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Reliability Optimization for Series Systems under Uncertain Component Failure Rates in the Design Phase

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Abstract

We develop an optimization model to determine the reliability design of critical components in a serial system. The system is under a service contract, and a penalty cost has to be paid by the OEM when the total system down time exceeds a predetermined level, which complicates the evaluation of the expected cost under a given reliability design. Furthermore, in the design phase for each critical component, all possible designs are subject to uncertain component failure rates. Considering the computational intractability of evaluating the system performance, we develop approximate evaluation methods which take the system uncertainty into account. Numerical results show that the method which includes randomness in the number of failures, failure rates and repair times leads to efficient and accurate evaluations and to close-to-optimal design decisions when used in an enumeration procedure for the optimization problem. We also show that ignoring these three types of uncertainty may result in bad design decisions.

Key words: Capital goods, Reliability optimization, Performance-based contracting, Life cycle cost

1. Introduction

Capital goods are machines or products that are used by manufacturers to produce their end-products or that are used by service organizations to deliver their services. Advanced technical systems such as medical systems, manufacturing systems, and defense systems, are examples of capital goods that are critical for the operational processes of their customers. System downtime of these capital goods can have serious consequences (e.g., millions of euros of reduced production output, extra waiting time of passengers,
failure of military missions) and maintaining these high-tech systems is too challenging for customers to take care of by themselves. Original equipment manufactures (OEMs) can take care of the maintenance and guarantee high system availability levels. These OEMs can be seen as performance providers rather than only solution providers (Helander and Möller, 2007). The guaranteed system availability levels are generally specified in Service Level Agreements (SLAs) within service contracts. Customers pay a price for the service contracts. When an OEM fails to meet the predetermined level of availability, the OEM needs to pay a penalty cost to the customer. Different types of service contracts are mentioned in Cohen et al. (2006), among which performance-based contracts (PBCs). According to Guajardo et al. (2012), “Performance-based contracting compensates the supplier based on the same outcome that the customer cares about (i.e., product utilization), and hence the supplier is motivated to increase product performance, associated with metrics such as product reliability and availability”. Therefore PBCs are a certain type of service contracts, in which system performance translates into financial bonuses and penalties (Selviaridis and Wynstra, 2015). In the main model studied in this paper, we include the penalty side of a PBC contract. We also show how the bonus side can be included (see Section 6.1).

Under a SLA on system availability, one of the OEM’s major concerns is the life cycle cost (LCC), defined as the total cost incurred in the design/development, production, operation, maintenance, support, and final disposition of a system over its anticipated useful life span (Barringer and Weber, 1996). There is literature aiming at cost saving under such a SLA (Öner et al., 2010). Measurements reported in Öner et al. (2007) for an engineer-to-order system show that the sum of maintenance cost and downtime cost is larger than the acquisition cost and constitutes a significant portion of the LCC. The service cost is incurred by system failures which are highly determined by system designs. Therefore, it is important that the LCC is taken into account in the reliability design decision.

Customers of capital goods measure the availability of these complex systems at the end of service contract periods. In the literature (Al Hanbali and Van der Heijden, 2013, De Souza E Silva and Gail, 1986 and Takacs, 1957), this availability during a service contract period is denoted as the interval availability. The realized interval availability of a capital good should meet the required performance levels. When the interval availability is below its target, or equivalently, when the interval downtime is above the target down-time, the OEMs will pay a penalty cost to the customer that is generally proportional to the exceedance. Therefore, it is important for the OEMs to have a method to determine the exceedance of the target downtime under a given design. This method can then be used when optimizing the reliability design.
In reality, engineers have to select a certain design from all possible alternatives for each critical component in a system during the design phase. The outcome of any development process for a certain design is uncertain with respect to its reliability level. For example, since the failure mechanisms of some emerging technologies (e.g., micro-electromechanical systems) are complex, it is often difficult to predict the actual reliability levels of the critical components before the development. Therefore newly-designed devices have been found to have component failure rates that deviate significantly from the expectations after the completion of a design. Brown and Burke (2000) and Brown et al. (2004) showed how individual system failure rates can deviate from the average failure rate of a population of similar equipment by collecting empirical data from the power delivery industry. This uncertainty in component failure rates also needs to be considered in the reliability design.

In this paper, we study the system reliability design problem by minimizing the LCC and considering both uncertain component reliability and interval availability under a SLA on system availability. So far, this problem has not been studied in the literature. For this new problem, our contribution is as follows. The key issue is the calculation of the exceedance of the target downtime under a given reliability design. In this calculation, one needs to take three uncertainties into account: the uncertainty in the component failure rates, the stochastic nature of the number of failures during a service contract period, and the stochastic repair times. This may be done by simulation, but that leads to a relatively long computation time per evaluation of a reliability design and to too long computation times for the optimization problem for instances of a reasonable size. Therefore, we propose a fast approximate evaluation method that takes all three uncertainties into account. This method is called the full-uncertainty method. We compare its performance to the performance of two other methods: a stochastic method ignoring the uncertain failure rates (partial method), and a deterministic method using expected total downtime as the actual total downtime (zero-uncertainty method). These approximate evaluation methods are also used in an optimization procedure for the reliability design, and hence lead to heuristic solutions for the reliability design problem. We show that the full-uncertainty method clearly outperforms the other two methods, both for the evaluation of a given design and when used in an enumeration procedure for the optimization problem. The use of the other two methods for the optimization problem may lead to bad reliability design decisions.

The remainder of the paper is organized as follows. In Section 2, we briefly review related literature. Section 3 gives the model description and model formulation. We describe the three approximate evaluation methods in Section 4. The numerical results are presented in Section 5. In Section 6, we first discuss how the bonus side of a PBC
contract can be included. Next, we show the extension to a contract period with multiple subperiods and an interval availability target per subperiod. Conclusions and directions for future research are presented in Section 7.

2. Literature

We review the literature regarding the main characteristics of our problem: Interval availability, reliability optimization, and uncertain component failure rates.

As defined by Nakagawa and Goel (1973), interval availability is the fraction of time that a system is operational during a time period \([0, T]\). In the literature, several methods have been proposed to measure interval availability during a service period. Takacs (1957) considers a general stochastic on-off process and derives an exact expression for the distribution function of the total length of the off periods during a time period \([0, T]\). These off periods may represent the availability of a technical system. The exact expression has a high computational complexity, so that it can only be used for smaller problem instances. In Van der Heijden (1988), an approximate evaluation of the interval availability distribution is developed based on two-moment fits for the on and off periods. This method is accurate and can solve large problem instances in short computation times. De Souza E Silva and Gail (1986) consider a Markov process on a finite state space, where a subset of states represents 'good states' and they derive an exact expression for the distribution function of the total amount of time that the Markov process is in good states during a time period \([0, T]\). The good states may represent states in which a given technical system works. Also this exact expression of De Souza E Silva and Gail (1986) has a high computational complexity, so that it only can be used for smaller problem instances. Al Hanbali and Van der Heijden (2013) consider a two-echelon spare parts inventory system consisting of a single depot and multiple bases, and they study the logistics availability of technical systems installed at the bases during a time period \([0, T]\). They derive an approximate Markov process where a subset of states corresponds with logistics availability. They follow a numerical approach that can solve large problem instances within reasonable computation times. For more references and approaches on interval availability, we refer to the literature discussion in Al Hanbali and Van der Heijden (2013).

The evaluation of a given reliability design is related to the interval availability literature. Like Takacs (1957) and De Souza E Silva and Gail (1986), we derive an exact formula for exceedance of the target downtime, which is equivalent to deriving the distribution function of the interval availability. Our formula is different because we assume that the off periods are very short and they occur according to Poisson processes. In addition, we have to take uncertainty in the failure rates into account. Next we develop approximate,
numerical approaches in order to be able to evaluate large problem instances. In these numerical approaches, we use two-moment fits, which is a general technique that was also used by Van der Heijden (1988). Nevertheless, our approach differs because it is based on a different exact formula.

Regarding reliability optimization, a lot of work has been done in this area since the 1990s (Kuo and Wan (2007)). For example, Mettas and Kallenberg (2000) determined the minimum required reliability for each component of a system in order to achieve a system reliability goal with minimum cost. The cost function for each component in this paper has been used in other papers as well; see e.g. Huang et al. (2007), Öner et al. (2010), and Jin and Wang (2012). Many papers maximize the system reliability by different techniques. For example, a random search process has been proposed by Beraha and Misra (1974) to determine the optimal reliability for each stage of a multi-stage system. Hwang (1975) used sequential unconstrained minimization, and Li and Haines (1992) developed a 3-level decomposition approach to allocate the resources among subsystems optimally.

Some papers also built reliability allocation models to find optimal warranty policies for systems sold with traditional warranty contracts. For example, to minimize the system LCC, Monga and Zuo (1998) used genetic algorithms to solve the optimization problem and Öner et al. (2010) introduced a decision support model to jointly optimize the reliability level and spare parts inventory level of a single-component system. To max-
imize the profit, Huang et al. (2007) proposed a model to compute the optimal warranty policy under different market situations by using the maximum principle method. Park et al. (2015) formulated a model to determine the optimal warranty period for the manufacturer. They minimize the warranty cost consisting of the repair cost and downtime cost. In recent years a growing number of papers built reliability optimization models within the context of service contract. Jin and Tian (2012) developed a model to optimize the reliability design and inventory level. They minimize the life cycle cost under a non-stationary demand rate, and consider a dynamic stocking policy. Selçuk and Ağralı (2013) jointly optimized reliability levels of components and stock levels of spare parts for a multi-item system. They minimize the sum of holding and emergency shipment cost subject to different types of service constraints. Jin et al. (2015) integrated spare part inventory, maintenance and repair capacity into one model. They maximize the utility of both the supplier and the customer within a game-theoretic framework. They use a gradient-based heuristic and a hybrid algorithm to solve the problem for a single-item system and multi-item system, respectively. Öner et al. (2013) minimize the LCC of a number of identical systems by jointly optimizing the component redundancy and spare parts inventory.

In most previous work on the system reliability optimization problem (see e.g. Kuo and Wan, 2007, Jin and Wang, 2012, Kim et al., 2017), all parameters are assumed to be precise. However in reality there is considerable uncertainty and inaccuracy in the estimation of model parameters. In particular, one has uncertain reliability. To measure the uncertain system reliability due to insufficient component-level failure data, Coit (1997), Jin and Coit (2001), and Ramirez-Marquez and Levitin (2008) estimated the confidence intervals of the system reliability for different systems. Hussain and Murthy (1998) developed a model to determine the optimal redundancy design considering quality uncertainty due to manufacture variability, and obtained the best tradeoff between the manufacturing cost and warranty cost. In Hussain and Murthy (2003), the uncertain component failure rate has been modeled by a reliability growth model, and an optimization model has been proposed to find the best trade-off between the development cost and the warranty cost. Feizollahi and Modarres (2012) proposed a reliability design framework to address the uncertain component failure rates by using the Min-Max regret (also known as robust deviation) approach and transformed the nonlinear programming formulation to a linear binary version to get the exact solutions. None of the above works considered interval availability.

In this paper, we focus on the cases in which all three aspects in Figure 1 are considered. We propose a reliability optimization model with uncertain component failure rates and approximately evaluate the LCC under an interval availability constraint (as
3. Model

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
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<tbody>
<tr>
<td>$I$, $</td>
<td>I</td>
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<tr>
<td>$J_i$, $</td>
<td>J_i</td>
</tr>
<tr>
<td>$T$</td>
<td>length of the service period</td>
</tr>
<tr>
<td>$x_{ij}$</td>
<td>decision variable for whether design $j$ of component $i$ is selected or not</td>
</tr>
<tr>
<td>$x_i = (x_{i1}, x_{i2}, \ldots, x_{ij_i})$</td>
<td>the alternative that has been chosen for component $i$</td>
</tr>
<tr>
<td>$x = (x_1, x_2, \ldots, x_{</td>
<td>I</td>
</tr>
<tr>
<td>$B_{ij}$, $B_i(x_i)$</td>
<td>random repair time for design $j$ of component $i$ and for component $i$</td>
</tr>
<tr>
<td>$B_i^{(s)}(x_i)$</td>
<td>Sum of $s$ independent repair times for component $i$</td>
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<tr>
<td>$r_{ij}$, $v_{ij}$</td>
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<tr>
<td>$S_{ij}$, $S_i(x_i)$</td>
<td>number of failures in $[0, T]$ of design $j$ of component $i$ and of component $i$</td>
</tr>
<tr>
<td>$\Lambda_{ij}$, $\Lambda_i(x_i)$</td>
<td>failure rate of design $j$ of component $i$ and of component $i$</td>
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<td>$f_{\Lambda_{ij}}$, $\mu_{ij}$, $\sigma_{ij}$</td>
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<td>$D_{ij}$, $D_i(x_i)$, $D(x)$</td>
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<tr>
<td>$D_0$</td>
<td>target downtime of the system</td>
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<tr>
<td>$c_{ij}$, $c^p$</td>
<td>repair cost for each failure of design $j$ of component $i$, penalty rate for the exceeded downtime</td>
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<tr>
<td>$c_{ij}^a$, $A_i(x_i)$, $A(x)$</td>
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</tr>
<tr>
<td>$R_i(x_i)$, $R(x)$</td>
<td>expected repair cost of component $i$ and of the system in $[0, T]$</td>
</tr>
<tr>
<td>$P(x)$</td>
<td>expected system penalty cost in $[0, T]$</td>
</tr>
<tr>
<td>$\pi(x)$</td>
<td>expected LCC in $[0, T]$</td>
</tr>
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</table>

During the design phase of a single system, engineers have to select a certain design from all possible alternatives for each critical component in the system. Suppose the system is comprised of a set of critical components $I$; the components are numbered $1, 2, \ldots, |I|$. If one of these critical components fails, the system as a whole stops working. For each critical component, one design needs to be selected from possible alternatives denoted by $J_i$; these alternatives are numbered $1, 2, \ldots, |J_i|$. Each design candidate in $J_i$ has its own uncertain failure rate and its own cost and repair parameters. We aim to find the optimal combination of designs for the system so that the expected LCC over the service period $[0, T]$ of a service contract is minimized (so, $T$ denotes the length of the service period).

We assume that the failure process of each design for each component is independent of other components and their designs, and it follows a Poisson process. This implies that the lifetimes of the components are independent and exponentially distributed. For a certain design $j$ of component $i$ ($i \in I$, $j \in J_i$), we denote its failure rate as $\Lambda_{ij}$. The outcome of any development process for a certain design is uncertain. Therefore, the failure rate $\Lambda_{ij}$ of design $j$ for component $i$ is usually not known for sure before the development of the
design. We use \( f_{\Lambda_{ij}}(\cdot) \) as the probability density function of the random failure rate \( \Lambda_{ij} \) before the development of the design, which reflects the prior belief/information about the failure rate uncertainty of the technologies used in the design. The expectation and standard deviation of \( \Lambda_{ij} \) are denoted by \( \mu_{ij} \) and \( \sigma_{ij} \); it is assumed that \( \mu_{ij} > 0 \). In the evaluation of the expected LCC over the service period \([0, T]\), these design uncertainties will be taken into account.

The system will be sold together with a SLA over a service period \([0, T]\). The OEM is responsible for all repairs in \([0, T]\). Moreover the total downtime of the service period should be lower than a predetermined level \( D_0 \). A penalty cost will be paid by the OEM to compensate the customer if the total downtime exceeds \( D_0 \). As a result, the expected total cost of a system over \([0, T]\) consists of three parts: (a) acquisition cost, (b) repair cost, and (c) penalty cost.

Define the binary decision variable \( x_{ij} \) as

\[
x_{ij} = \begin{cases} 
1 & \text{if design } j \text{ for component } i \text{ is selected}, \\
0 & \text{otherwise}.
\end{cases}
\]

The OEM selects one design from all possible candidates for each component, so we have \( \sum_{j \in J_i} x_{ij} = 1 \). The vector of \( x_{ij} \)-s of a given component \( i \), \( x_i = (x_{i1}, x_{i2}, \ldots, x_{i|J_i|}) \) denotes which component design has been chosen for component \( i \). The failure rate of the chosen design for component \( i \in I \) is denoted by \( \Lambda_i(x_i) \). The vector of \( x_i \)-s, \( x = (x_1, x_2, \ldots, x_{|I|}) \), denotes the selection of a design for each component. The expected LCC, denoted by \( \pi(x) \), is the sum of the total design cost \( A(x) \), the expected system repair cost \( R(x) \) and the expected penalty cost \( P(x) \). These functions are further developed in Subsections 3.1-3.3.

Due to the randomness of the failure rates and the occurrence of failures according to Poisson processes, the total life cycle cost is random. We assume that the OEM is risk-neutral (Kim et al., 2007) and hence aims to minimize the expected LCC \( \pi(x) \). Our optimization problem is formulated as:

\[
\begin{align*}
(P) \quad & \min_x \pi(x) \\
\text{s.t.} \quad & \sum_{j \in J_i} x_{ij} = 1, \quad \text{for all } i \in I \\
& x_{ij} \in \{0, 1\}, \quad \text{for all } i \in I, j \in J_i
\end{align*}
\]

where \( \pi(x) = A(x) + R(x) + P(x) \).

**Remark 1.** The service period, referring to the contract period of the OEM and its
customer, is assumed to cover a large part of the life time of the system. Its length is $T$, and may be 20-30 years. The service period itself is denoted by the interval $[0, T]$. LCC is defined as the sum of all costs incurred in $[0, T]$. We assume that the acquisition cost is incurred at time 0. After the service period, the system may still be used for another period, but this can depend on various factors such as the state of the system, how well the system meets the requirement of the customer at that time, and the alternative systems that can be bought at that time. We assume that the value of the system at the end of the service period is negligible relative to all costs included in our model.

Remark 2. We assume constant failure rates. For electronic parts, as mentioned in Minges (1989), this assumption is reasonable. Hence, our model fits for systems with mainly electronic parts. Our model may also fit for systems with components that degrade over time, such as most mechanical parts. If the increase in the failure rates is limited for all components and no preventive maintenance is applied, then assuming constant failure rates may still be appropriate. For each component, the failure rate can be taken equal to the average failure rate during the lifetime of the component. If some components would have a strongly increasing failure rate, then it is likely that preventive maintenance is applied and then our model would not fit (i.e., one would have to develop a more advanced model that models the preventive maintenance policy and in which the preventive maintenance policy is adapted over time depending on the realizations of lifetimes of the component).

3.1. Acquisition cost

Let $c_{ij}$ denote the cost of designing and manufacturing component $i$ according to design $j$ ($i \in I$, $j \in J_i$). For the design, it includes all involved cost elements, e.g., for human resources, experimental equipment, and testing or prototype units. The acquisition cost for component $i$ is given by

$$A_i(x_i) = \sum_{j \in J_i} c_{ij}x_{ij},$$

and the total system acquisition cost is given by

$$A(x) = \sum_{i \in I} A_i(x_i) = \sum_{i \in I} \sum_{j \in J_i} c_{ij}x_{ij}. \quad (1)$$

Obviously, this formula enables a simple exact evaluation of the total acquisition cost under a given design.

3.2. Repair cost

When a failure occurs in period $[0, T]$, a repair will be performed by the OEM. Let $c_{ij}$ be the repair cost for each failure of the $j$-th design for component $i$ ($i \in \{1, 2, ..., |I|\}$,
\( j \in \{1, 2, \ldots, |J_i|\} \). The repair cost \( c_{ij}^r \) corresponds to diagnosis cost, replacement cost, and other service costs for each repair. Let \( S_i(x_i) \) denote the total number of failures for component \( i \) during \([0, T]\). The expected number of repairs for component \( i \) during \([0, T]\) is given by:

\[
E[S_i(x_i)] = E[\Lambda_i(x_i)T] = \sum_{j \in J_i} E(\Lambda_{ij})Tx_{ij} = \sum_{j \in J_i} \mu_{ij}Tx_{ij},
\]

where \( \Lambda_i(x_i) = \sum_{j \in J_i} \Lambda_{ij}x_{ij} \) is the random failure rate of component \( i \) given a certain design implied by vector \( x_i \). The expected repair cost for component \( i \) is expressed by:

\[
R_i(x_i) = \sum_{j \in J_i} E(\Lambda_{ij})Tc_{ij}x_{ij} = \sum_{j \in J_i} \mu_{ij}Tc_{ij}x_{ij}.
\]

The expected system repair cost in \([0, T]\) is given by:

\[
R(x) = \sum_{i \in I} R_i(x_i) = \sum_{i \in I} \sum_{j \in J_i} \mu_{ij}Tc_{ij}x_{ij}.
\]

(2)

Obviously, this formula enables a simple exact evaluation of the total repair cost under a given design.

3.3. Penalty cost

We assume that the repair time per failure of component \( i \) with design \( j \) \((i \in I, j \in J_i)\), \( B_{ij} \), is a generally distributed random variable with mean \( r_{ij} \) and standard deviation \( v_{ij} \). We assume that this random repair time is negligibly small compared to the service period \([0, T]\) (the \( B_{ij} \) are in the order of hours while the service period \([0, T]\) is in the order of years). Hence the repair time can be assumed to have no effect on the total number of failures of a component during service period \([0, T]\). Implicitly, we already made use of this property when we determined the repair cost.

When the total system downtime over the service period \([0, T]\) exceeds \( D_0 \), a penalty cost has to be paid by the OEM to customers with a rate \( c^p \) (\( D_0 \) is at the same time scale as \( B_{ij} \)). We allow that the system downtime of each failure varies among different components with different designs. Hence the total system downtime \( D(x) \) over the service period \([0, T]\) depends on the number of failures \( S_i(x_i) \) and the repair time per failure \( B_i(x_i) \) for component \( i \in I \) in \([0, T]\). Notice that the number of failures of component \( i \), \( S_i(x_i) \), is a Poisson distributed random variable. Hence, the distribution of \( S_i(x_i) \) is given as

\[
P[S_i(x_i) = s_i] = \sum_{j \in J_i} x_{ij} \mathbb{P}(S_{ij} = s_i)
= \sum_{j \in J_i} x_{ij} \int_0^{\infty} \mathbb{P}(S_{ij} = s_i | \Lambda_{ij} = \lambda) f_{\Lambda_{ij}}(\lambda)d\lambda
= \sum_{j \in J_i} x_{ij} \int_0^{\infty} e^{-\lambda T}(\lambda T)^{s_i} \frac{s_i!}{s_i!} f_{\Lambda_{ij}}(\lambda)d\lambda,
\]
where $S_{ij}$ is the number of failures of component $i \in I$ with design $j \in J_i$. The expected penalty cost due to exceeding the target downtime $D_0$ is given as

$$P(x) = E\left\{ \left[ D(x) - D_0 \right]^+ e^p \right\} = \sum_{s_1=0}^{\infty} \sum_{s_2=0}^{\infty} \cdots \sum_{s_{|I|}=0}^{\infty} \prod_{i \in I} P \left[ S_i(x_i) = s_i \right] E \left[ \sum_{i \in I} B_i^{(s_i)}(x_i) - D_0 \right]^+ e^p. \quad (3)$$

This formula for $P(x)$ contains an $|I|$-fold summation and multiple integrations over the ranges of the random failure rates are needed per term of the summation (to obtain the probabilities $P[S_i(x_i) = s_i]$). This becomes computationally intractable even for a small number of components, for $|I| \geq 5$, say. Therefore, in the next section, approximate evaluation methods are developed.

4. Approximate evaluation

In this section, we are going to explain how to approximately evaluate a given design for the whole system. For a given $x = (x_1, x_2, \ldots, x_{|I|})$, the design cost $A(x)$ and the expected repair cost $R(x)$ can be determined by (1) and (2). These two cost terms are linear functions of the decision variables $x = (x_1, x_2, \ldots, x_{|I|})$.

For the exact evaluation of the expected penalty cost $P(x)$, we will suffer from the “curse of dimensionality” when the number of critical components is larger than 5, say, since each critical component contributes a dimension in computing the summation and its terms in (3). From (3), we can also observe that there are three types of uncertainty existing in $D(x)$ throughout $[0, T]$. The first type of uncertainty originates from the number of failures per component under a given design with a given failure rate, which is a Poisson distributed random variable. The second level of uncertainty comes from the failure rates $\Lambda_{ij}$ ($i \in I$, $j \in J_i$), which are generally distributed random variables. The third type of uncertainty is due to the stochastic repair times $B_{ij}$ ($i \in I$, $j \in J_i$).

We now introduce three approximation methods to estimate the expected penalty cost, which vary in dealing with the uncertainty types of $D(x)$. In the first evaluation method, called zero-uncertainty method, we use the expected downtime as the actual downtime, thus ignoring all three types of uncertainty. In the current literature, the uncertainty existing in the failure rates is often ignored. So, in the second evaluation method, called partial-uncertainty method, we only consider the uncertainty of the number of failures of the system and the stochastic repair times of each component and we assume the expected failure rate for the selected design per component. In the third evaluation method, called full-uncertainty method, we take all three uncertainty types of $D(x)$ into account.

All three evaluation methods are based on expressions for the first two moments of $D(x)$. They are obtained as follows. For the total downtime in $[0, T]$ of the $j$-th design
for component $i$, denoted by $D_{ij}$, the first moment is given by:

$$\mathbb{E}(D_{ij}) = \int_0^\infty \int_0^\infty \mathbb{E}
\left[
D_{ij}\left|\Lambda_{ij} = \lambda, B_{ij} = b\right.
\right] f_{\Lambda_{ij}}(\lambda) f_{B_{ij}}(b) d\lambda db = \int_0^\infty \lambda T b f_{\Lambda_{ij}}(\lambda) f_{B_{ij}}(b) d\lambda db = \mu_{ij} T \tau_{ij}$$  \hspace{1cm} (4)

For the second moment and variance of $D_{ij}$, we obtain (we use the property that, under a given failure rate, $D_{ij}$ is the sum of all compounds of a compound Poisson process in an interval $[0, T]$):

$$\mathbb{E}(D_{ij}) = \int_0^\infty \mathbb{E}
\left[
D_{ij}^2\left|\Lambda_{ij} = \lambda, B_{ij} = b\right.
\right] f_{\Lambda_{ij}}(\lambda) f_{B_{ij}}(b) d\lambda db$$

$$= \int_0^\infty \left\{\lambda T \mathbb{E}(B_{ij})^2 + \lambda^2 T^2 \mathbb{E}(B_{ij})^2\right\} f_{\Lambda_{ij}}(\lambda) d\lambda$$

$$= r_{ij}^2 (\mu_{ij}^2 T^2 + \sigma_{ij}^2 T^2 + \mu_{ij} T) + v_{ij}^2 \mu_{ij} T$$

$$\text{Var}(D_{ij}) = \mathbb{E}(D_{ij})^2 - \left[\mathbb{E}(D_{ij})\right]^2 = r_{ij}^2 (\sigma_{ij}^2 T^2 + \mu_{ij} T) + v_{ij}^2 \mu_{ij} T$$  \hspace{1cm} (5)

Then, for component $i$, we have:

$$D_i(x_i) = \sum_{j \in J_i} D_{ij} x_{ij},$$

$$\mathbb{E}[D_i(x_i)] = \sum_{j \in J_i} r_{ij} \mu_{ij} T x_{ij},$$

$$\text{Var}[D_i(x_i)] = \sum_{j \in J_i} \left[r_{ij}^2 (\sigma_{ij}^2 T^2 + \mu_{ij} T) + v_{ij}^2 \mu_{ij} T\right] x_{ij}.$$  \hspace{1cm} (6)

Finally, for the total downtime of the system in $[0, T]$, we obtain:

$$D(x) = \sum_{i \in I} D_i(x_i) = \sum_{i \in I} \sum_{j \in J_i} D_{ij} x_{ij},$$

$$\mathbb{E}[D(x)] = \sum_{i \in I} \mathbb{E}[D_i(x_i)] = \sum_{i \in I} \sum_{j \in J_i} r_{ij} \mu_{ij} T x_{ij},$$

$$\text{Var}[D(x)] = \sum_{i \in I} \text{Var}[D_i(x_i)] = \sum_{i \in I} \sum_{j \in J_i} \left[r_{ij}^2 (\sigma_{ij}^2 T^2 + \mu_{ij} T) + v_{ij}^2 \mu_{ij} T\right] x_{ij}.$$  \hspace{1cm} (8)

4.1. Zero-uncertainty method

Under the zero-uncertainty method, the downtime $D(x)$ is simply approximated by its expected value:

$$D_{zero}(x) = \sum_{i \in I} \sum_{j \in J_i} r_{ij} \mu_{ij} T x_{ij}.$$  

Then the expected excess downtime $D^E_{zero}(x)$ and penalty cost $P_{zero}(x)$ are approximated as:

$$D^E_{zero}(x) = \left[D_{zero}(x) - D_0\right]^+, \hspace{2cm} P_{zero}(x) = \left[D_{zero}(x) - D_0\right]^+ e^p.$$
4.2. Partial-uncertainty method

Under the partial-uncertainty method, the failure rates $\Lambda_{ij}$ ($i \in I$, $j \in [J_i]$) are approximated by their means $\mu_{ij}$. This is equivalent to pretending that all $\sigma_{ij}$ are equal to 0. The expressions for $\text{Var}(D_{ij})$, $\text{Var}[D_i(x_i)]$, and $\text{Var}[D(x)]$ then simplify to (see (5), (6), (8)):

\[
\begin{align*}
\text{Var}(D_{ij}) &= (v_{ij}^2 + r_{ij}^2)\mu_{ij}T, \\
\text{Var}[D_i(x_i)] &= \sum_{j \in J_i} (v_{ij}^2 + r_{ij}^2)T\mu_{ij}x_{ij}, \\
\text{Var}[D(x)] &= \sum_{i \in I} \sum_{j \in J_i} (v_{ij}^2 + r_{ij}^2)T\mu_{ij}x_{ij}
\end{align*}
\]

By (7) and (9), the coefficient of variation of $D(x)$ is given as (notice that both $E[D(x)]$ and $\text{Var}[D(x)]$ are strictly positive): $c_v(D(x)) = \frac{\sqrt{\text{Var}[D(x)]}}{E[D(x)]}$.

We now fit a mixed Erlang distribution on the mean $\mu_D = E[D(x)]$ and coefficient of variation $c_v^D = c_v(D(x))$, and then we compute the expected excess downtime based on the fitted distribution. For the two-moment fit, we use an Erlang($k - 1, k$) distribution if $0 < c_v^D \leq 1$ and a hyperexponential distribution otherwise. This is further explained below.

Suppose $0 < c_v^D \leq 1$. Then we fit an Erlang($k - 1, k$) with parameters with parameters $(k, \theta, q)$, $k \in \mathbb{N}$, $k \geq 2$, $\theta > 0$, $0 < q \leq 1$, on $\mu_D$ and $c_v^D$. We get such a fit via the following formulas (see Tijms (1994), pp. 335-337). The $k$ is chosen such that $1/k < (c_v^D)^2 \leq 1/(k - 1)$. Next, $q$ and $\theta$ are taken equal to

\[
q = \frac{1}{1 + (c_v^D)^2} \left[ k(c_v^D)^2 - \sqrt{k(1 + (c_v^D)^2) - k^2(c_v^D)^2} \right], \quad \theta = \frac{k - q}{\mu_D}
\]

Then the expected excess downtime can be approximated as (see Appendix B.2):

\[
D_{\text{part}}^E(x) = \left( \frac{k - q}{\theta} - D_0 \right) \sum_{j=0}^{k-2} \frac{(\theta D_0)^j}{j!} e^{-\theta D_0} + \left( \frac{k - q}{\theta} \right) \frac{(\theta D_0)^{k-1}}{(k-1)!} e^{-\theta D_0}.
\]

Suppose $c_v^D \geq 1$. Then we fit an hyperexponential distribution with parameters $(\theta_1, \theta_2, q)$, $\theta_1 > 0$, $\theta_2 > 0$, $0 < q \leq 1$, on $\mu_D$ and $c_v^D$. We get such a fit via the following formulas (see Tijms (1994), pp. 335-337):

\[
\theta_1 = \frac{2}{\mu_D} \left( 1 + \sqrt{\frac{(c_v^D)^2 - q}{(c_v^D)^2 + 1}} \right), \quad \theta_2 = \frac{4}{\mu_D} - \theta_1, \quad q = \frac{\theta_1(\theta_2 \mu_D - 1)}{\theta_2 - \theta_1}.
\]

Then the expected excess downtime can be approximated as (see Appendix B.2):

\[
D_{\text{part}}^E(x) = \frac{q}{\theta_1} e^{-\theta_1 D_0} + \frac{1 - q}{\theta_2} e^{-\theta_2 D_0}
\]

Finally, $P(x)$ is approximated by: $P_{\text{part}}(x) = D_{\text{part}}^E(x)c_p$. 

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4.3. **Full-uncertainty method**

Under the full-uncertainty method, we take both the uncertainty of the failure rates as well as the number of failures into account. We use the formulas (7) and (8) for the mean and variance of $D(x)$. Next, we determine the corresponding coefficient of variation by $c_v(x) = \sqrt{\frac{\text{Var}[D(x)]}{E[D(x)]}}$.

We now fit a mixed Erlang distribution on the mean $\mu_D = E[D(x)]$ and coefficient of variation $c^D_v = c_v(D(x))$, and then we compute the expected excess downtime based on the fitted distribution. These steps are the same as under the partial-uncertainty method. The resulting approximation for the expected excess downtime is denoted by $D^E_{\text{full}}(x)$. Finally, $P(x)$ is approximated by: $P_{\text{full}}(x) = D^E_{\text{full}}(x)c^p$.

5. **Computational results**

In this section, we execute two numerical experiments to test the accuracy of our approximate evaluation methods. In Section 5.1, we investigate the quality of the approximate evaluation results generated by the zero-uncertainty method, partial-uncertainty method, and full-uncertainty method under given designs; here, we compare the approximate results to simulated results. In Section 5.2, we investigate the quality of the heuristic policies generated when solving Problem (P) via enumeration and approximate evaluations.

5.1. **Experiment 1**

5.1.1. **Test bed**

To assess the quality of the three approximate evaluation methods under given designs, we compare results of these methods with simulated results. We use a Monte Carlo simulation method; see Appendix A for more details on this method. The essence of the approximate evaluation methods is that they approximate the expected excess downtime $E\{D(x) - D_0\}^+$. For the rest, no approximations are made. Hence, we compare the evaluation methods with simulation on the basis of the generated values for $E\{D(x) - D_0\}^+$.

We use a full factorial design for the test bed. We vary three factors: the number of the critical components $|I|$, the coefficient of variation $c_v$ for the component failure rates and the so-called downtime budget factor $D_f$. Per instance, we have one design per component and thus one design for the whole system. As a result, in this experiment the notation can be simplified. We distinguish one stochastic failure rate $\Lambda_i$ with mean $\mu_i$ and standard deviation $\sigma_i$ per component $i \in I$. We assume that each $\Lambda_i$ is lognormally distributed and choose the parameters of the lognormal distribution such that the mean and standard deviation are equal to $\mu_i$ and $\sigma_i$ respectively. Further, we have one mean repair time $r_i$ and one corresponding standard deviation $v_i$ per component $i \in I$. In
Table 1: Parameter settings for $|I|$, $c_v$, and $D_f$ in Experiment 1

| $|I|$ | $c_v$       | $D_f$       |
|------|------------|------------|
| 5, 25, 50, 75, 100 | 0.2, 0.5, 0.8, 1.1, 1.4 | 1, 1.05, 1.1, 1.15, 1.2, 1.25, 1.3 |

Each instance of the test bed, we take values for $\mu_i$ and $r_i$ that vary over the components $i \in I$. For the standard deviations of the failure rates $\Lambda_i$, we use $c_v$; we take $\sigma_i = c_v \mu_i$ for all $i \in I$. We assume that the standard deviations $v_i$ for the repair times are equal to 0, i.e., that the repair times are deterministic. In Section 5.1.3, we will execute an additional experiment with stochastic repair times. The factor $D_f$ is used to generate different values of $D_0$ by the following expression:

$$D_0 = D_f \sum_{i \in I} \mu_i r_i T,$$

where $\sum_{i \in I} \mu_i r_i T$ is the expected total downtime. Thus, if $D_f$ is one, the target downtime $D_0$ is set equal to the expected total downtime. The length of the service period is chosen equal to $T = 10$ years.

The test bed consists of 175 instances that are obtained by taking all combinations of the values for $|I|$, $c_v$, and $D_f$ as shown in Table 1. The values for $\mu_i$ (in failures per year) and $r_i$ (in hours) are given in Table 2. For the zero-uncertainty method, it is apparent that when $D_f \geq 1$, $D_{E_{zero}}^E = 0$. Hence, this is true for all instances. For the partial-uncertainty method, $D_{E_{part}}^E$ does not depend on the values for the $\sigma_i$, and thus we get the same outcome for all instances that only differ with respect to the value for $c_v$.

### 5.1.2. Results

Per instance of the test bed, we determine the approximations $D_{E_{zero}}^E$, $D_{E_{part}}^E$, and $D_{E_{full}}^E$ via the three evaluation methods and we determine $D_{E_{sim}}^E$ via simulation. The 95% confidence intervals of all the simulation results are relatively small (the width of a confidence interval is at most 0.001 times the simulated value $D_{E_{sim}}^E$, and hence we can use $D_{E_{sim}}$ to determine the accuracy of the approximations). Each of the approximations and the simulated excess downtime is normalized by $D_0$, which gives:

$$\hat{D}_k^E = \frac{D_k^E}{D_0}, \quad k \in \{zero, part, full, sim\}.$$

Per instance, the accuracy of each approximation is assessed by the absolute gaps for the normalized excess downtime:

$$Gap = |\hat{D}_k^E - \hat{D}_{E_{sim}}^E|, \quad k \in \{zero, part, full\}.$$
The results for these Gaps are presented in Table 3. In this table, the *Avg Gap* and *max Gap* columns show the average gap and maximum gap of each method for a group of instances that has the same value of one of the three factors. For example, the values 0.93% and 3.20% in the first row are the average and maximum gaps of the full-uncertainty method in the 35 instances with $|I| = 5$ components in the system. In the last row, the results for the whole set of 175 instances are given.

For the zero-uncertainty method, the average gap is 6.70% and the max gap is 31.93% for all instances. The average and max gap for the partial-uncertainty method is 2.39% and 12.17%, respectively. For the full-uncertainty method, the average gap is 0.25% and the maximum gap is 3.20%. The results show that the full-uncertainty method gives accurate results in general, while the zero-uncertainty method leads to a poor approximation on average. The partial-uncertainty method performs significantly worse than the full-uncertainty method. The computation time per instance of the simulation method is ranging from less than 2 minutes to 76.18 hours with an average number of 2.30 hours. For the approximation methods, the computation times are less than 0.03 seconds for each of the instances. All numerical results are run on a computer with Intel Core 2 Duo E7500 processor at 2.93GHz and 4 gigabytes physical RAM available (plus 4 gigabytes virtual memory).

Table 3: Average gap and maximum gap for the three approximate evaluation methods in Experiment 1

<table>
<thead>
<tr>
<th></th>
<th>zero-uncertainty method</th>
<th>partial-uncertainty method</th>
<th>full-uncertainty method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Avg Gap (%)</td>
<td>max Gap (%)</td>
<td>Avg Gap (%)</td>
</tr>
<tr>
<td>$</td>
<td>I</td>
<td>$</td>
<td>(%)</td>
</tr>
<tr>
<td>5</td>
<td>18.32</td>
<td>31.93</td>
<td>5.44</td>
</tr>
<tr>
<td>25</td>
<td>6.41</td>
<td>15.49</td>
<td>2.58</td>
</tr>
<tr>
<td>50</td>
<td>3.81</td>
<td>11.19</td>
<td>1.68</td>
</tr>
<tr>
<td>75</td>
<td>2.76</td>
<td>9.22</td>
<td>1.25</td>
</tr>
<tr>
<td>100</td>
<td>2.19</td>
<td>8.04</td>
<td>1.00</td>
</tr>
<tr>
<td>$D_f$</td>
<td>1</td>
<td>11.91</td>
<td>3.12</td>
</tr>
<tr>
<td>1.05</td>
<td>9.36</td>
<td>28.63</td>
<td>2.95</td>
</tr>
<tr>
<td>1.1</td>
<td>7.43</td>
<td>25.78</td>
<td>2.70</td>
</tr>
<tr>
<td>1.15</td>
<td>5.96</td>
<td>23.26</td>
<td>2.41</td>
</tr>
<tr>
<td>1.2</td>
<td>4.85</td>
<td>21.03</td>
<td>2.10</td>
</tr>
<tr>
<td>1.25</td>
<td>4.01</td>
<td>19.07</td>
<td>1.84</td>
</tr>
<tr>
<td>1.3</td>
<td>3.36</td>
<td>17.31</td>
<td>1.61</td>
</tr>
<tr>
<td>$c_v$</td>
<td>0.2</td>
<td>4.44</td>
<td>0.14</td>
</tr>
<tr>
<td>0.5</td>
<td>5.22</td>
<td>22.73</td>
<td>0.92</td>
</tr>
<tr>
<td>0.8</td>
<td>6.47</td>
<td>25.79</td>
<td>2.16</td>
</tr>
<tr>
<td>1.1</td>
<td>7.93</td>
<td>28.95</td>
<td>3.62</td>
</tr>
<tr>
<td>1.4</td>
<td>9.43</td>
<td>31.93</td>
<td>5.12</td>
</tr>
<tr>
<td>All</td>
<td>6.70</td>
<td>31.93</td>
<td>2.39</td>
</tr>
</tbody>
</table>

Under all three methods, the gaps become smaller for increasing values of $|I|$. This is due to the fact that the total downtime is the sum of $|I|$ independent random variables. The coefficient of variation of the total downtime decreases for increasing $|I|$, and thus
the effect of the uncertainties of the failure rates $\Lambda_i$ and the resulting numbers of failure in the service period $[0, T]$ decreases. For $|I| \to \infty$, the total downtime converges to the expected downtime $\sum_{i \in I} \mu_i r_i T$ in distribution; this also holds for the approximations, and thus all gaps become 0 in that case. When considering the gaps for increasing values of $D_f$, we see that they decrease under all three methods, but the decrease is much stronger for the zero-uncertainty method than for the other two methods. When considering the gaps for increasing values of $c_v$, we see that they increase under all three methods, but now the increase is much less for the full-uncertainty method than for the other two methods.

![Figure 2](image)

**Figure 2:** The probability density function for the total downtime as obtained via simulation and the full-uncertainty method for $|I| = 50$ and $c_v = 1.1$.

![Figure 3](image)

**Figure 3:** The probability density function for the total downtime as obtained via simulation and the full-uncertainty method for $|I| = 5$ and $c_v = 1.4$.

In order to better demonstrate the accuracy of the full-uncertainty method, we also compare the probability density functions and cumulative probability functions of the total downtime as obtained by simulation with the ones estimated by the full-uncertainty method; see Figure 2 and Figure 3. As we can see in Figure 2, generally, the full-uncertainty method gives an accurate approximation for the simulated curve for the probability density functions as well as the cumulative probability functions of the total
downtime for various settings of $|I|$ and $c_v$. Only when $|I| = 5$ and $c_v = 1.4$, the shape of the approximation curve for the probability density function is different from the shape of the related simulation curve when the total downtime is smaller than 20 hours. However, the approximation for the cumulative probability function is reasonable for all values of the total downtime.

5.1.3. Stochastic vs. deterministic repair time

In this section we investigate the effect of stochastic instead of deterministic repair times on the results of the previous section.

Table 4: Parameter settings for $|I|$, $c_v$, and $D_f$ in Experiment 1'

| $|I|$ | $c_v$ | $D_f$ |
|------|------|------|
| 5, 25, 50 | 0.2, 0.8, 1.4 | 1, 1.1, 1.2, 1.3 |

We use a subset of the test bed described in Section 5.1.1, see Table 4. There are 36 instances in the test bed. To simulate all instances, for stochastic repair times, we assume that the repair time per component $B_i$ is exponentially distributed with rate $r_i$, $i \in I$ (i.e., $v_i = r_i$ for all $i \in I$). The results for the stochastic and deterministic repair time test bed are shown in Table 5 and Table 6, respectively.

Table 5: Average gap and maximum gap for the three approximate evaluation methods with stochastic repair time in Experiment 1'

| $|I|$ | zero-uncertainty method | partial-uncertainty method | full-uncertainty method |
|------|------------------------|---------------------------|-------------------------|
|      | Avg Gap (%) | max Gap (%) | Avg Gap (%) | max Gap (%) | Avg Gap (%) | max Gap (%) |
| 5    | 24.37      | 30.75        | 5.52        | 12.38       | 0.77        | 2.07        |
| 25   | 9.90       | 20.01        | 3.26        | 7.76        | 0.95        | 1.72        |
| 50   | 6.40       | 14.78        | 2.41        | 6.12        | 0.87        | 1.77        |
| $D_f$ | 1         |              |             |             |             |             |
| 1.1  | 14.76      | 32.73        | 3.97        | 11.30       | 0.87        | 1.77        |
| 1.2  | 10.96      | 27.20        | 3.56        | 10.32       | 0.86        | 1.92        |
| 1.3  | 8.28       | 22.81        | 3.11        | 9.45        | 0.85        | 2.07        |
| $c_v$ | 0.2        | 9.66         | 26.65       | 0.51        | 1.83        | 0.66        | 2.07        |
| 0.8  | 13.24      | 32.82        | 3.08        | 5.45        | 0.69        | 1.06        |
| 1.4  | 17.76      | 39.75        | 7.60        | 12.38       | 1.24        | 1.77        |
| All  | 13.55      | 39.75        | 3.73        | 12.38       | 0.86        | 2.07        |

The results in Tables 5 and 6 show that the gaps under stochastic repair times are somewhat higher than under deterministic times. But, for the rest, we get the same conclusions as in Section 5.1.2. The full-uncertainty method produces accurate approximations under all parameter settings, while the zero-uncertainty method has the largest average and maximum gap. The full-uncertainty method significantly outperforms the
partial-uncertainty method. Furthermore, the gaps of the zero-uncertainty and partial-
uncertainty method and the average gap of the full-uncertainty method are changing in
the exact same directions. That is, the gap decreases for increasing values of $|I|$ and $D_f$
and increases for increasing values of $c_v$.

Table 6: Average gap and maximum gap for the three approximate evaluation methods with deterministic
repair in Experiment 1

<table>
<thead>
<tr>
<th></th>
<th>zero-uncertainty method</th>
<th>partial-uncertainty method</th>
<th>full-uncertainty method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Avg Gap (%)</td>
<td>max Gap (%)</td>
<td>Avg Gap (%)</td>
</tr>
<tr>
<td>$</td>
<td>I</td>
<td>$</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>6.69</td>
<td>15.49</td>
</tr>
<tr>
<td></td>
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<tr>
<td>$D_f$</td>
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<td></td>
<td>1.3</td>
<td>5.41</td>
<td>17.31</td>
</tr>
<tr>
<td>$c_v$</td>
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<td>6.67</td>
<td>20.62</td>
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<td></td>
<td>0.8</td>
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<td></td>
<td>1.4</td>
<td>13.24</td>
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<tr>
<td>All</td>
<td>9.79</td>
<td>31.93</td>
<td>3.32</td>
</tr>
</tbody>
</table>

The average computation time of the simulations for the stochastic repair time in-
stances is 6.14 times more than for the deterministic repair time instances. That was a
main reason to limit the analysis in this section to a subset of the whole test bed of Sec-
tion 5.1.1. Because stochastic and deterministic repair times lead to the same conclusions
and insights, we can limit ourselves to deterministic repair times in the rest of Section 5.

5.2. Experiment 2

In the second experiment, we solve Problem (P) by enumeration. In this enumeration,
simulation or one of the approximate evaluation methods can be used to evaluate each
given solution. The solution that is obtained via simulation is generally optimal or very
close to optimal. The corresponding costs are used as estimate for the optimal costs.
The use of each of the approximate evaluation methods leads to a heuristic solution for
Problem (P). We investigate the quality of these heuristic solutions. In Section 5.2.1, we
describe the test bed of Experiment 2. The quality of the heuristic solutions is discussed
in Section 5.2.2. Finally, managerial insights are given in Section 5.2.3.

5.2.1. Test bed

For the test bed for Experiment 2, we use a full factorial design, in which 5 factors
are varied. For all instances, we assume that $|I| = 10$, which is the largest $|I|$ that is
computationally tractable under the use of simulation. For the same reason, we have \(|J_i| = 2\) designs per component \(i \in I\). The five factors that are varied are as follows: the downtime factor \(D_f\), the acquisition cost \(c_{ij}^a\) \((i \in I, j \in J_i)\), the expected failure rate \(\mu_{ij}\) \((i \in I, j \in J_i)\), the coefficient of variation \(c_v\), and the penalty rate \(c^p\). The values of these five factors are given in Table 7. For each factor, we choose three values, so in total 243 instances are obtained. The target downtime \(D_0\) (in hours) is set equal to the product of \(D_f\) and the average value of the expected downtimes where the same weight is taken for all designs, i.e., \(D_0 = D_f \sum_{i \in I} \frac{1}{|J_i|} \sum_{j \in J_i} \mu_{ij} r_{ij} T\), with \(T = 10\). All repair times are assumed to be deterministic and their means \(r_{ij}\) are taken equal to \(r_{ij} = 3\) hours \((i \in I, j \in J_i)\). The length of the service period is fixed at \(T = 10\) years. The standard deviations \(\sigma_{ij}\) are set at \(\sigma_{ij} = c_v \mu_{ij}\) \((i \in I, j \in J_i)\). The cost per repair \(c_{ij}^r\) \((i \in I, j \in J_i)\) is equal to 30% of the corresponding acquisition cost \(c_{ij}^a\).

Table 7: Parameter settings for \(D_f\), \(c_{ij}^a\), \(\mu_{ij}\), \(c_v\), and \(c^p\) in Experiment 2

<table>
<thead>
<tr>
<th>Name of parameter</th>
<th>No. val.</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downtime budget factor ((D_f))</td>
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<td>1, 1.2, 1.4</td>
</tr>
<tr>
<td>Acquisition cost ((c_{ij}^a))</td>
<td>3</td>
<td>\begin{cases} c_{ij}^{a_1} : &amp; [500, \ldots, 500i, \ldots, 5000] \ c_{ij}^{a_2} : &amp; 1.5 \times [500, \ldots, 500i, \ldots, 5000] \ c_{ij}^{a_3} : &amp; [500, \ldots, 500i, \ldots, 5000] \end{cases}</td>
</tr>
<tr>
<td>Expected failure rates ((\mu_{ij}))</td>
<td>3</td>
<td>\begin{cases} \mu_1 : &amp; 0.15, 0.1, 0.14, 0.12, 0.08, 0.06, 0.04, 0.02 \ \mu_2 : &amp; 0.1, 0.12, 0.11, 0.06, 0.03, 0.02, 0.01 \ \mu_3 : &amp; 0.15, 0.14, 0.12, 0.08, 0.06, 0.04, 0.02 \end{cases}</td>
</tr>
<tr>
<td>Coefficient of variation ((c_v))</td>
<td>3</td>
<td>0.3, 0.9, 1.5</td>
</tr>
<tr>
<td>Penalty cost factor ((c^p))</td>
<td>3</td>
<td>5000, 10000, 20000</td>
</tr>
</tbody>
</table>

In our test bed, the acquisition cost of the second design of every component is higher than for the first design. So, we refer to the second design as the "expensive" design and to the first design as the "cheap" design. Notice that for the expensive design of every component, the average and standard deviation of the failure rate \(\Lambda_{ij}\) are always smaller than the ones for the cheap design. As a result, there is an incentive in all cases to choose for the expensive design.

5.2.2. Results

For each instance, we solve Problem (P) by enumeration, where 4 different methods are used for the evaluations of given solutions: simulation and each of the three approximate evaluation methods. The solution that is obtained under the use of simulation is denoted by \(x_{sim}^*\). This solution will generally be optimal or close to optimal. We use
the corresponding cost \( \pi(x_{\text{sim}}) \) as an estimate for the optimal cost. Under the use of the zero-, partial-, and full-uncertainty method, we obtain a heuristic solution \( x_{\text{zero}}^*, x_{\text{part}}^*, \) and \( x_{\text{full}}^* \), respectively. The corresponding total cost equals \( \pi(x_{\text{zero}}^*), \pi(x_{\text{part}}^*), \) and \( \pi(x_{\text{full}}^*) \), where this total cost is evaluated by simulation. For each of the heuristic solutions we determine the relative optimality gap

\[
OG_k = \frac{\pi(x_k^*) - \pi(x_{\text{sim}}^*)}{\pi(x_{\text{sim}}^*)}, \quad k \in \{\text{zero}, \text{part}, \text{full}\}.
\]

The results for the optimality gaps are given in Table 8. Per line, we give the averages over the instances with the same value for one of the 5 factors that is varied. At the last line, we give the averages over all instances. Per heuristic, we also give the percentage of instances in which the heuristic solution \( x_k^* \), \( k \in \{\text{zero}, \text{part}, \text{full}\} \), deviates from \( x_{\text{sim}}^* \) (for at least one component). This percentage is denoted by \( NOS_k \), where NOS stands for ”No Optimal Solution”. Further, we consider the percentage of components for which the expensive design is chosen under solution \( x_k^* \), \( k \in \{\text{zero}, \text{part}, \text{full}\} \), which we denote by \( PExp_k \). We compare this percentage with the corresponding percentage \( PExp_{\text{sim}} \) under \( x_{\text{sim}}^* \). The absolute difference is denoted by

\[
\Delta PExp_k = |PExp_k - PExp_{\text{sim}}|, \quad k \in \{\text{zero}, \text{part}, \text{full}\}.
\]

The averages of these absolute differences are also listed in Table 8. The computation times per instance under the use of simulation are in the order of 60-334 hours, while they are all less than one second under the use of the approximate evaluation methods.

<table>
<thead>
<tr>
<th></th>
<th>Zero-uncertainty</th>
<th>Partial-uncertainty</th>
<th>Full-uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( OG_{\text{zero}} )</td>
<td>( NOS_{\text{zero}} )</td>
<td>( \Delta PExp_{\text{zero}} )</td>
</tr>
<tr>
<td>( D_f )</td>
<td>105.7 (%)</td>
<td>100 (%)</td>
<td>71 (%)</td>
</tr>
<tr>
<td>1.2</td>
<td>83.9 (%)</td>
<td>100 (%)</td>
<td>61 (%)</td>
</tr>
<tr>
<td>1.4</td>
<td>60.1 (%)</td>
<td>100 (%)</td>
<td>49 (%)</td>
</tr>
<tr>
<td>( c_{ij} )</td>
<td>110.3 (%)</td>
<td>100 (%)</td>
<td>73 (%)</td>
</tr>
<tr>
<td>(1)</td>
<td>79.2 (%)</td>
<td>100 (%)</td>
<td>59 (%)</td>
</tr>
<tr>
<td>(2)</td>
<td>60.2 (%)</td>
<td>100 (%)</td>
<td>48 (%)</td>
</tr>
<tr>
<td>( \mu_{ij} )</td>
<td>21.9 (%)</td>
<td>100 (%)</td>
<td>47 (%)</td>
</tr>
<tr>
<td>(1)</td>
<td>72.5 (%)</td>
<td>100 (%)</td>
<td>65 (%)</td>
</tr>
<tr>
<td>(2)</td>
<td>155.3 (%)</td>
<td>100 (%)</td>
<td>68 (%)</td>
</tr>
<tr>
<td>( c^p )</td>
<td>31.8 (%)</td>
<td>100 (%)</td>
<td>45 (%)</td>
</tr>
<tr>
<td>5000</td>
<td>72.4 (%)</td>
<td>100 (%)</td>
<td>61 (%)</td>
</tr>
<tr>
<td>10000</td>
<td>145.6 (%)</td>
<td>100 (%)</td>
<td>74 (%)</td>
</tr>
<tr>
<td>( c_v )</td>
<td>80.9 (%)</td>
<td>100 (%)</td>
<td>54 (%)</td>
</tr>
<tr>
<td>0.3</td>
<td>84.9 (%)</td>
<td>100 (%)</td>
<td>61 (%)</td>
</tr>
<tr>
<td>1.5</td>
<td>83.9 (%)</td>
<td>100 (%)</td>
<td>65 (%)</td>
</tr>
</tbody>
</table>

The results in Table 8 show that the average optimality gap of the zero-uncertainty method is large. Under this method, one never obtains the optimal solution (i.e., one gets always another solution than \( x_{\text{sim}}^* \)) and chooses much less frequently for the expensive
designs of components than under $x^*_\text{sim}$. The average optimality gap of the partial-uncertainty method is only 1.61%, while in 51.0% of the instances another solution is obtained than $x^*_\text{sim}$. The average optimality gap of the full-uncertainty method is 0.02%, which is very low. This method gives the same solution as $x^*_\text{sim}$ in 86.4% of the instances and only in 13.6% of the instances a slightly different solution is obtained. We may conclude that the full-uncertainty method generates the best heuristic solutions. This method performs very well, both in terms of the total cost of the generated solution and in terms of the generated solution itself. Hence, this method is very appropriate to solve Problem (P).

5.2.3. Managerial insights

In this section, we further analyze the close-to-optimal solutions $x^*_\text{full}$ generated by the full-uncertainty method. Extra results of these solutions are given in Table 9 and Table 10. In Table 9, first of all we list $P\text{Exp}_{\text{full}}$, the percentage of components for which the expensive design is chosen. We give the average, maximum, and minimum value over all (last line) or subgroups (other lines) of instances. Next, we give results for $PPC_{\text{full}}$, which denotes the probability that a penalty cost has to be paid, i.e., the probability that the total downtime exceeds the target $D_0$. We also give results for the expected exceeded downtime $D_{\text{E}}(x^*_\text{full})$ and for the same downtime but then divided by the target value $D_0$. In Table 10, we consider the changes in the objective function under $x^*_\text{full}$, i.e., in comparison to the optimal cost $\pi^*_\text{ref}$ that has been obtained for a reference instance. The reference instance is defined as the instance where the second value is chosen for each of the parameters listed in Table 7. For this reference instance, the values

<table>
<thead>
<tr>
<th>$D_f$</th>
<th>$P\text{Exp}_{\text{full}}$ (%)</th>
<th>$PPC_{\text{full}}$ (%)</th>
<th>$D_{\text{E}}(x^*_\text{full})$ (hrs)</th>
<th>$D_{\text{E}}(x^*_\text{full})/D_0$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg.</td>
<td>max</td>
<td>min</td>
<td>Avg.</td>
<td>max</td>
</tr>
<tr>
<td>1</td>
<td>70.37</td>
<td>90.00</td>
<td>70.37</td>
<td>25.99</td>
</tr>
<tr>
<td>1.2</td>
<td>61.11</td>
<td>90.00</td>
<td>10.00</td>
<td>17.76</td>
</tr>
<tr>
<td>1.4</td>
<td>50.49</td>
<td>90.00</td>
<td>10.00</td>
<td>12.71</td>
</tr>
<tr>
<td>$c_{ij}$ (1)</td>
<td>73.83</td>
<td>90.00</td>
<td>20.00</td>
<td>15.12</td>
</tr>
<tr>
<td>(2)</td>
<td>59.14</td>
<td>90.00</td>
<td>10.00</td>
<td>18.82</td>
</tr>
<tr>
<td>(3)</td>
<td>49.01</td>
<td>90.00</td>
<td>10.00</td>
<td>22.52</td>
</tr>
<tr>
<td>$\mu_{ij}$ (1)</td>
<td>48.52</td>
<td>90.00</td>
<td>10.00</td>
<td>27.30</td>
</tr>
<tr>
<td>(2)</td>
<td>65.68</td>
<td>90.00</td>
<td>20.00</td>
<td>18.57</td>
</tr>
<tr>
<td>$c_p$ 5000</td>
<td>45.80</td>
<td>90.00</td>
<td>20.00</td>
<td>23.47</td>
</tr>
<tr>
<td>10000</td>
<td>61.85</td>
<td>80.00</td>
<td>10.00</td>
<td>17.95</td>
</tr>
<tr>
<td>20000</td>
<td>74.32</td>
<td>90.00</td>
<td>10.00</td>
<td>15.04</td>
</tr>
<tr>
<td>$c_v$ 0.3</td>
<td>53.83</td>
<td>90.00</td>
<td>20.00</td>
<td>17.92</td>
</tr>
<tr>
<td>0.9</td>
<td>60.86</td>
<td>90.00</td>
<td>10.00</td>
<td>18.55</td>
</tr>
<tr>
<td>1.5</td>
<td>67.28</td>
<td>90.00</td>
<td>10.00</td>
<td>20.00</td>
</tr>
<tr>
<td>All</td>
<td>60.66</td>
<td>90.00</td>
<td>10.00</td>
<td>18.82</td>
</tr>
</tbody>
</table>

$\pi(x^*_\text{full})$ in comparison to the optimal cost $\pi^*_\text{ref}$ that has been obtained for a reference instance. The reference instance is defined as the instance where the second value is chosen for each of the parameters listed in Table 7. For this reference instance, the values
of $\pi^*_\text{ref}$, and the underlying cost terms $A^*_\text{ref}$, $R^*_\text{ref}$ and $P^*_\text{ref}$ are 64666, 43000, 9998 and 11669, respectively. We list values for the ratio of the total cost of a given instance and the total cost in the reference instance. This ratio is equal to $\pi(x^*_\text{full})/\pi^*_\text{ref}$. Similarly, we list ratios for the underlying cost components, i.e., we list values for $A(x^*_\text{full})/A^*_\text{ref}$, $R(x^*_\text{full})/R^*_\text{ref}$, and $P(x^*_\text{full})/P^*_\text{ref}$.

Table 10: Analysis of the solutions $x^*_\text{full}$ generated by the full-uncertainty method - Part 2

<table>
<thead>
<tr>
<th>$D_f$</th>
<th>$\pi(x^<em>_\text{full})/\pi^</em>_\text{ref}$</th>
<th>$A(x^<em>_\text{full})/A^</em>_\text{ref}$</th>
<th>$R(x^<em>_\text{full})/R^</em>_\text{ref}$</th>
<th>$P(x^<em>_\text{full})/P^</em>_\text{ref}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>avg. max min</td>
<td>avg. max min</td>
<td>avg. max min</td>
<td>avg. max min</td>
</tr>
<tr>
<td>1</td>
<td>123 271 68</td>
<td>99 127 66</td>
<td>93 159 51</td>
<td>240 901 19</td>
</tr>
<tr>
<td>1.2</td>
<td>103 216 65</td>
<td>92 127 65</td>
<td>90 152 54</td>
<td>154 619 17</td>
</tr>
<tr>
<td>1.4</td>
<td>90 177 63</td>
<td>85 127 65</td>
<td>87 148 54</td>
<td>108 432 6</td>
</tr>
<tr>
<td></td>
<td>avg. max min</td>
<td>avg. max min</td>
<td>avg. max min</td>
<td>avg. max min</td>
</tr>
<tr>
<td>(1)</td>
<td>92 234 63</td>
<td>84 90 66</td>
<td>76 100 51</td>
<td>138 879 6</td>
</tr>
<tr>
<td>(2)</td>
<td>106 253 67</td>
<td>94 106 65</td>
<td>92 129 69</td>
<td>165 901 25</td>
</tr>
<tr>
<td>(3)</td>
<td>117 271 67</td>
<td>99 127 66</td>
<td>102 159 84</td>
<td>198 901 55</td>
</tr>
<tr>
<td></td>
<td>avg. max min</td>
<td>avg. max min</td>
<td>avg. max min</td>
<td>avg. max min</td>
</tr>
<tr>
<td>$c_{ij}$</td>
<td>124 271 66</td>
<td>88 127 65</td>
<td>105 159 88</td>
<td>289 901 49</td>
</tr>
<tr>
<td></td>
<td>avg. max min</td>
<td>avg. max min</td>
<td>avg. max min</td>
<td>avg. max min</td>
</tr>
<tr>
<td>(1)</td>
<td>105 197 67</td>
<td>95 127 67</td>
<td>95 122 75</td>
<td>149 521 26</td>
</tr>
<tr>
<td>(2)</td>
<td>87 137 63</td>
<td>97 127 74</td>
<td>70 88 51</td>
<td>63 223 6</td>
</tr>
<tr>
<td>(3)</td>
<td>103 187 64</td>
<td>93 127 65</td>
<td>90 133 54</td>
<td>151 538 12</td>
</tr>
<tr>
<td></td>
<td>avg. max min</td>
<td>avg. max min</td>
<td>avg. max min</td>
<td>avg. max min</td>
</tr>
<tr>
<td>$\mu_{ij}$</td>
<td>126 271 66</td>
<td>102 127 69</td>
<td>96 159 51</td>
<td>244 901 15</td>
</tr>
<tr>
<td></td>
<td>avg. max min</td>
<td>avg. max min</td>
<td>avg. max min</td>
<td>avg. max min</td>
</tr>
<tr>
<td>(1)</td>
<td>91 182 63</td>
<td>87 127 65</td>
<td>88 152 54</td>
<td>106 432 6</td>
</tr>
<tr>
<td>(2)</td>
<td>103 187 64</td>
<td>93 127 65</td>
<td>90 133 54</td>
<td>151 538 12</td>
</tr>
<tr>
<td>(3)</td>
<td>87 137 63</td>
<td>97 127 74</td>
<td>70 88 51</td>
<td>63 223 6</td>
</tr>
<tr>
<td></td>
<td>avg. max min</td>
<td>avg. max min</td>
<td>avg. max min</td>
<td>avg. max min</td>
</tr>
<tr>
<td>$c^p$</td>
<td>5000</td>
<td>87 127 63</td>
<td>82 111 65</td>
<td>107 369 6</td>
</tr>
<tr>
<td></td>
<td>avg. max min</td>
<td>avg. max min</td>
<td>avg. max min</td>
<td>avg. max min</td>
</tr>
<tr>
<td>10000</td>
<td>103 187 64</td>
<td>93 127 65</td>
<td>90 133 54</td>
<td>151 538 12</td>
</tr>
<tr>
<td></td>
<td>avg. max min</td>
<td>avg. max min</td>
<td>avg. max min</td>
<td>avg. max min</td>
</tr>
<tr>
<td>20000</td>
<td>126 271 66</td>
<td>102 127 69</td>
<td>96 159 51</td>
<td>244 901 15</td>
</tr>
<tr>
<td>$c_v$</td>
<td>0.9</td>
<td>91 182 63</td>
<td>87 127 65</td>
<td>106 432 6</td>
</tr>
<tr>
<td></td>
<td>avg. max min</td>
<td>avg. max min</td>
<td>avg. max min</td>
<td>avg. max min</td>
</tr>
<tr>
<td>1.5</td>
<td>122 271 67</td>
<td>97 127 66</td>
<td>92 159 51</td>
<td>241 901 23</td>
</tr>
<tr>
<td></td>
<td>avg. max min</td>
<td>avg. max min</td>
<td>avg. max min</td>
<td>avg. max min</td>
</tr>
<tr>
<td>All</td>
<td>105 271 63</td>
<td>92 127 65</td>
<td>90 159 51</td>
<td>167 901 6</td>
</tr>
</tbody>
</table>

The results in Table 9 show that the expensive designs are chosen for 60.66% of the components, when we look at all instances of the test bed. The average probability $PPC_{\text{full}}$ that a penalty cost has to be paid is 18.82%. The excess downtime normed by $D_0$ is on average 5.89%. The values of $PE\text{xp}_{\text{full}}$ show that the expensive designs of components are more often chosen when: (i) $D_f$ decreases (i.e., the target $D_0$ decreases); (ii) the differences $c^a_{i2} - c^a_{i1}$ in acquisition cost between the expensive and cheap design decrease (when going from (3) to (1) for the $c^a_{ij}$, see Table 7); (iii) the differences $\mu_{i1} - \mu_{i2}$ in expected failure rates increase (when going from (1) to (3) for the $\mu_{ij}$); (iv) the penalty cost $c^p$ increases; (v) the standard deviations $\sigma_{ij}$ increase (i.e., the factor $c^v$ increases). These effects can be explained as follows. When $D_f$ decreases or $c^p$ increases, there is a higher need for more reliable components. When the $c^a_{i2} - c^a_{i1}$ decrease or the $\mu_{i1} - \mu_{i2}$ increase, it becomes more attractive to choose the expensive designs. When the standard deviations $\sigma_{ij}$ increase, the distribution of the total downtime $D(\mathbf{x})$ gets a higher coefficient of variation, and thus generally the penalty costs will increase under target downtimes $D_0$ that are higher than the expected downtime. We do have such target downtimes $D_0$ for our solutions $x^*_\text{full}$; see the values for $PPC_{\text{full}}$ in Table 9. Hence, increasing $\sigma_{ij}$ leads to more excess downtime and thus a stronger need to choose for the expensive design for more components.
The effects of increasing/decreasing parameters on $PPC_{full}$ are sometimes the same as for $PExp_{full}$ and sometimes they are opposite. In all cases, the effects on $D_{f_{full}}^E(x^*_{f_{full}})$ and on $D_{f_{full}}^E(x^*_{f_{full}})/D_0$ are the same as for $PPC_{full}$. That $PPC_{full}$, $D_{f_{full}}^E(x^*_{f_{full}})$, and $D_{f_{full}}^E(x^*_{f_{full}})/D_0$ decrease when $c^p$ increases, does make sense. Under an increasing $c^p$ more expensive designs are chosen and thus the downtime distribution decreases and so does the excess downtime and the probability that one has an excess downtime. Similarly, the effect of decreasing $c^a = c^a_{i2} - c^a_{i1}$ and increasing $\mu_{i1} - \mu_{i2}$ can be explained. The effects of a decreasing $D_f$ and increasing $c_a$ are not so easy to explain because of effects that work against each other (e.g., a decreasing $D_f$ gives a decreasing downtime target $D_0$ and at the same time failure rates decrease because of more expensive designs that are chosen).

The results in Table 10 show that the costs $\pi(x^*_{f_{full}})$, which are close to the optimal costs, increase when: (i) $D_f$ decreases (i.e., the target $D_0$ decreases); (ii) the acquisition cost factors $c^a_{i2}$ increase (when going from (1) to (3) for the $c^a_{ij}$, see Table 7); (iii) the failure rates $\mu_{ij}$ increase (when going from (3) to (1) for the $\mu_{ij}$); (iv) the penalty cost factor $c^p$ increases; (v) the standard deviations $\sigma_{ij}$ increase (i.e., the factor $c_v$ increases). For the underlying cost terms, we see the same effects in general. Furthermore, when $D_f$ decreases, we know that more expensive components are chosen, and thus the acquisition cost increases. We also see an increase in repair cost; the effect of the higher cost per repair appears to be stronger than the decrease in number of repairs. It also leads to a very strong increase in downtime cost, which is due to the stricter downtime requirement. When $c^a_{i2}$ gets larger, although less expensive components are chosen, the acquisition cost still increases, as well as the penalty cost and repair cost. When $\mu_{i2}$ decreases, more expensive components are chosen, which results in increasing acquisition cost. Since the savings from the repair cost and penalty cost are larger than the increment of the acquisition cost, the total cost reduces with decreasing $\mu_{i2}$. When $c^p$ or $c_v$ increases, more expensive components are chosen but the repair cost and penalty cost still increases.

6. Extensions

6.1. Including a bonus

As denoted in the introduction, in our model, we included the penalty side of a PBC contract. In this subsection, we discuss how our model can be adapted to include also the bonus side of a PBC contract. Let $c^c$ be the compensation rate, where we may assume that $c^c \leq c^p$. The expected bonus under design $x$ is denoted by $W(x) = \mathbb{E}[D(x) - D_0]c^c$. This function can be rewritten as

$$W(x) = \mathbb{E}[D(x) - D_0]c^c - \mathbb{E}[D(x) - D_0]c^c = P(x)\frac{c^c}{c^p} - c^c \left( \sum_{i \in I} \sum_{j \in J} r_{ij}T x_{ij} - D_0 \right).$$
With the bonus being added, we get an optimization problem that is the same as Problem (P) but with a modified objective function $\pi'(x)$ instead of objective function $\pi(x)$. The modified objective function is equal to

$$
\pi'(x) = A(x) + R(x) + P(x) - W(x) = A(x) + R(x) + \frac{c_p}{c_p - c_c} [P(x) + c_p \left( \sum_{i \in I} \sum_{j \in J_i} r_{ij} \mu_{ij} T_{x_{ij}} - D_0 \right)].
$$

This modified objective function is similar to the original objective function and hence the new optimization procedure can be solved in the same way as Problem (P).

### 6.2. Multiple subperiods with a target downtime per subperiod

In our model, we have assumed one long service period with a target downtime for that full period. In this subsection, we briefly discuss the effect of having multiple subperiods instead of one period, with a target downtime per subperiod.

Suppose that the contract period $[0, T]$ is divided into $M$ subperiods, which are numbered $1, \ldots, M$. For subperiod $m$, the length is $T_m > 0$ and the downtime target is $D^0_m > 0$. The $T_m$ and $D^0_m$ are such that $\sum_{m=1}^{M} T_m = T$ and $\sum_{m=1}^{M} D^0_m = D_0$. The penalty costs for subperiod $m$, $P_m(x)$, are given by

$$
P_m(x) = \sum_{s_i=0}^{\infty} \cdots \sum_{s_{|I|=0}}^{\infty} \prod_{i \in I} P \left[ S^m_i(x_i) = s_i \right] E \left[ \sum_{i \in I} B_i^{(s_{|I|})}(x_i) - D^0_m \right] c^p,
$$

where $S^m_i(x_i)$ is the number of failures of component $i$ in subperiod $m$. The new LCC function is equal to

$$
\pi''(x) = A(x) + R(x) + \sum_{m=1}^{M} P_m(x).
$$

This function replaces the objective function $\pi(x)$ in Problem (P). The penalty functions $P_m(x)$ can be approximated in the same way as the penalty function $P(x)$. The modified optimization problem can again be solved via enumeration.

To show the impact of having multiple subperiods instead of one large service period, we execute a small experiment. We use one instance of the full factorial test bed of Experiment 2. For each of the parameters specified in Table 7, we take the second option; i.e., we take $D_f = 1.2$, $c_v = 0.9$, $c^p = 10000$, and option (2) is taken for the $c^p_{ij}$ and $\mu_{ij}$. The number of
subperiods $M$ is varied from 1 to 5, and we take subperiods of equal length and divide the downtime target equally over the subperiods, i.e., $T_m = T/M$ and $D^m_0 = D_0/M$ for all $m = 1, \ldots, M$. In the enumeration method, we use the full-uncertainty method for the evaluations. The results are given in Figure 4.

We see that the LCC increases strongly when the number of subperiods increases. The percentage of expensive components increases from 16.31% to 22.82% when going from 1 to 5 subperiods, which is also strong. The reason for both increases is as follows. Under more subperiods, the number of events (failures) per subperiod is much smaller and thus one gets less close to the expected downtime per subperiod. To avoid too high penalty costs, it helps to choose more expensive components which leads to less failures. But still the LCC increases a lot. This small experiment shows that an OEM has to be careful when guaranteeing a maximum downtime per subperiod instead of a maximum downtime for one large service period.

7. Conclusion

In this paper, we considered the reliability design for a serial system with uncertain component failure rates. The system is sold with a full service contract and hence it is relevant to minimize the total life cycle cost when deciding on the reliability design. The total life cycle cost includes the penalty cost for exceeding a given target downtime during the term of the service contract. In this problem, we distinguish three types of uncertainties, being the uncertain component failure rates themselves, the uncertainty in the number of failures during the service period under given failure rates, and the uncertain repair times. We developed the so-called full-uncertainty method which takes all three types of uncertainty into account and which is based on two-moment fits to determine the total downtime and the penalty cost. We have shown that this method: (i) gives fast and accurate approximations for the total cost under a given design; (ii) works well in combination with enumeration for the reliability design problem for which close-to-optimal solutions are generated. We also showed that this method outperforms two other methods.

In future research, we would like to extend our work to situations where the expected failure rate can be chosen from a given interval (i.e., where the alternative designs form a continuous set of designs).
Appendices

A. Procedures of the Monte Carlo simulation

Per instance of Experiment 1, the following simulation procedure is used:

Step 1 First, we generate the sequences of \( r_i, \mu_i \) and \( \sigma_i, i \in |I| \). Then we get \( D_0 \) immediately from (11). Then, for each component \( i \), we take one sample \( \hat{\Lambda}_i \) for \( \Lambda_i \sim G(\mu_i, \sigma_i) \), where \( G(\mu_i, \sigma_i) \) is a lognormal distribution with mean \( \mu_i \) and standard deviation \( \sigma_i \). Next, given that the number of failures of component \( i \), denoted by \( S_i \), is Poisson distributed with parameter \( \hat{\Lambda}_i T \), we take one sample \( \hat{S}_i \) for \( S_i \sim \text{Pois}(\hat{\Lambda}_i T) \). This gives one simulation result \( \hat{D}_E^{\text{sim}} \):

\[
\hat{D}_E^{\text{sim}} = (\sum_{i \in I} \hat{S}_i r_i - D_0)^+.
\]

Step 2 Step 1 is repeated 400000 times to get \( \hat{D}_E^{\text{sim},1}, \ldots, \hat{D}_E^{\text{sim},400000} \). Next, we determine the average \( \bar{D}_E^{\text{sim}} = \frac{1}{400000} \sum_{k=1}^{400000} \hat{D}_E^{\text{sim},k} \) of this series. This completes one subrun.

Step 3 Step 2 is repeated \( m \) times until a certain requirement* is met to get \( \bar{D}_E^{\text{sim},1}, \ldots, \bar{D}_E^{\text{sim},m} \). Next, we determine the average \( D_E^{\text{sim}} = \frac{1}{m} \sum_{k=1}^{m} \bar{D}_E^{\text{sim},k} \) of this series. The corresponding 95% percent confidence interval is given as:

\[
(D_E^{\text{sim}} - t_{(m-1,2.5\%)} \sqrt{\frac{S^2}{m}}) \leq \bar{D}_E^{\text{sim},k} - D_E^{\text{sim}} \leq (D_E^{\text{sim}} + t_{(m-1,2.5\%)} \sqrt{\frac{S^2}{m}}),
\]

where \( S^2 = \frac{1}{(m-1)} \sum_{k=1}^{m} (\bar{D}_E^{\text{sim},k} - D_E^{\text{sim}})^2 \) and \( t_{(m-1,2.5\%)} \) is the upper 2.5% critical point for the t-distribution with \((m-1)\) degrees of freedom.

*: Step 2 is repeated until the width of the confidence interval divided by the average value is smaller than 0.001.

B. First partial moment for mixed Erlang distributions

B.1. Erlang\((k-1,k)\) distribution

Consider an Erlang\((k-1,k)\) distribution for a random variable \( X \) with parameters \((k, \theta, q), k \in \mathbb{N}, k \geq 2, \theta > 0, 0 < q \leq 1 \). The probability density function and the cumulative distribution function are given by

\[
e_{k-1,k}(x) = q^{k-1} \frac{x^{k-2}}{(k-2)!} e^{-\theta x} + (1-q) \theta^k \frac{x^{k-1}}{(k-1)!} e^{-\theta x}, x \geq 0,
\]

\[
E_{k-1,k}(x) = q \left( 1 - \sum_{j=0}^{k-2} \frac{(\theta x)^j}{j!} e^{-\theta x} \right) + (1-q) \left( 1 - \sum_{j=0}^{k-1} \frac{(\theta x)^j}{j!} e^{-\theta x} \right), x \geq 0.
\]
Let \( x_0 \) be a nonnegative constant. Then the first partial moment \( \mathbb{E}[(X - x_0)^+] \) is equal to

\[
\mathbb{E}[(X - x_0)^+] = \int_0^\infty (x - x_0)^+ e_{k-1, k}(x) \, dx
\]

\[
= \frac{q(k-1)}{\theta} \int_{x_0}^{\infty} x e^{\theta x} \, dx + \frac{k(1-q)}{\theta} \int_{x_0}^{\infty} \frac{x^k}{k!} e^{\theta x} \, dx - x_0 \int_{x_0}^{\infty} e_{k-1, k}(x) \, dx.
\]

Let the cumulative distribution function of a pure Erlang-\( k \) distribution with scale parameter \( \theta > 0 \) be denoted by \( E_{k}^{\theta}(x) = 1 - \sum_{j=0}^{k-1} \frac{(\lambda x)^j}{j!} e^{-\lambda x}, \quad x \geq 0 \). Then the formula for \( \mathbb{E}[(X - x_0)^+] \) can be further rewritten as

\[
\mathbb{E}[(X - x_0)^+] = \frac{q(k-1)}{\theta} \left[ 1 - E_{k}^{\theta}(x_0) \right] + \frac{k(1-q)}{\theta} \left[ 1 - E_{k+1}^{\theta}(x_0) \right] - x_0 \left[ 1 - E_{k-1, k}^{\theta}(x_0) \right]
\]

\[
= \left( \frac{k-q}{\theta} - x_0 \right) \sum_{j=0}^{k-2} \left( \frac{\theta x_0}{j!} \right)^j e^{-\theta x_0} + \left( \frac{k-q}{\theta} \right) \left( \frac{\theta x_0}{(k-1)!} \right) e^{-\theta x_0}.
\]

B.2. Hyperexponential distribution

Consider a hyperexponential distribution for a random variable \( X \) with parameters \( (\theta_1, \theta_2, q) \), \( \theta_1 > 0 \), \( \theta_2 > 0 \), \( 0 < q \leq 1 \). The probability density function and the cumulative distribution function are given by

\[
h_2(x) = q \theta_1 e^{-\theta_1 x} + (1-q) \theta_2 e^{-\theta_2 x}, \quad x \geq 0,
\]

\[
H_2(x) = q(1 - e^{-\theta_1 x}) + (1-q)(1 - e^{-\theta_2 x}), \quad x \geq 0.
\]

Let \( x_0 \) be a nonnegative constant. Then the first partial moment \( \mathbb{E}[(X - x_0)^+] \) is equal to

\[
\mathbb{E}[(X - x_0)^+] = \int_0^\infty (x - x_0)^+ h_2(x) \, dx
\]

\[
= \frac{q}{\theta_1} \int_{x_0}^{\infty} (x - x_0) \theta_1 e^{-\theta_1 x} \, dx + (1-q) \int_{x_0}^{\infty} (x - x_0) \theta_2 e^{-\theta_2 x} \, dx
\]

\[
= \frac{q}{\theta_1} e^{-\theta_1 x_0} + \frac{1-q}{\theta_2} e^{-\theta_2 x_0}.
\]

8. References

References


