.1. Accuracy of the ECTA evaluation procedure

To assess the effects of the discretization factor dt on the result accuracy of the ECTA evaluation method, the ECTA is obtained as a function of 1/dt (for the sake of visual clarity) for $N = 5$, $M = 2$, $H = 1$ and $K = 1$ as shown in figure 3.

Figure 3 also shows the running time of the C programming language implementation of the numerical ECTA evaluation procedure (section 3.4) on a PC with 3.7 GHz. The evaluation results converge rapidly as dt decreases. For instance, the discrepancy between ECTA evaluated for d$t = 0.08$ and d$t = 0.02$ is 0.94%. The discrepancy between ECTA evaluated for d$t = 0.04$ and d$t = 0.02$ is 0.308%. d$t = 0.025$ is adopted in the further calculations in this case study. The value of the ECTA to which the evaluation results converge as dt decreases is $E = 192.2$.

The procedure for ECTA evaluation for arbitrary SBP is fast, which allows obtaining the optimal SBP using brute force enumeration of all possible values of integer policy parameters N, M, H and K.

4.2. Effects of shocks information availability on the ECTA

Using information about the number of shocks impacting the operating component and the standby component before inspections can reduce the ECTA compared to the case where such a information is unavailable. To demonstrate the influence of the information, we compare the ECTA for the case where shocks are observable and where only information about the duration of components stays in the OPM and STM is available, and a new component is put into the OPM when the previous operating component fails before inspection, whereas a new component is put to the STM if the same operating component resides in the OPM during at least H inspections (see [47]).

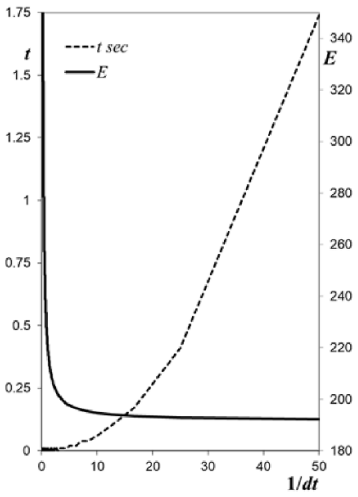


Figure 3. ECTA and the running time as functions of 1/dt.

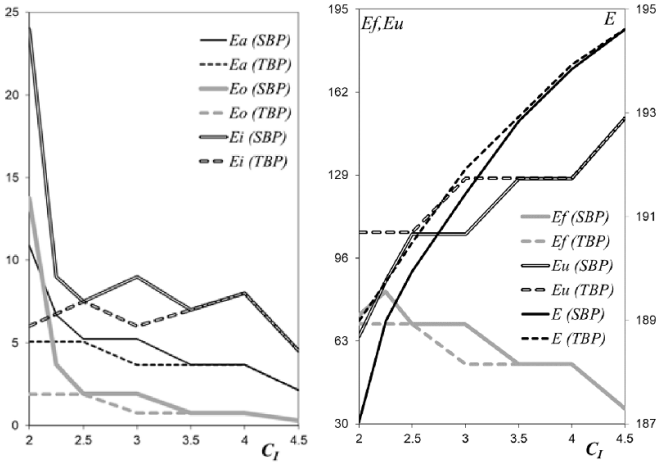


Figure 4. Comparison of EML and its components for best obtained SBP and TBP.

Figure 4 presents the minimum ECTA and its components obtained for both cases as functions of the inspection cost C_I. Tables 1 and 2 present the SBP and TBP, and the corresponding expected costs for distinct values of C_I.

As the cost of inspection increases, the optimal value of N decreases, causing a reduction in the total inspection cost during mission E_{i}, the expected cost of placing components in STM and OPM E_{a}, the expected cost of operation E_{o}, and the expected component failure cost E_{f} because fewer components participate in the mission. However, the expected downtime cost E_{d} increases because the failed components cannot be replaced timely.

Table 1. Best obtained SBP and corresponding ECTA as functions of inspection cost.

C_I	N	M	H	K	E_a	E_f	E_u	E_o	E_i	E
0.1	45	1	1	—	22.63	76.34	17.75	19.17	4.5	140.39
2	12	1	1	—	10.91	73.38	64.74	13.75	24.25	187.04
2.25	4	1	0	1	6.71	82.67	86.88	3.67	9.06	188.99
2.5	3	1	0	1	5.23	69.72	105.53	1.91	7.54	189.94
3	3	1	0	1	5.23	69.72	105.53	1.91	9.05	191.44
3.5	2	1	0	1	3.69	53.83	127.54	0.75	7.03	192.84
4	2	1	0	1	3.69	53.83	127.54	0.75	8.03	193.84
4.5	1	1	0	1	2.13	36.12	151.54	0.31	4.51	194.61

Table 2. Best obtained TBP and corresponding ECTA as functions of inspection cost.

C_I	N	H	E_a	E_f	E_u	E_o	E_i	E
0.1	22	12	10.19	96.04	48.82	15.72	2.2	173.04
2	3	0	5.06	69.79	106.23	1.87	6.03	188.98
2.25	3	0	5.06	69.79	106.23	1.87	6.79	189.74
2.5	3	0	5.06	69.79	106.23	1.87	7.54	190.49
3	2	0	3.66	53.83	127.66	0.74	6.02	191.92
3.5	2	0	3.66	53.83	127.66	0.74	7.03	192.93
4	2	0	3.66	53.83	127.66	0.74	8.03	193.93
4.5	1	0	2.13	36.12	151.54	0.31	4.51	194.61

It is observed that the SBP enables obtaining smaller ECTA than the TBP of [47]. The difference increases when C_I decreases and more inspections are performed during the mission. When $C_I = 0.1$, the SBP allows an achievement of 18.9% lower ESTA than the TBP. Compared to the TBP, the SBP achieves a reduction in all of the ECTA components at the price of slightly increased system downtime.

4.3. Effects of cost parameters A_S and A_O

Figure 5 shows the optimal values of N, H and the corresponding ECTA E as functions of the costs of placing components into OPM and STM (A_O and A_S, respectively). For all the obtained solutions, $M = 1$. In this example and all the examples below, the optimal value of the parameter K is one. When the cost of placing components into OPM and STM increases, it is less beneficial to add/replace components, and the optimal number of inspections when these actions can be performed decreases. Besides, when A_O increases and A_S decreases, it becomes more beneficial to keep a component in the STM to avoid placing a new component in the OPM when the operating component fails and performing the STM-OPM transfer instead. Intuitively, the ECTA increases with increasing A_O and A_S.

4.4. Effects of component failure and downtime costs

Figure 6 shows the optimal values of N, M, H and the corresponding ECTA E as functions of the cost incurred by component failure and downtime. When the downtime cost c_D increases, more inspections should be performed to activate/replace the operating component timely, the value of M decreases allowing the operating component to remain in the OPM after experiencing fewer shocks and H also decreases eventually dropping to zero, which means that a component should reside in the STM after any inspection. When the component failure cost C_F increases, it becomes less beneficial to use many components. Hence, the number of inspections decreases, and the threshold H increases, which prevents placing too many components to the STM. It is intuitive that the ECTA increases when C_F and c_D increase.

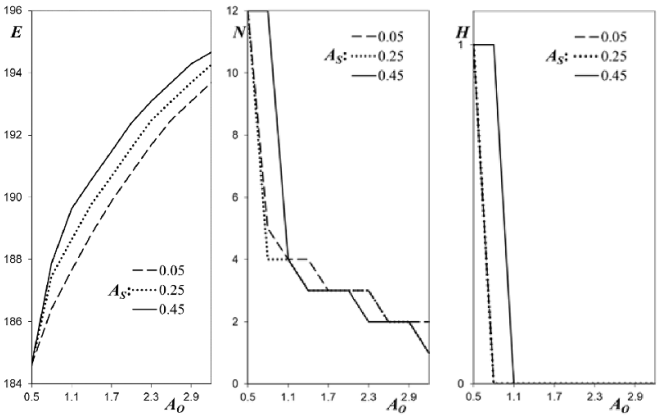


Figure 5. Optimal SBP parameters and corresponding ECTA $E(N,M,H,K)$ as functions of A_O and A_S.

4.5. Effects of operation, standby cost parameters c_O, c_S

Figure 7 shows the optimal values of N, H and the corresponding ECTA E as functions of the per unit time cost of operation and standby (c_O and c_S respectively). For all the obtained solutions, $M = 1$. When the operation cost is low ($c_O = 0.1$), it is beneficial to keep a component in the OPM for as much time as possible during the mission, which is provided by performing many inspections ($N = 12$) and replacements of the operating component ($M = 1$). Under this policy, the operating component has a very small chance of failing between inspections, and the standby component is not needed ($M = H > 0$, which means that no standby component is used, and the ECTA does not depend on c_S).

As the cost of operation increases, the value of N (i.e. the number of inspections) decreases and H drops to 0 ($H < M = 1$), which corresponds to an SBP where the online operating component is always backed up by a standby component. The ECTA increases as the standby cost c_S increases. However, when c_S increases to 0.1, it becomes not beneficial to keep a component in the STM and the SBP changes to a non-standby one with $M = N = 1$. The absence of the standby component is compensated by more frequent inspections (N increases to 10).

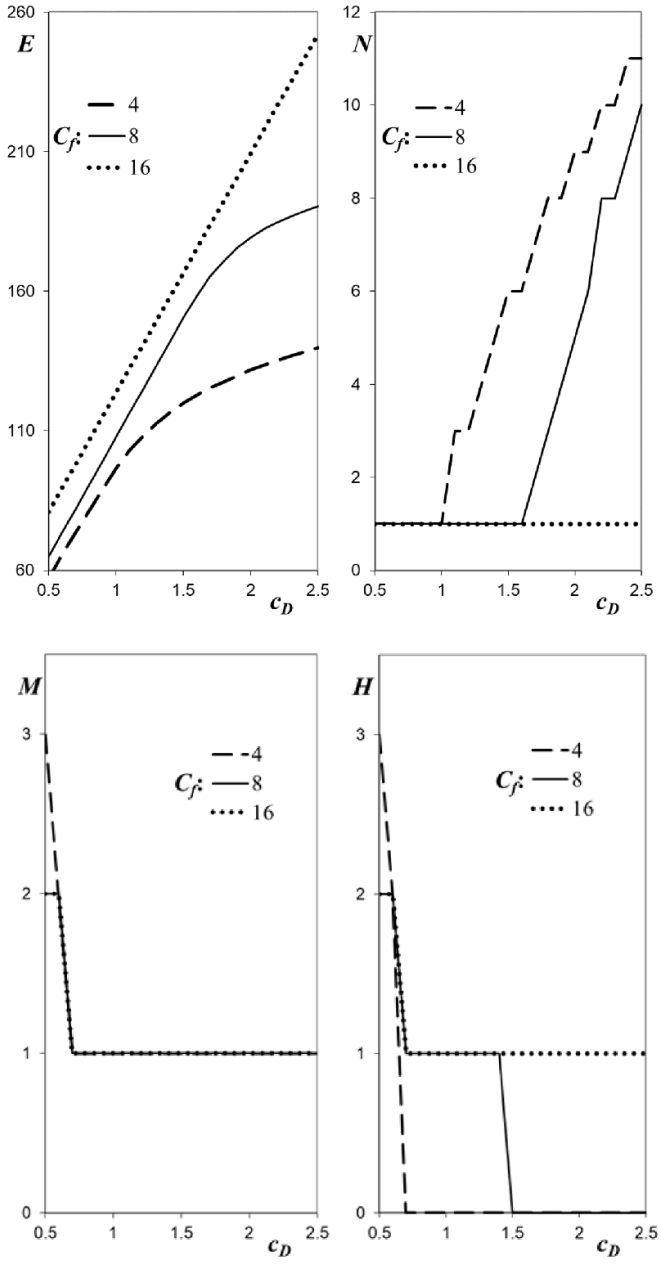


Figure 6. Optimal SBP parameters and corresponding ECTA $E(N, M, H, K)$ as functions of costs incurred by component failure and downtime.

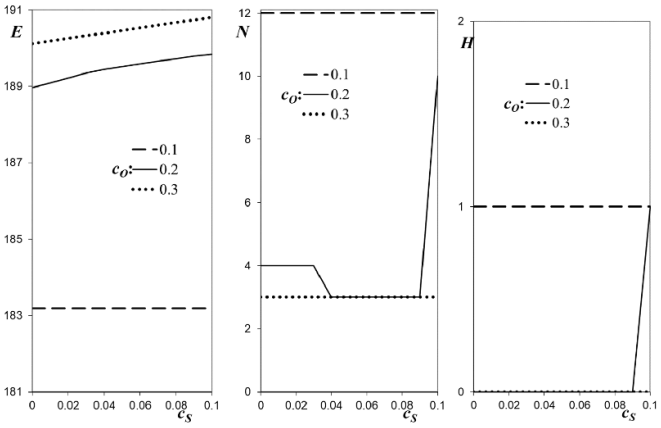


Figure 7. Optimal SBP parameters and corresponding ECTA $E(N, M, H, K)$ as functions of per unit time cost of standby and operation.

4.6. Effects of OPS and CMS arrival rates

Figure 8 shows the optimal values of N, M, H and the corresponding ECTA E as functions of shock rates for CMS and OPS for $c_D = 2$. When the CMS rate is low ($\Lambda = 0.05$), it is beneficial to always keep a component in the STM because this component is exposed only to the CMS process. It is also beneficial to replace the operating component when it experiences at least one shock before inspections. The number of inspections N decreases when the OPS rate λ exceeds 0.21.

When the CMS rate reaches the value of $\Lambda \geqslant 0.1$ and the OPS rate remains relatively small ($\lambda < 0.18$), the number of inspections remains high, and $M = H = 1$, which means that the operating component is replaced when it experiences at least one shock before inspection and no standby component is used. When the OPS rate increases, the SBP changes to $M = 1$ and $H = 0$, which means that the operating component is replaced, and the standby component is applied. A further increase in the OPS rate to above 0.24 leads to the SBP in which the operating component is never replaced upon inspection. The increasing downtime in this case is compensated by allowing replacing the standby component that has experienced at least one shock when the operating component experienced H shocks (H increases in λ from 0 to 2).

When the CMS rate reaches the value of $\Lambda \geqslant 0.2$, the SBP changes from a certain value of the shock rate λ from replacing the operating component experiencing one shock to not replacing the operating component until its failure and using no standby components ($M = H = Z = 7$). This change in the SBP allows to decrease the excessive number of component failures though causing an increase in the mission downtime.

For the same reason, the number of inspections drops as both shock rates increase. When $\Lambda = 0.3$, only a single inspection is used. Intuitively, the ECTA increases with increasing shock rates.

Figure 9 presents the optimal values of N, H and the corresponding ECTA E as functions of CMS and OPS rates for $c_D = 4$ (for all the optimal solutions $M = K = 1$). Unlike the case presented in figure 8, when c_D is high, reducing the downtime becomes more important than reducing the number of components' failures.

In the case of the CMS rate being low ($\Lambda \leqslant 0.1$), the optimal SBP presumes always keeping a component to the STM to back up the operating component ($M = 1$, $H = 0$). The number of inspections is greater than that for $c_D = 2$ and increases in both Λ and γ, which allows one to replace operating and standby components frequently and keep low downtime.

When the CMS rate is higher ($\Lambda > 0.1$), the optimal SBP presumes using no standby components but compensates it by very frequent inspections in which the operating component can be replaced. However, with such a high number of replacements, the number of failed components can increase sharply

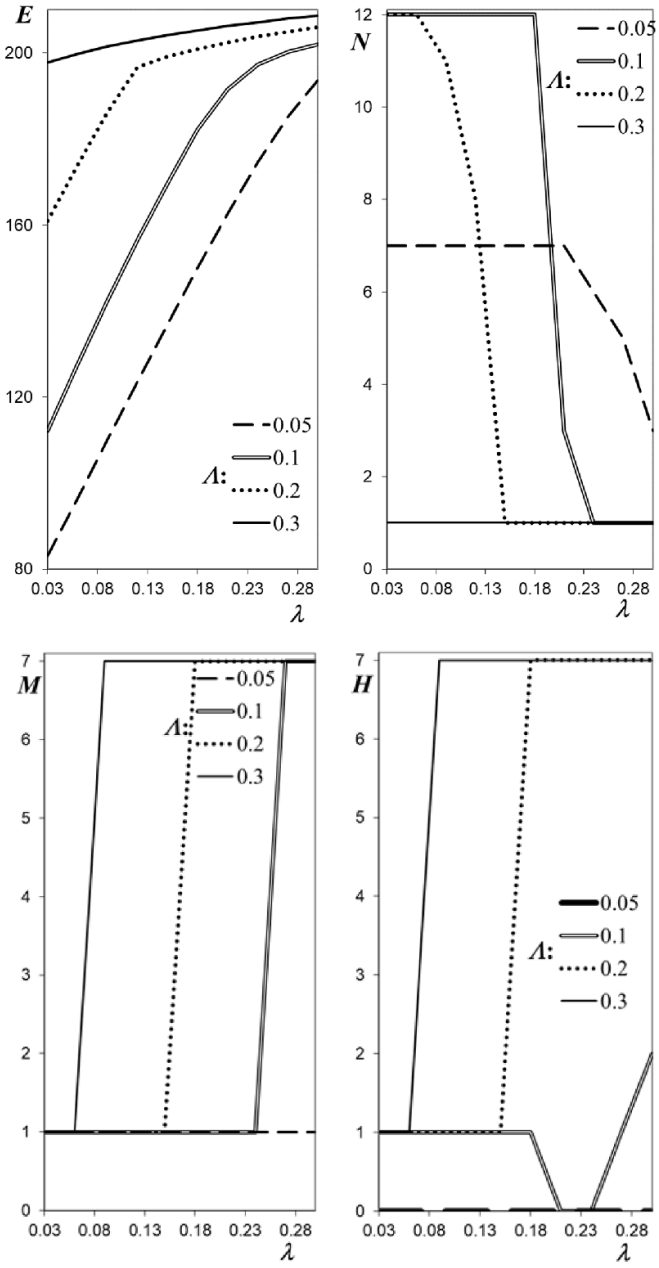


Figure 8. Optimal SBP parameters and corresponding ECTA $E(N,M,H,K)$ as functions of CMS rate and OPS rate for $c_D = 2$.

as the shock rates increase and the increase in the expected failure cost can exceed the savings associated with the downtime cost reduction. Therefore, for high values of shock rates, the number of inspections declines to keep the balance between the failure and downtime costs.

5. Conclusion and future research problems

We model standby systems where the operating component and the standby component may be replaced according to the component and shock statuses revealed through periodic inspections. Two independent shock processes from different

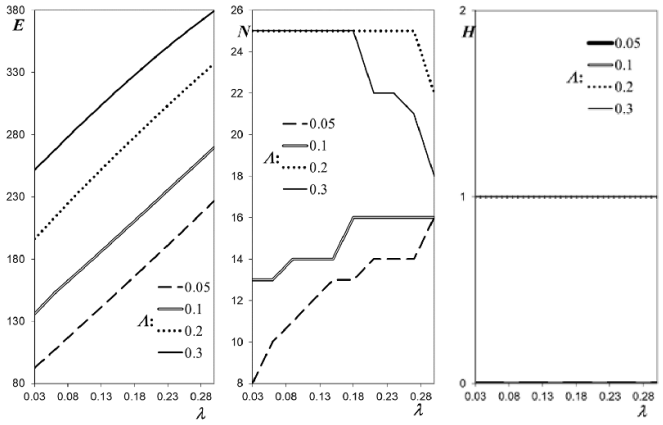


Figure 9. Optimal SBP parameters and corresponding ECTA $E(N,M,H,K)$ as functions of CMS rate and OPS rate for $c_D = 4$.

sources affecting different sets of components are considered. To optimize the standby system performance, a system state transitions-based numerical procedure has been proposed to assess the ECTA and an ECTA minimization problem has been further solved to identify the optimal inspection and shock-based SBP. As illustrated by the analysis of a sensor standby system, the proposed ECTA numerical evaluation procedure can converge rapidly. The comparison between the SBP and the TBP of [47] reveals that the SBP can obtain lower ECTA, and the difference increases as the inspection cost decreases, implying more inspections performed during the mission.

In the case study, we examine the influences of shock rates and key cost parameters on ECTA and on the optimization results, providing managerial guidance including

(1) As the cost of placing components into the OPM (A_O) and STM (A_S) increases, the ECTA increases, making it less beneficial to add or replace components. The optimal number of inspections when these actions can be carried out decreases.
(2) As A_O increases and A_S decreases, it is more beneficial to keep a component in the STM.
(3) As the cost of system downtime c_D increases, the overall ECTA increases, and it is beneficial to carry out more inspections to replace or refill the operating component timely.
(4) As the component failure cost C_F increases, the overall ECTA increases, and it is beneficial to conduct fewer inspections, which prevents placing too many components to the STM.
(5) With the low operation cost (c_O), it is beneficial to perform many inspections to keep a component in the OPM as much time as possible and no standby component is needed.
(6) As the CMS and OPS arrival rates increase, the ECTA increases and the optimal number of inspections drops, balancing the failure and downtime costs.

In the proposed model, only external shocks can deteriorate system components, and all the system components are identical. One direction of our future work is to consider internal deterioration of heterogeneous components in addition to the impact of external shocks. Another direction is to model standby systems with more than one online operating component as well as multiple standby components. The proposed model could also be extended to consider adaptive replacement policies where the values of parameters *M, H*, and *K* can be changed. In addition, we are interested in addressing imperfect switching or mode transfer mechanisms [56, 57] and inspections with imperfect detection of the number of occurred shocks, which can be modeled based on [58]. The model with dynamic parameters should also be developed and analyzed. Machine learning methods [59, 60] like reinforcement learning and Markov decision process could be explored for determining the optimal SBP.

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Conflict of interest

The authors declare no conflict of interest.

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