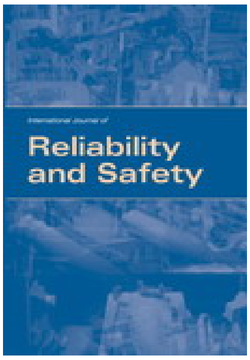

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Availability assessment of repairable Markov systems with an uncertain inspection period incorporating (M/M/s): (∞/FCFS) queue

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Availability assessment of repairable Markov systems with an uncertain inspection period incorporating (M/M/s): (∞/FCFS) queue

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Abstract: In this research, a novel model for a Markov repairable system has been proposed wherein there is an uncertainty in the inspection period, i.e., the inspection period is taken in such a way that whenever a fault is identified throughout the inspection, the inspection period is shortened for the next inspection. Further, if the time taken to repair the system failure is less than the pre-determined critical value, the failed elements of the system are repaired. And, if the system takes longer than the critical time to fully recover, it is considered completely failed and then the failed system is replaced with a new one. The system is repaired under the (M/M/s):(∞/FCFS) queue model, including working vacations. We have evaluated the proposed model's availability as a measure of reliability. For clarification, the results are supported by a numerical example.

Keywords: availability; Markov repairable system; uncertainty; critical repair time; (M/M/s):(∞/FCFS) queue.

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1 Introduction

Reliability and availability are two major concerns for most complex repairable systems. As it is not possible to throw away all the failures that have happened previously or will occur in the future, the principle of reliability simply promotes the avoidance of failures and their consequences. Since the 1970s, there has been a surge of interest in system maintenance modelling, and several kinds of research have been done to address many system attributes, including reliability measures like mean time to failure, availability and average long-run average cost. Markov repairable systems occupy a prominent place among numerous repairable systems (Bao and Cui, 2010; Wang et al., 2013; Rao and Naikan, 2015; Wang et al., 2016; Du et al., 2017). Considering the intervals between two consecutive inspections, the inspections are categorised into two main types: periodic and non-periodic (Taghipour and Banjevic, 2012; Berrade et al., 2013; He et al., 2015; Qiu et al., 2017; Hajipour and Taghipour, 2016; Yang et al., 2018; Pant et al., 2020; Pant and Singh, 2021; Agarwal and Singh, 2021). Pant and Singh (2021) examined the availability of a system exposed to various failure modes experiencing periodic inspections using a calendar-based inspection approach. Qiu and Cui (2019b) studied the availability of repairable systems with a pre-defined repair time threshold limit. Cui and Xie (2005) presented the formulae of steady-state availability for periodically inspected systems under random repair or replacement times along with their properties. Klutke and Yang (2002) derived an expression for the limiting average availability of a system that has been exposed to disruptions and gradual deterioration.

When a working component fails, it is often assumed that a repair will begin immediately. However, the system can be considered operational if a short repair period does not affect the system's operation. This may be the case if the customers do not place too many demands on the system, which can cause them to skip a short repair period or they can hardly experience a minor delay in receiving service. To be specific, if the performance of the system is unaffected by a short maintenance time, we can consider the system operational throughout the repair period. This is quite analogous to the scenario in an Ion-Channel theory, where a channel alternates between open and closed states; however, numerous spans are so small that they are undetectable at the recording system's resolution. In ion-channel modelling, the open and closed states are respectively equivalent to the up and down states in reliability. This motivates us to construct a repairable system with the exclusion of repair time. In general, this kind of system is called fault-tolerant, and it is an idea that is broadly put into play for the safety and reliability of software-based systems (Jain and Meena, 2020; Mani and Mahendran, 2017).

The vast majority of delay time-based maintenance models assume that once a defective state is recognised, the replacement will be executed immediately. Alternatively, we can loosen this belief and allow the replacement to be delayed for cost-cutting reasons. In this study, the duration of the system's repair time determines whether or not to replace the faulty system. Specifically, the replacement is postponed when the time between the onset of the failure and the end of the repair is below a given threshold. When the time required to restore the system to full functionality exceeds the threshold limit, the system is deemed operational, and the replacement is instant. Unlike an immediate replacement, a deferred replacement allows for the pre-arrangement of service equipment, like repairers and replacement parts. Furthermore, it can reduce the life-cycle cost by preventing unnecessary maintenance and extending the average system lifespan (Yang et al., 2013, 2019). To investigate the circumstances under which maintenance may not always be performed right away after a fault is revealed, Berrade et al. (2017) created a delay time model for a system with delayed replacement. Some studies have also been conducted to investigate the availability and optimal maintenance policy for systems incorporating a downtime threshold (Zheng et al., 2006; Bao and Cui, 2010; Qiu et al., 2019; Pant and Singh, 2022).

Whenever a failed system is brought in for repair, the very first question is: Can it be fixed right away? If that's not the case, the system will have to wait for its turn. This will result in the formation of a queue, which is a common scenario in daily life. A further practical concern is the availability of a repair person. Since the repairman may not always be available during the repair period, it is not always possible to quickly fix the collapsed system. During the repair, the repairman can either be in a busy period or on vacation, and both circumstances result in a queue. Assume that if the system collapses, the customer can wait for at most ten minutes. If within ten minutes or less, the default is fixed, the customer can consider the system operational and remain in it during the repair period. But if within ten minutes, the system failure cannot be repaired completely, then after waiting for ten minutes, the customer departs the system, concluding that the service system has failed. In general, once a customer enters the queue, he waits for a certain amount of time for the system to be repaired, and then he gets impatient and leaves the queue without receiving service. Queuing theory plays a significant role in reliability engineering; particularly while analysing systems waiting for repairs and replacements (Shanmugasundaram and Banumathi, 2017). By repairing the failed components under the (M/M/s):(∞/FCFS) queue model, the availability of the system can be increased due to the fact that it contains multiple servers. In addition, by using (M/M/s):(∞/FCFS) queue, the system can be made more efficient because it helps in reducing the waiting time of failed systems and improving their repair time. Queuing models are very useful in determining how to use a queuing system most effectively. It is also worth noting that delivering additional services to keep the system running incurs immoderate costs. However, inadequate service results in unnecessary delays and their subsequent consequences. Queuing systems make it possible to establish a suitable equilibrium between the maintenance cost and the waiting time.

In most of the literature on the above-mentioned subject, the system's parameters are taken to be constant. However, in some real-world scenarios, the parameters (like inspection time or failure/repair rate) may not have constant values and hence are uncertain, particularly during the assessment of the reliability characteristics of modern designed complex systems. For example, for each device and each failure, the repair time is different and thus the service rate continues to change. In response to the constantly changing service rate, the conditions of waiting in the queue, which may be significant to customers when deciding whether to join the queue or not, may vary. Thus, the system is always subject to uncertainty. A method for assessing the reliability of some replaceable networks has been given. The networks under consideration have some uncertainties associated with them, and their reliability has been evaluated employing three indices, viz., terminal reliability, broadcast reliability and network reliability (Khati and Singh, 2021, 2022). In order to address the aforementioned issues, there is a need to integrate the above facts into the reliability modelling and estimation.

In the field of reliability engineering, availability has consistently remained a subject of growing interest because it is a key characteristic of the construction and operation of all modern-engineered complex systems. This research work aims to plan a maintenance model for a competing-risk system. We derive the expressions for the instantaneous availability and the upper and lower bounds of the long-run availability under critical repair time conditions, incorporating the $(\mathrm{M}/\mathrm{M}/s):(\infty/\mathrm{FCFS})$ queue model with a semi-vacation policy under uncertainty. Then, we clarify the validity of the derived results with a numerical example of a ventilator system.

We now turn to the continuation of this paper. Section 2 discusses the notations used in the research. Section 3 explains how the planned model will be constructed. A discussion of the system's availability follows in Section 4. Section 5 provides a numerical example to demonstrate the findings. Finally, Section 6 compiles the results and discussions.

2 Nomenclature

t	Time scale
ε	System's life-span
$F_\varepsilon(x)$	Probability distribution function of ε
τ_i	Inspection period
ϕ	System's repair time
$F_\phi(y)$	Probability distribution function of ϕ (waiting + service time)
T	Critical repair time
I	Number of inspections conducted when a failure is discovered in the system
$A(t)$	System's instantaneous availability at time t
A	System's steady-state availability
λ	System's failure rate
μ	System's repair rate
W_s	Waiting time in the system

3 System description

In the proposed model, to trace the system failures, the inspections will be carried out after each time-interval τ, where $\tau \in [\tau_{i,} \tau_j]$. Also, a critical repair time, T, will be pre-established, depending on the real-life experiences. If any downtime is shorter than T, i.e., the system is repaired completely within the pre-specified period T, the system can be regarded as working throughout the downtime and if the downtime surpasses T, the system is deemed to be functional from the commencement of the failure up to the downtime surpassing T. The failed components will be repaired under the $(\mathrm{M/M}/s):(\infty/\mathrm{FCFS})$ queue model with a semi-vacation policy.

We can define a renewal cycle as the time frame between the setup of a fresh system and the completion of the first repair, or it can be defined as the period between two subsequent completions of repairs.

The fundamental postulates governing the availability analysis are as:

a) At first, a new system is introduced.

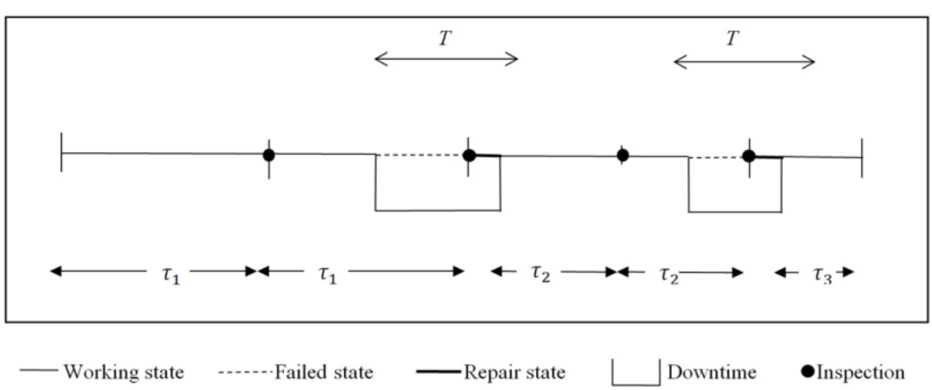
b) If a fault is observed, a quick repair action is taken, which requires a random time ϕ with distribution function $F_\phi(x)$. Each repair can transform a defective component into a working component.

c) The failed components are repaired using the $(\mathrm{M/M}/s):(\infty/\mathrm{FCFS})$ queue model with working vacations.

d) A critical repair time, T, is predefined. If the time required to repair the system is less than T, the system will be regarded as operational throughout the downtime; otherwise, if the system is taking a time longer than T to get back completely into action, the system will be considered as completely failed and, in that case, we will replace the system with a new one.

e) The inspection period, τ, is reduced whenever a failure is detected while inspecting the system.

Figure 1 A feasible model of the proposed competing-risk system



Let τ_1 be the initial inspection period. Figure 1 illustrates that no failure is detected during the first inspection, whereas a fault is revealed in the system during the second inspection, resulting in an instant repair. Because the system's downtime is less than the critical time T, the system is deemed functional. Since a failure is detected, we reduce the inspection time from τ_1 to τ_2. Now during the third inspection, no failure is found, but during the fourth inspection a fault is identified, and thus a repair is executed instantly. Here, also the system's downtime is less than T, thus the system is deliberated as functional. Then again, the inspection period is reduced from τ_1 to τ_2.

4 Availability analysis

Theorem 1: *The proposed system's instantaneous availability $A(t)$ at instant t incorporating $(\mathrm{M}/\mathrm{M}/s):(\infty/\mathrm{FCFS})$ queue is expressed as*

$$A(t)=R(t)+\sum_{i=1}^{\lfloor t/\tau \rfloor}\left\{R\left[(i-1)\tau\right]-R(i\tau)\right\}\int_{0}^{t-i\tau}A(t-i\tau-y)\,dF_{\phi}(y).$$

where τ is the respective inspection period and $\lfloor a \rfloor$ symbolises the last integer which is not more than a.

Proof: For determining the system's instantaneous availability, let us define a stochastic process given as follows:

$$\varepsilon(t)=\begin{cases}1 & \text{the system is working at instant } t\\ 0 & \text{otherwise}\end{cases}$$

The system's instantaneous availability at instant t is given as:

$$\begin{aligned}A(t)&=P(\text{the system is in an operating condition at time } t)\\ &=P(\varepsilon(t)=1)\\ &=P(\varepsilon(t)=1,\varepsilon<t)+P(\varepsilon(t)=1,\varepsilon>t)\end{aligned}\tag{1}$$

The system's failure time, ε, is linked with the amount of inspections performed when a defect is observed throughout a renewal cycle, I, as $(I-1)t<\varepsilon<It$.

The probability mass function of I can be calculated as follows:

$$\begin{aligned}P_i&=P(I=i)\\ &=P((i-1)\tau<\varepsilon<i\tau)\\ &=R\left[(i-1)\tau\right]-R(i\tau)\end{aligned}\tag{2}$$

The first and the second terms of equation (1), correspondingly symbolise the cases that the first failure takes place before time t and no system failure takes place before time t. Thus, we can express the first term as:

$$P(\varepsilon(t)=1,\varepsilon<t)=R(t)$$

When we take into account the inspection interval during which the system fails for the first time, we obtain:

$$P(\varepsilon(t)=1,\varepsilon<t)=\sum_{i=1}^{\lfloor t/\tau\rfloor}P(\varepsilon(t)=1,I=i)+P(\varepsilon(t)=1,\lfloor t/\tau\rfloor\tau<\varepsilon(t)) \tag{3}$$

where $\lfloor a\rfloor$ represents the greatest integer that is not greater than a.

Now according to the second part of equation (3), the system comes up short in the time interval $((\lfloor t/\tau\rfloor\tau,t),t)$. Because of this, the system breakdown can be noticed only at $(\lfloor t/\tau\rfloor+1)\tau$ and thus at that time the instantaneous availability is 0.

We can write the first term of equation (3) as:

$$\sum_{i=1}^{\lfloor t/\tau\rfloor}P(\varepsilon(t)=1,I=i)=\sum_{i=1}^{\lfloor t/\tau\rfloor}P(\varepsilon(t)=1,I=i).\{R[(i-1)\tau]-R(i\tau)\} \tag{4}$$

Whenever the system collapses, the respective corrective repair takes an arbitrary time ϕ, so we have:

$$\begin{aligned}P(\varepsilon(t)=1,I=i)&=\int_0^{t-i\tau}P(\varepsilon(t)=1,I=i,\phi\in(y,y+\Delta y))dF_\phi(y)\\&=\int_0^{t-i\tau}P(\varepsilon(t-i\tau-y)=1)dF_\phi(y)\\&=\int_0^{t-i\tau}A(t-i\tau-y)dF_\phi(y)\end{aligned} \tag{5}$$

Equation (4) is attained by using equation (5) as:

$$\sum_{i=1}^{\lfloor t/\tau\rfloor}P(\varepsilon(t)=1,I=i)=\sum_{i=1}^{\lfloor t/\tau\rfloor}\{R[(i-1)\tau]-R(i\tau)\}\int_0^{t-i\tau}A(t-i\tau-y)dF_\phi(y) \tag{6}$$

The system's instantaneous availability is determined by using equations (3), (4) and (6) as follows:

$$A(t)=R(t)+\sum_{i=1}^{\lfloor t/\tau\rfloor}\{R[(i-1)\tau]-R(i\tau)\}\int_0^{t-i\tau}A(t-i\tau-y)dF_\phi(y) \tag{7}$$

Theorem 2: *The long-run availability 'A' of the proposed competing-risk system employing* $(\mathrm{M/M}/s):(\infty/\mathrm{FCFS})$ *queue model is given as*:

$$A=\frac{\lambda+\int_0^{\tau}G(x)dx}{\sum_{i=1}^{\infty}i\tau\{R[(i-1)\tau]-R(i\tau)\}+W_s}$$

where $G(x)=\int_0^x\sum_{i=1}^{\infty}\{R[(i-1)\tau]-R(i\tau-x+y)\}dF_\phi(y)+e^{-\mu x}$, W_s is the waiting plus service time of the system in the queue.

Proof: The long-run availability '*A*' of the proposed system can be accessed via the key renewal theorem which is stated as:

$$A = \frac{E(U)}{E(U) + E(D)} \tag{8}$$

where $E(U)$ equates to the system's expected uptime and $E(D)$ to the expected downtime of the system in a renewal cycle.

The system's expected uptime is given as:

$$\begin{aligned} E(U) &= E(\varepsilon) + \int_0^T P\left((I\tau - \varepsilon + \varphi) > x\right) dx \\ &= \lambda + \int_0^T \{\int_0^x \sum_{i=1}^{\infty} \left\{R\left[(i-1)\tau\right] - R(i\tau - x + y)\right\} dF_\phi(y) + e^{-\mu x} dx\} \end{aligned} \tag{9}$$

Also, the expected length of a renewal cycle, $E(R)$, is given by:

$$E(R) = E(I\tau) + E(\varphi) = \sum_{i=1}^{\infty} i\tau \left\{R\left[(i-1)\tau\right] - R(i\tau)\right\} + W_s \tag{10}$$

Thus, the steady state availability of the proposed system can be obtained from equation (8) as:

$$A = \frac{E(U)}{E(R)} = \frac{\lambda + \int_0^T \{\int_0^x \sum_{i=1}^{\infty} \left\{R\left[(i-1)\tau\right] - R(i\tau - x + y)\right\} dF_\phi(y) + e^{-\mu x} dx\}}{\sum_{i=1}^{\infty} i\tau \left\{R\left[(i-1)\tau\right] - R(i\tau)\right\} + W_s} \tag{11}$$

It can be observed from equation (11) that A is an increasing function of τ as a larger value of τ reciprocates a larger steady-state availability.

Corollary: *The lower and upper bounds of the long-run availability A are respectively as follows*:

$$\underline{A} = \frac{\lambda}{\sum_{i=1}^{\infty} i\tau \left(R\left((i-1)\tau\right) - R(i\tau)\right) + W_s} \tag{12}$$

$$\overline{A} = \frac{\lambda + \int_0^T \{\int_0^x \sum_{i=1}^{\infty} \left(R\left((i-1)\tau\right) - R(i\tau - x + y)\right) dF_\phi(y) + e^{-\mu x} dx\}}{\sum_{i=1}^{\infty} i\tau \left(R\left((i-1)\tau\right) - R(i\tau)\right) + W_s} \tag{13}$$

5 Numerical example

Numerous practical areas, such as coal mine industries and manufacturing plants, rely heavily on ventilators. In order to ensure normal yield, ventilator systems must continuously deliver sufficient fresh air to specific locations while anticipating gas aggregation. Whenever a ventilation system collapses, as per security standards in the coal industry, a time lag should be permitted to manage the system. While this delay continues, solid underground security should also be ensured. As long as the ventilator is fixed inside the threshold limit, it remains in the up-state, implying that the consequences of the failure are abandoned or deferred. Let the system be inspected on a regular basis, i.e., periodically. Ventilator breakdowns will, without a doubt, result in massive damage. Hence, the analysis of the ventilato's availability is of critical importance in several practical fields. To get a better understanding of the concept of delayed or unconsidered downtime in the ventilator system, a practical situation is examined to demonstrate the results that were derived in the preceding section. Now, for a pre-specified non-negative threshold value τ, if the ventilator system is down for a time that is not more than τ, the system remains operable during that downtime. Or else, if the system's downtime surpasses *T*, the system continues to operate within the time-span τ. The consequences of generator failures are, thus, ignored or delayed. To demonstrate the obtained results, a realistic scenario depicting how the downtime can be ignored or postponed in the coal mine ventilation system is depicted in this section.

5.1 Instantaneous and long-run availability analysis

Let us assume that the system's lifetime follows an exponential distribution. Repairs are initiated as soon as a failure is noticed in the system. The repair time is distributed exponentially with a repair rate of 1, and let 0.1 be the failure rate of the system. Also, let us take the critical time, *T,* to be 0.1. The first inspection interval is τ_1 = 3, and the second inspection interval is τ_2 = 2.5. Figure 2 displays the instantaneous availability of the considered system, which can be evaluated from equation (7). Using equations (12) and (13), the lower and upper limits of the steady-state availability are obtained and are presented in Figure 3. It can be seen from Figure 3 that the upper and lower limits of the steady-state availability for the considered system are 0.5879 and 0.4394, respectively.

Figure 2 Instantaneous availability of the system

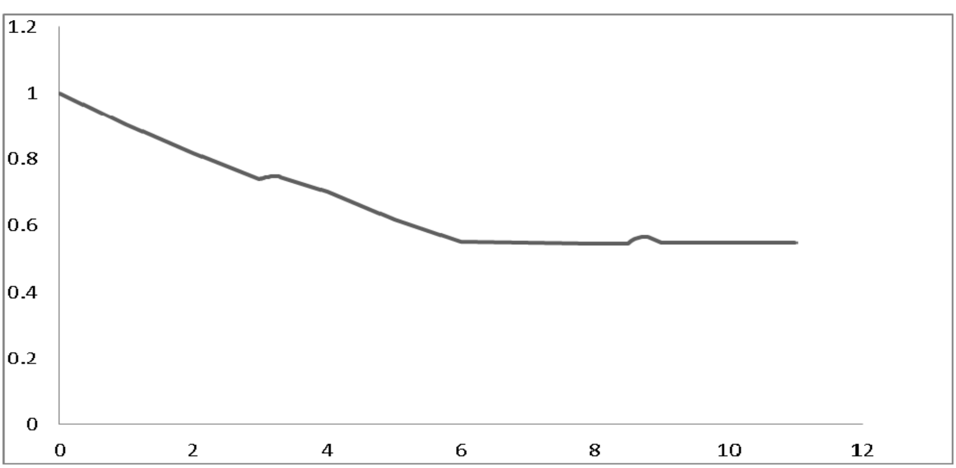
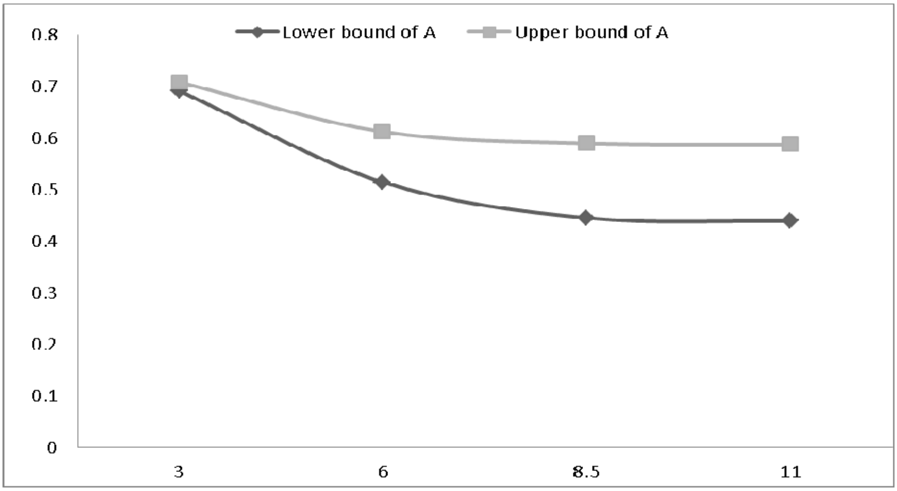


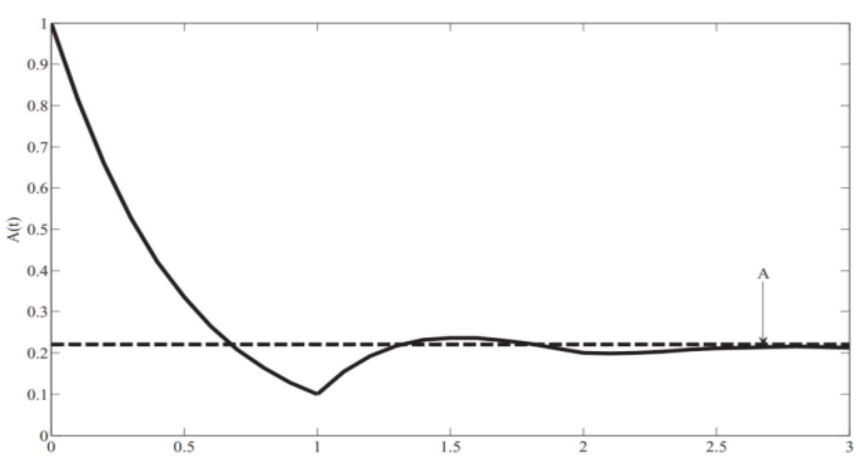
Figure 3 Long run availability of the system



5.2 Comparison of this model with Qiu and Cui's (2019a) model

Qiu and Cui (2019a) examined the availability of a competing-risk system undergoing periodic inspections. They analysed the system by assuming that it experiences multiple FMs and gave some theorems governing the point and steady-state availability of the system. From the perspective of the system's steady-state availability, we compare the two maintenance models. One main difference between our model and the model given by Qiu and Cui (2019a) is that their system undergoes inspections at regular intervals, while in our model the inspection time is not certain. Moreover, we incorporated the concept of critical repair time into our model. In spite of the fact that Qiu and Cui's (2019a) model is inspected more frequently than our model, the availability of their system is lower than that of our system, which can be observed from Figures 2 and 4.

Figure 4 Instantaneous availability of the system in Qiu and Cui's (2019a) model



6 Conclusion and discussion

This paper examines the instantaneous availability as well as the lower and upper bounds of steady-state availability for a Markov repairable system incorporating $(\mathrm{M}/\mathrm{M}/s):(\infty/\mathrm{FCFS})$ queue and critical repair time. An inspection-based maintenance strategy has been implemented. The inspection period has been deemed uncertain, i.e., every time a fault is discovered in the system, the inspection period is decreased. The system has been examined under the assumption that as long as the system is rectified within the critical time frame, the system will be considered operational across the downtime; or else, if it takes longer than the critical time for the system to be fully functional, then the system will be considered completely broken and will be replaced. The analytical results for the system's instantaneous availability and the lower and upper bounds of the system's steady-state availability have been derived and validated by means of a numerical illustration of a ventilator system. Also we have compared the results of our paper with the results of Qiu and Cui's (2019a) model, and the availability of our model is found higher than that of Qiu and Cui's (2019a) model.

One limitation of this paper is that the system is subjected to a single failure mode. In a more practical scenario, when failure modes are dependent, it could be useful to describe the characteristics of failure modes. In addition, our results have been restricted to cases in which inspections are perfect. Investigating various reliability indices for systems experiencing multiple failure modes with imperfect inspections would be interesting.

As a preliminary analysis, obviously, there are numerous other extensions which are worth exploring. Research on additional reliability measures, like the mean time to failure and reliability function, could be conducted in the future. The techniques employed in this work can be modified and applied to additional repairable systems, namely, series, parallel, *k*-out-of-*n* or standby systems. The Markov system is examined in this research, and in future research, the semi-Markov system could be used, allowing us to create a novel system relying upon the semi-Markov system that ignores or delays the consequences of system breakdown. The findings of this research can be applied to a study aimed at increasing system reliability. The derived outcomes on the system's availability are useful in many real-world applications, such as operations research and other engineering areas.

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