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Model Development for Reliability Cannibalization

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Abstract

This chapter looks at cannibalization as a method (procedure) of improving reliability of engineering systems. Cannibalization gives one the opportunity to use resources in the most efficient way. In this chapter, we have explored strategies to reduce the adverse effects of cannibalization on maintenance costs and personnel morale. The strategies developed in this chapter, at least, can be used to determine (1) which types of cannibalizations are appropriate, (2) cannibalization reduction goals and (3) the actions to be taken to meet the cannibalization reduction goals. In this chapter, we also presented a combined analytical and simulation model of a two-line, three-line and k-line system when cannibalization is not allowed and when cannibalization is allowed (with and without short interruptions to the system). It is clear from the analytical and simulation results that cannibalization can substantially increase the reliability of the systems where it is allowed. The improvement factor of unreliability obviously exists in systems where cannibalization is allowed as compared to those in which cannibalization is not allowed. Moreover, the improvement factor is larger when we have two-stage cannibalization (short interruptions) than without them.

Keywords: cannibalization, system, component, reliability, model

1. Introduction

Usually, policy dictates that systems of equipment are dispensed together with spare parts in case of components which are prone to failure. With failed components being replaced and/or repaired, the systems of equipment remain functional subservient to the said policy. Nevertheless, the two exceptions to the preceding policy are [1, 2] as follows: (1) as a result of the high acquisition and holding costs, high-technology manufacturing environments and organizations, which make use of expensive equipment, will not be able to always stock spare parts and (2) when equipment has reached its last life-cycle stage, failure rates have increased, spare
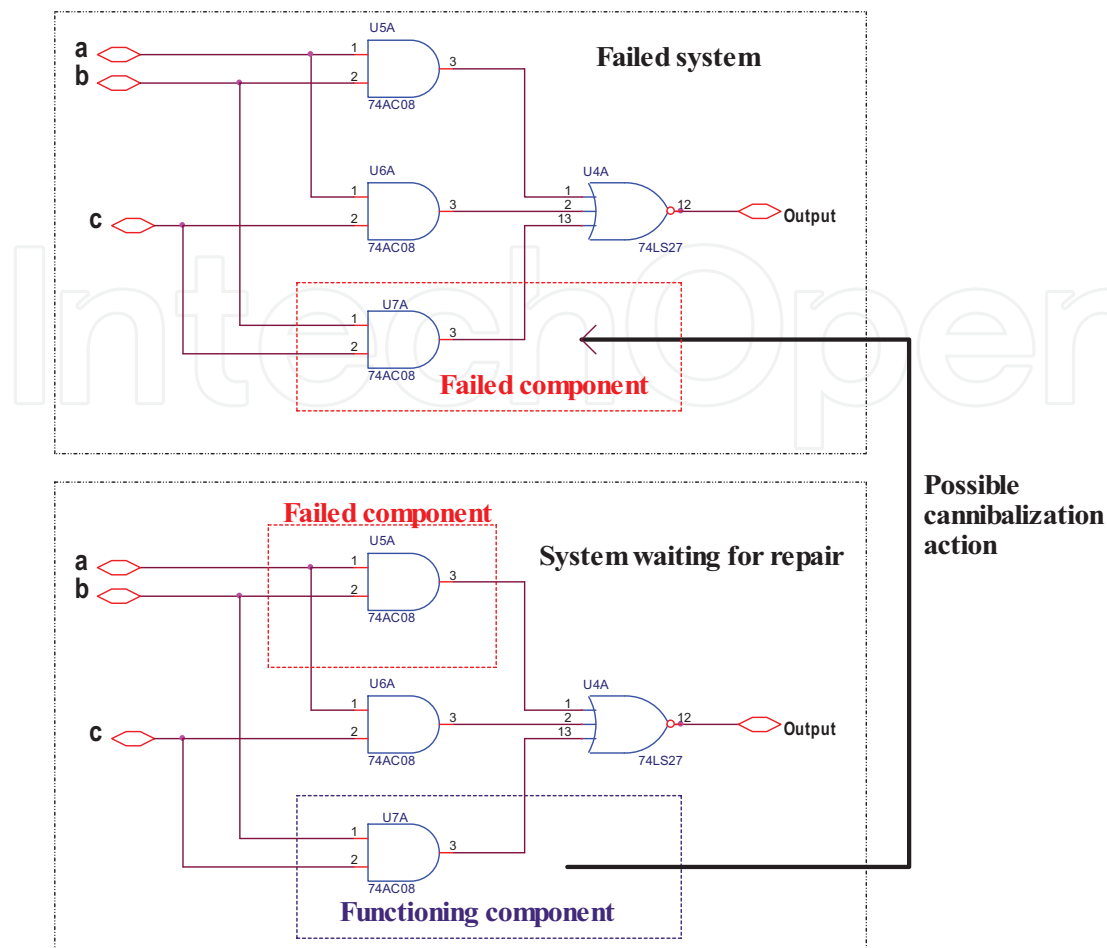
Figure 1. The cannibalization concept.

parts become increasingly difficult to acquire and there is a slump in the usage of the said equipment. Therefore, the inclination is not to acquire numerous spare parts as the said equipment will be phased out soon.

One conceivable way of maintaining systems whose spare parts have been depleted or are not available is through cannibalization. Readiness requirements and short maintenance turn-arounds in high-technology environments can be achieved through cannibalization. In general, 'cannibalization' ascribes to the process of removing a failed component from a system and replacing the said component by an operating component (of the same type) extracted from another part of the system. The concept of cannibalization is illustrated in **Figure 1**. The practice of cannibalization has a long history, especially in the military [3].

2. Strategies to conduct informed cannibalizations

Cannibalizations, when carried out imprudently, can have unintended negative effects. Cannibalization actions often bear negative connotations because of the following [4, 5]: (1) cannibalizations indicate that there are problems with the spare part supply chain, (2) there is a

potential of mechanically damaging systems during cannibalizations and (3) cannibalizations increase the workload of maintenance personnel and if practiced frequently will dampen their morale. Nonetheless, the practice of cannibalization is unlikely to be eliminated completely. Therefore, one has to consider the idea of (1) designated cannibalizations and (2) methodology-informed cannibalizations. These will then cushion against the negative effects of cannibalizations.

The idea of designated cannibalizations means the designation of components in the requirements database as cannibalizable (i.e. easy to cannibalize) or non-cannibalizable (i.e. difficult to cannibalize). It can be noted that the cannibalizable or non-cannibalizable of components is mainly dependent on their type. For example, the cannibalization of a fuse is a trivial task which maintenance personnel can conduct almost invariably rather than wait for long periods of time for the spare part to be delivered. On the other hand, the cannibalization of an aircraft wing spar, for example, is very costly (i.e. in terms of energy, time and money), very dangerous and unfathomed in the world of aircraft maintenance. Cannibalization of components designated as cannibalizable will provide serviceable components when the spare stock is depleted. Cannibalizations of components designated as non-cannibalizable will not be permitted as it may be too costly in labour or time or money, or too risky in that the component (system) may incur mechanical damage during removal.

The methodology-informed cannibalization is an alternative route to estimate optimum rates of cannibalization required to meet the set readiness and operational demand goals, given the system: (1) mean uptime (MUT) (also known as MTTF), (2) MTTR, (3) mean supply response time (MSRT), (4) mean maintenance and supply time (MMST) and (5) mean downtime (MDT). This methodology addresses designated cannibalizations only deemed necessary in the industry. The theoretical model is presented in Section 2.1. This model is an extension of the model developed in Ref. [6]. In the model developed in Ref. [6], it is assumed that the sum of the supply time and maintenance time uniquely classifies the total downtime. Nonetheless, in real-life situations, three categories of downtime, that are exclusive, exist. These are (1) maintenance time, (2) supply time and (3) overlapping MMST. Hence, we extend the model of Ref. [6] to accommodate these different categories of downtime because cannibalizations affect MTTR and MSRT, as well as MMST. In Section 2.2, we provide cannibalizations policy implications based on the results of Section 2.1.

2.1. Theoretical model to show the effects of cannibalization on mission time availability of systems

We begin with the following definition of system mission time average availability. The system mission time average availability ($MTAA_{system}$) denotes the mean proportion of mission time the system is functioning. It is assumed that every time a component (system) fails, it is restored to an 'as good as new' condition through repair and the said system mission time average availability is

$$MTAA_{system} = \frac{MUT}{MUT + MDT} \tag{1}$$

where *MUT* is the mean uptime (also referred to as *MTTF*) and *MDT* is the mean downtime. The *MUT* denotes the mean functioning of the system. The *MDT* is decomposed into three mutually exclusive activities: (1) the *MTTR*;, (2) the *MSRT* and (3) the *MMST*. If we substitute these three variables into Eq. (1), we get

$$MTAA_{system} = \frac{MUT}{MUT + MTTR + MSRT + MMST} \tag{2}$$

To simplify the calculations, one assumes a zero time for the decision to cannibalize and similarly a zero time for accomplishing the cannibalizations. Therefore, *MSRT* is calculated as follows [6]:

$$MSRT = (1 - GE)(1 - c)\mu \tag{3}$$

where *GE* denotes gross effectiveness—that is, the ratio of the parts required which can be obtained in the supply chain, *c* denotes the ratio of the parts requests which cannot be obtained in the supply chain and have to be cannibalized and μ is the mean customer wait time (*CWT*) for spare parts.

The U.S. Navy describes the cannibalization action to be the number of cannibalizations performed per 100 flight hours. This is referred to as the cannibalization rate and is denoted $CANN_{AF}$. In this research, it will suffice to use this definition. The ratio of all the parts requests which are cannibalized, *c*, is determined as follows [6]:

$$c = \frac{CANN_{AF}}{100(1 - GE)\theta} \tag{4}$$

where θ is the component mean failure rate.

If we substitute Eq. (4) into Eq. (3), we get

$$MSRT = \frac{-\left(\mu\left(CANN_{AF} - (100\theta) + (100GE\theta)\right)\right)}{100\theta} \tag{5}$$

It can be noted that Eq. (5) shows a negative linear relationship between *MSRT* and $CANN_{AF}$. If we hold θ, μ and *GE* constant, it can be deduced that when the cannibalization rate is higher the MSRT becomes lower.

If we substitute Eq. (5) into Eq. (2) and solve for $CANN_{AF}$, we get

$$CANN_{AF} = \frac{\left(\theta(100GE - 100)\left(\frac{MMST + MTTR + MUT - MUT}{MTAA_{system} - \mu(GE - 1)}\right)\right)}{\mu(GE - 1)} \tag{6}$$

We impose the following mathematical constraints when calculating with Eq. (6):

$$CANN_{AF} = 0 \; if \; (1 - GE)\mu \leq \frac{MUT}{MTAA_{SYSTEM} - MUT - MTTR - MMST} \tag{7}$$

$$MTAA_{\text{system}} \le \frac{MUT}{MUT + MTTR + MMST} \tag{8}$$

It is impossible to achieve an $MTAA_{\text{system}}$ value higher than this. It can only mean that the values set for the parameters in the model are not showing rational thought.

Using Eq. (6), we plot $CANN_{AF}$ as a function of μ for different values of $MTAA_{\text{system}}$ (with all the other parameters fixed at values given and shown in **Figure 2**. It can be deduced from **Figure 2** that μ approaches infinity as $CANN_{AF}$ reaches a maximum of 12.31 for an $MTAA_{\text{system}}$ of 0.65; 12.24 for an $MTAA_{\text{system}}$ of 0.60 and 12.17 for an $MTAA_{\text{system}}$ of 0.55.

Figure 3 shows that a policy to limit cannibalization activities is required. In the example of **Figure 3** (with all the other parameters fixed), it can be seen that a cannibalization rate above 14 does not add any value as the $MTAA_{\text{system}}$ is now 1.

### 2.2. Policy implications of the theoretical model

In this section, we state a number of conclusions based on our simulations using Eqs. (1)–(6). These conclusions have implications on cannibalization policies. The conclusions are as follows:

a. The gradient $\frac{\partial CANN_{AF}}{\partial \mu}$ of the graph in **Figure 2** is positive. This shows that the longer μ is the higher $CANN_{AF}$ is (for different values of $MTAA_{\text{system}}$ all other parameters being held constant). Thus, cannibalization activities may be reduced by decreasing μ;
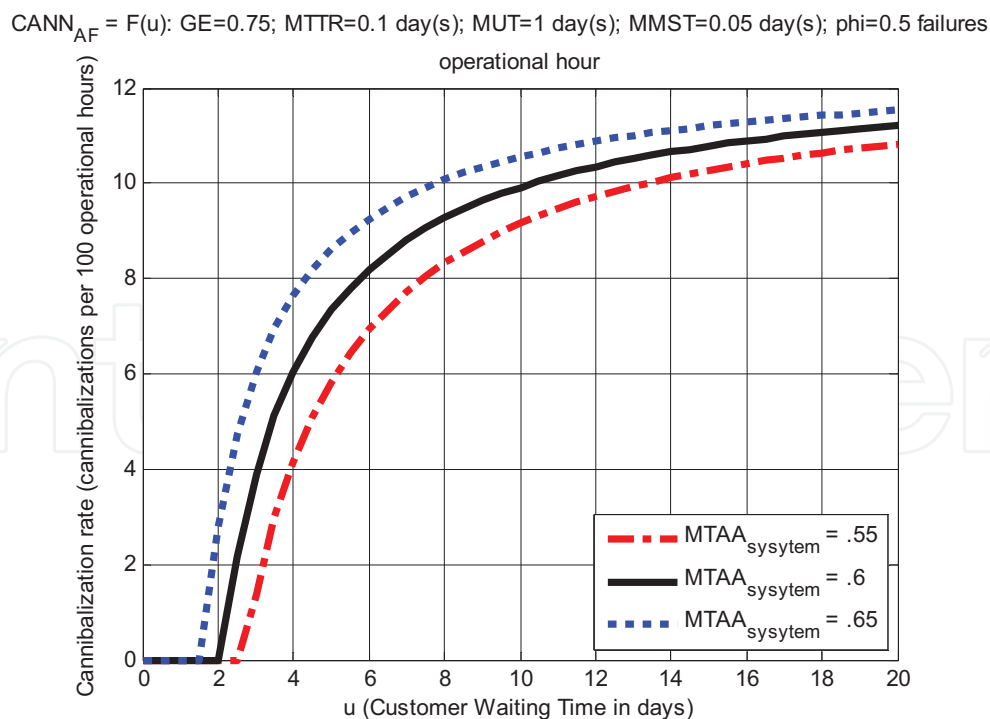
Figure 2. $CANN_{AF}$ versus μ for different $MTAA_{\text{system}}$ values.

MTAA$_{\text{system}}$ = F(CANN$_{AF}$): GE=0.75; MTTR = 0.1 day(s); MMST=0.05 day(s); MUT=1 day(s); u= day(s); phi=0.5 failures per operational hour
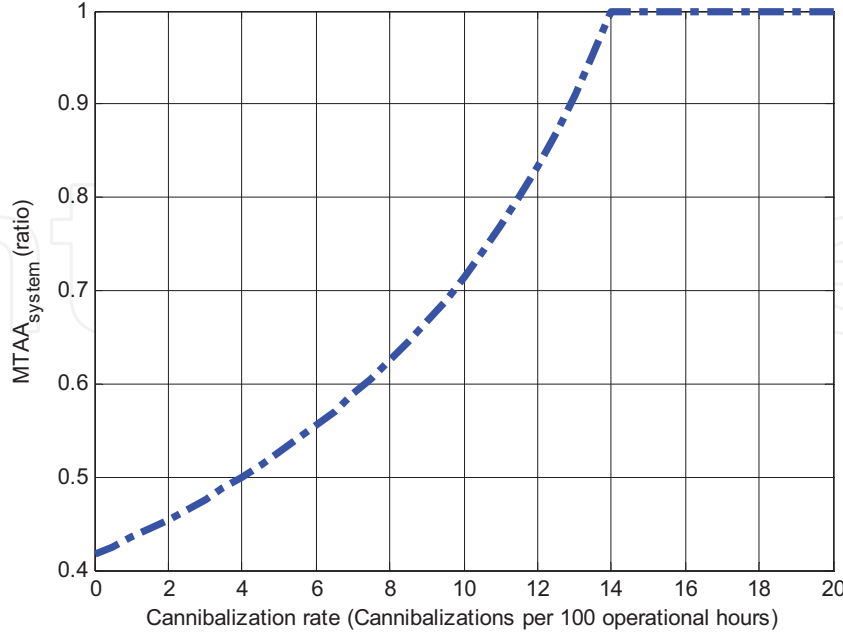
Figure 3. $MTAA_{\text{system}}$ versus $CANN_{AF}$.

b. The function $MTTR = F(CANN_{AF})$ is positive. Hence, more cannibalization activities imply longer maintenance time;

c. The gradient $\frac{\partial CANN_{AF}}{\partial MUT}$ is negative. Thus, it shows that with higher system reliability or with longer mean uptime, cannibalization rates become lower (for different values of $MTAA_{\text{system}}$ with all other parameters being held constant). Thus, cannibalization activities can be reduced when systems are designed taking cognisance of probabilistic design for reliability;

d. It can be deduced that the gradient $\frac{\partial CANN_{AF}}{\partial MTTR}$ is positive. It implies that with longer repair time ($MTTR$), the cannibalization rate becomes high (for different values of $MTAA_{\text{system}}$ with all other parameters being held constant). Therefore, cannibalization activities may be reduced with a more efficient maintenance operation system (i.e. better trained and qualified maintenance personnel);

e. The gradient $\frac{\partial CANN_{AF}}{\partial GE}$ is negative. It implies that the higher the GE, the lower the cannibalization rate (for different values of $MTAA_{\text{system}}$ all other parameters being held constant). Hence, increasing the availability of spare parts in the supply chain reduces cannibalization activities;

f. It can be seen from the results that cannibalization activities serve a useful purpose in the maintenance and operation of high performance and complex systems. Cannibalization activities are necessary, viable and cost-effective, only if the optimum cannibalization rate is sought for specific operating parameters; and

g. Lastly, when the actual data on cannibalization rates and other parameters (i.e. the ones related to $MTAA_{\text{system}}$) is available, the models presented in Sections 2 and 3 can be empirically tested.

3. Cannibalization revisited: theoretical model and example

This section considers a situation where repair facilities or spare components are not immediately available so that the probability of survival of a system can only be enhanced by extracting needed replacement components from another part of the system. We develop a model of cannibalization for the probability of survival (at time t) of a system with k-lines in parallel of n series-connected components when short interruptions to the system are allowed and when short interruptions to the system are not allowed. It is assumed for practical reasons that the lines are identical. Let all components be also identical, with exponentially distributed lifetimes with parameter λ. We can generalize the approach to the case of non-identical components and lines but the resulting expressions will be extremely cumbersome. We start with two lines as follows:

i. Assume that when only one line is left, the time for replacing the failed component of this remaining line (if one has a spare, e.g. from the failed line) is not allowed. Then, there is no possibility of cannibalization in this system and the survival function can be easily obtained.

ii. The time for replacing the failed component is allowed. Then, when one line fails, all $n − 1$ non-failed components of the failed line can be used as spares for the operable line. The corresponding formulas (survival function) are then derived and this is cannibalization.

Then, we consider the case of three lines:

i. No time is allowed for replacing the failed component. However, cannibalization is still performed here. Indeed, when one line fails, we can use $n − 1$ spares for the system of two lines (i.e. cannibalization) and when they will be exhausted, then no cannibalization, as in the case with two lines. The formula for probability of survival (at time t) is then written for the case with cannibalization and without and compared.

ii. Time for replacing the failed component is allowed. Then, the two-stage cannibalization goes. When the first line fails, $n − 1$ non-failed components can be used to maintain the two lines. When this is exhausted and one of the two lines fails, the same process as in the previous case is followed and then the corresponding relationships are obtained.

We generalize the approach to the case when we have more than three lines and obtain the corresponding recurrent equations for survival probabilities in this case that can be solved numerically.

It can be noted that short interruptions to the system give us the possibility to use some components of a system as spares.

3.1. Notation

X: lifetime of a system.

$S_{kn}^{-}(t)$: probability of survival (at time t) of a system with k -lines of n -series-connected components with cannibalization (when short interruptions of the system are not allowed).

$S_{kn}^{+}(t)$: probability of survival (at time t) of a system with k -lines of n -series-connected components with cannibalization (when short interruptions of the system are allowed).

$S_{kn}^{nc}(t)$: probability of survival (at time t) of a system with k -lines of n -series-connected components when no cannibalization at all is allowed.

$q_{kn}^{-+}(t) = \frac{1 - S_{kn}^{-}(t)}{1 - S_{kn}^{+}(t)}$: improvement factor of unreliability (at time t) for k -lines of n -series-connected components with cannibalization due to allowing short interruptions.

$q_{kn}^{nc}(t) = \frac{1 - S_{kn}^{nc}(t)}{1 - S_{kn}^{-(+)}(t)}$: improvement factor due to cannibalization of unreliability (at time t) for k -lines of n -series-connected components when initially no cannibalization at all is allowed.

$$k = 1, \ 2, \ \dots.$$
$$n = 1, \ 2, \ \dots$$

Note: The improvement factor of unreliability shows how much the unreliability has decreased due to cannibalization being allowed.

3.2. One-line system

This section is concerned with the probability of survival (at time t) evaluation of standard series network occurring in engineering systems. The series network is the basic building block of the work in this section. In this incident, n number of components form a series network, as illustrated in **Figure 4**. The system fails if any one of the components fails. All components constituting the system must not fail in order to ensure a successful system operation.

The four wheels of a car illustrate a typical example of a series system. The car cannot be driven for practical purposes with any one of the tyres punctured. It therefore follows that these four car tyres form a series system. When one assumes independent and identical components (each component $i(i = 1,2,\dots,n)$ with a lifetime that is exponentially distributed with failure rate λ), it then follows that the probability of survival for the series system as shown in **Figure 4** is

$$S_{1n}^{nc}(t) = e^{-n\lambda t} \tag{9}$$

3.3. Two-line system

Now consider two identical lines of series-connected components as shown in **Figure 5**. Now, we compute the probability of survival for two cases [7, 8]: (Section 3.3.1) when no short interruptions to the system are allowed (i.e. no possibility of cannibalization: this is indeed
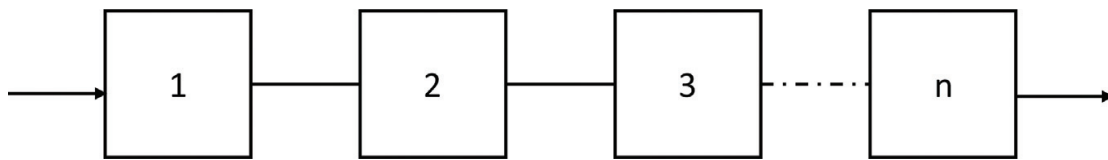
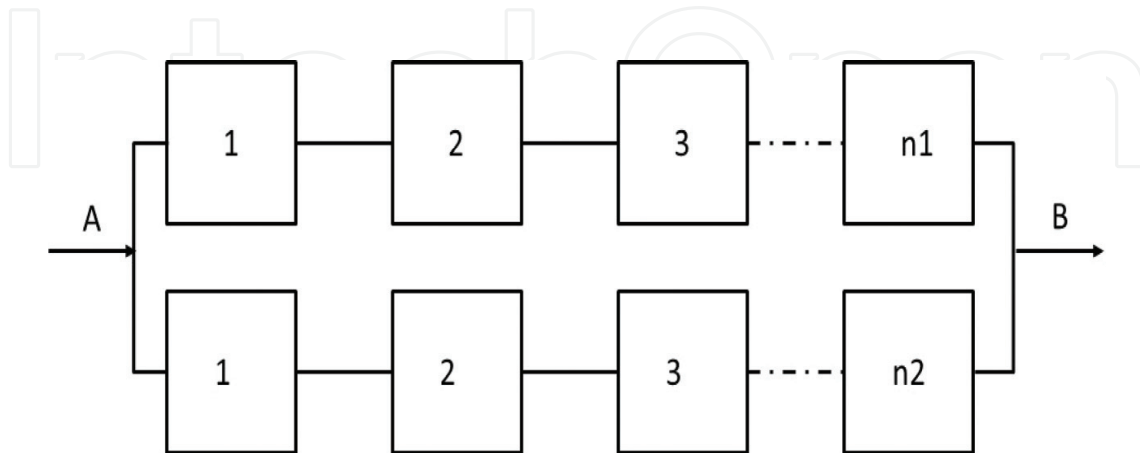**Figure 4.** One line of series-connected components.

Figure 5. Two lines of series-connected components.

the only case without cannibalization, but if we have three or more lines and no interruptions, we already have cannibalization) and (Section 3.3.2) when short interruptions to the system are allowed (i.e. when cannibalization can be executed).

3.3.1. No short interruptions to the system are allowed (i.e. no possibility of cannibalization)

The formula for $Pr(X \geq t)$ (i.e. the probability of survival) is written obviously as follows:

$$S_{2n}^{-}(t) = S_{2n}^{nc}(t) = Pr(X \geq t) = 1 - (1 - e^{-n\lambda t})^2 \tag{10}$$

3.3.2. Short interruptions to the system are allowed (i.e. cannibalization is allowed)

When one line fails, the time for replacing the failed component of the remaining line is allowed and all $n - 1$ non-failed components of the failed line can be used as spares for the operable line. The cannibalization formula for $Pr(X \geq t)$ (i.e. the probability of survival) is written as follows:

$$S_{2n}^{+}(t) = Pr(X \geq t) = e^{-2n\lambda t} + \int_0^t \left(2n\lambda e^{-2n\lambda x} \sum_{i=0}^{n-1} e^{-n\lambda(t-x)} \frac{\left(n\lambda(t-x)\right)^i}{i!} \right) dx \tag{11}$$

where $e^{-2n\lambda t}$ in the first term in Eq. (11) means that both lines have survived (i.e. by the law of total probability); the integral corresponds to the probability that one line failed and then the remaining line has survived with $n - 1$ spares and $2n\lambda e^{-2n\lambda x} dx$ means the density of the first failure of $2n$ components. Then with one line left, there will be no further failures.

One can compare probabilities with and without cannibalization. More appropriately, we compare probabilities of failures. Therefore, we compute the improvement factor of unreliability for the two-line system as $q_{kn}^{nc}(t) = \frac{1 - S_{kn}^{nc}(t)}{1 - S_{kn}^{+}(t)}$ as shown in **Figure 6**.

3.4. Three-line system

Now consider three identical lines of series-connected components in a similar manner to the two-line system. Now, we compute $Pr(X \geq t)$ for three cases [7, 8] (Section 3.4.1) when no cannibalization is allowed at all (just three lines of n series parallel-connected components) (Section 3.4.2), when no short interruptions to the system are allowed (cannibalization is made possible here as we are using the operable components of the failed line as spares, as reflected in Eq. (13)) and (Section 3.4.3) when short interruptions to the system are allowed (i.e. when cannibalization is allowed).
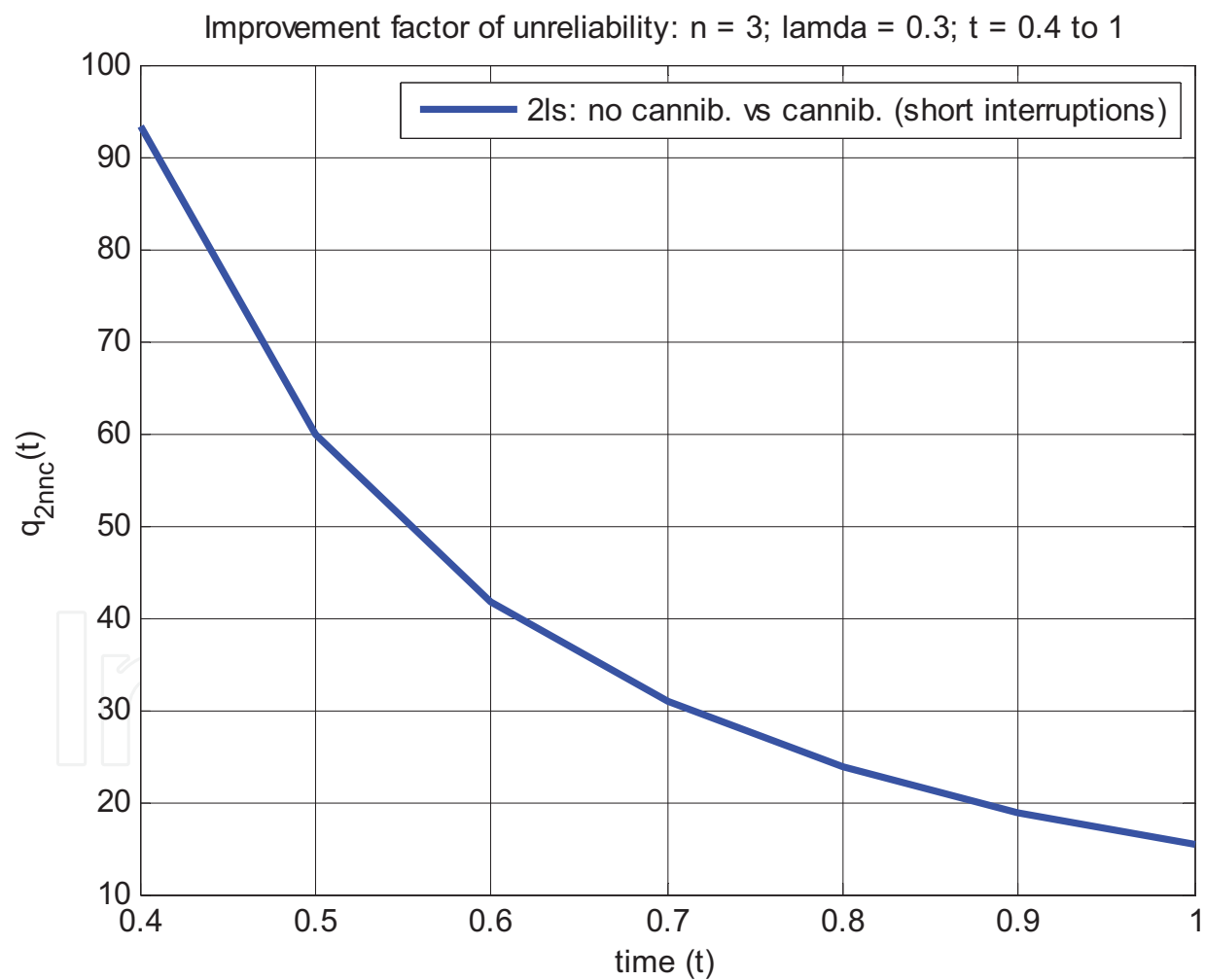
Figure 6. Improvement factor of unreliability for a two-line system (comparison of a system with no cannibalization and that with cannibalization when short interruptions to the system are allowed).

3.4.1. No cannibalization is allowed at all (just three lines of n series parallel-connected components)

The formula for $Pr(X \geq t)$ (i.e. the probability of survival) is written, obviously, as follows:

$$S_{3n}^{nc}(t) = Pr(X \geq t) = 1 - (1 - e^{-n\lambda t})^3 \tag{12}$$

3.4.2. No short interruptions to the system are allowed (i.e. cannibalization is made possible here by operable components of the failed line which are used as spares)

Cannibalization can still be done here. Indeed, when one line fails, we can use $n - 1$ spares for the system of two lines. When the $n - 1$ non-failed components are exhausted, then no cannibalization can be done. The formula is written as follows:

$$S_{3n}^{-}(t) = Pr(X \geq t)$$

$$= e^{-3n\lambda t} + \int_0^t \left(3n\lambda e^{-3n\lambda x} \left(\sum_{i=0}^{n-1} e^{-2n\lambda(t-x)} \frac{\left(2n\lambda(t-x)\right)^i}{i!} \right. \right.$$

$$\left. \left. + \int_0^{t-x} \frac{(2n\lambda)^n}{(n-1)!} y^{n-1} e^{-2n\lambda y} e^{-n\lambda(t-x-y)} dy \right) \right) dx \tag{13}$$

where $e^{-3n\lambda t}$ in the first term in Eq. (13) means that all three lines have survived (i.e. by the law of total probability); the integral corresponds to the probability that one line failed and then the remaining two lines survived with $n - 1$ spares, and $3n\lambda e^{-3n\lambda x} dx$ means the density of the first failure of $3n$ components. Then with two lines with $n - 1$ spares and the nth failure with intensity 2λ will 'ruin' it and one line will be left and no further failures.
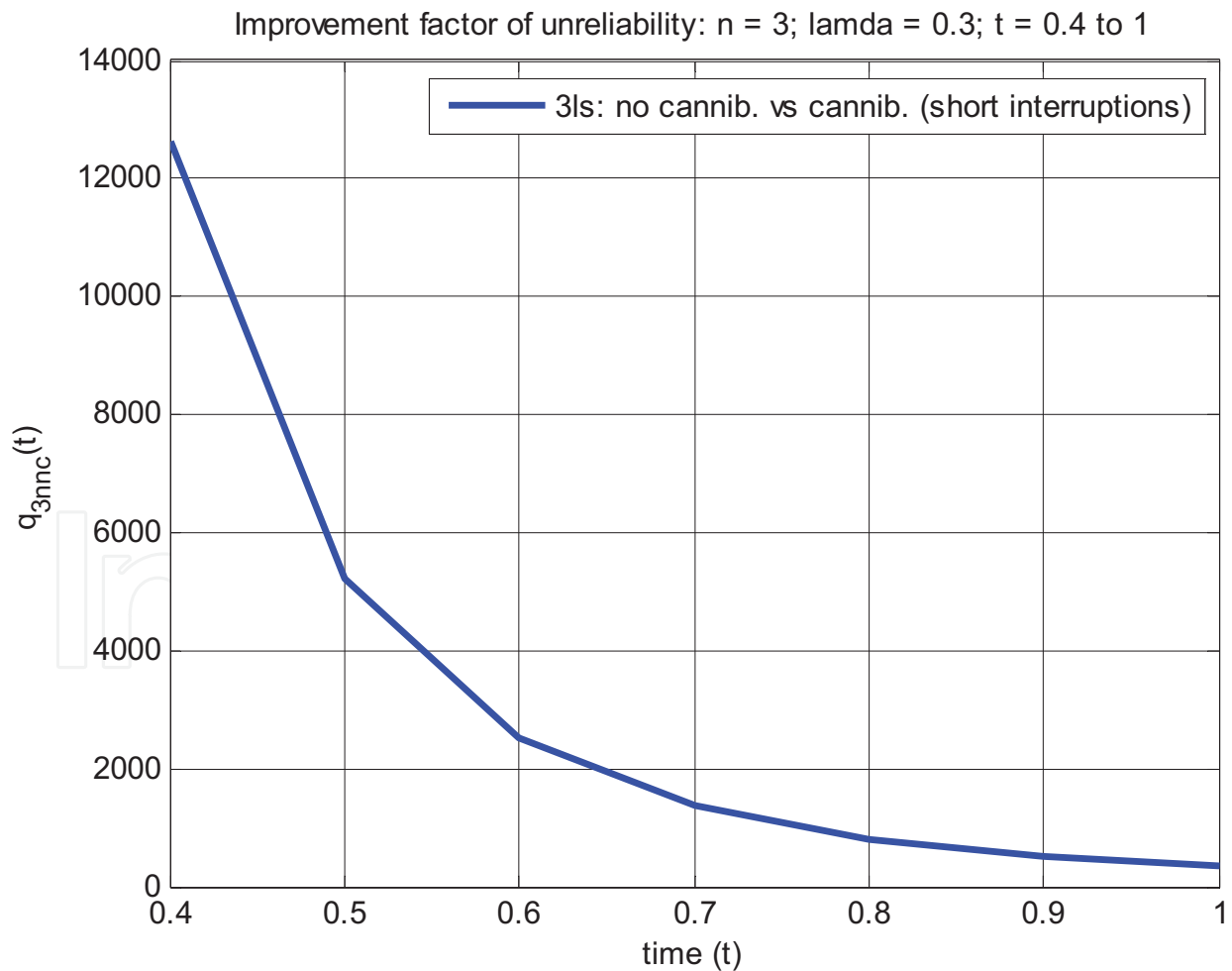
3.4.3. Short interruptions to the system are allowed (i.e. cannibalization is allowed)

The two-stage cannibalization goes. When the first line fails, the time for replacing the failed component of the two remaining lines is allowed. $n - 1$ non-failed components of the failed line can be used to maintain the two remaining lines. When these components are exhausted and one of the two lines fails, the $n - 1$ non-failed components of the failed line can be used as spares for the remaining operable line. The corresponding cannibalization formula for $Pr(X \geq 1)$ is written as follows:

$$S_{3n}^{+}(t) = Pr(X \geq t)$$

$$= e^{-3n\lambda t} + \int_0^t \left(3n\lambda e^{-3n\lambda x} \left(\sum_{i=0}^{n-1} e^{-2n\lambda(t-x)} \frac{\left(2n\lambda(t-x)\right)^i}{i!} \right. \right.$$

$$\left. \left. + \int_0^{t-x} \frac{(2n\lambda)^n}{(n-1)!} y^{n-1} e^{-2n\lambda y} \sum_{i=0}^{n-1} e^{-n\lambda(t-x-y)} \frac{\left(n\lambda(t-x-y)\right)^i}{i!} dy \right) \right) dx \tag{14}$$

where $e^{-3n\lambda t}$ in the first term in Eq. (14) means that all three lines have survived; the integral corresponds to the probability that one line failed and then the remaining two lines survived with $n-1$ spares; $3n\lambda e^{-3n\lambda x}dx$ means the density of the first failure of $3n$ components, and $\frac{(2n\lambda)^n}{(n-1)!}y^{n-1}e^{-2n\lambda y}$ is the density of the nth event from the Poisson process with rate $2n$. Then with two lines with $n-1$ spares and the nth failure with intensity 2λ will 'ruin' it and one line will be left and no further failures.

Here, we can compare probabilities with no cannibalization at all (just three lines of n-series parallel-connected components) and that with cannibalization (with and without short interruptions). More suitably, we compare probabilities of failures. Hence, we compute the improvement factor of unreliability for the three-line system (i.e. that for no cannibalization and cannibalization with and without short interruptions) as $q_{3n}^{nc}(t) = \frac{1-S_{3n}^{nc}(t)}{1-S_{3n}^{(+)}(t)}$ and $q_{3n}^{-+}(t) = \frac{1-S_{3n}^{-}(t)}{1-S_{3n}^{+}(t)}$ as depicted in **Figures 7** and **8**, respectively.

Figure 7. Improvement factor of unreliability for a three-line system (comparison of a system with no cannibalization and that with cannibalization when short interruptions to the system are allowed).
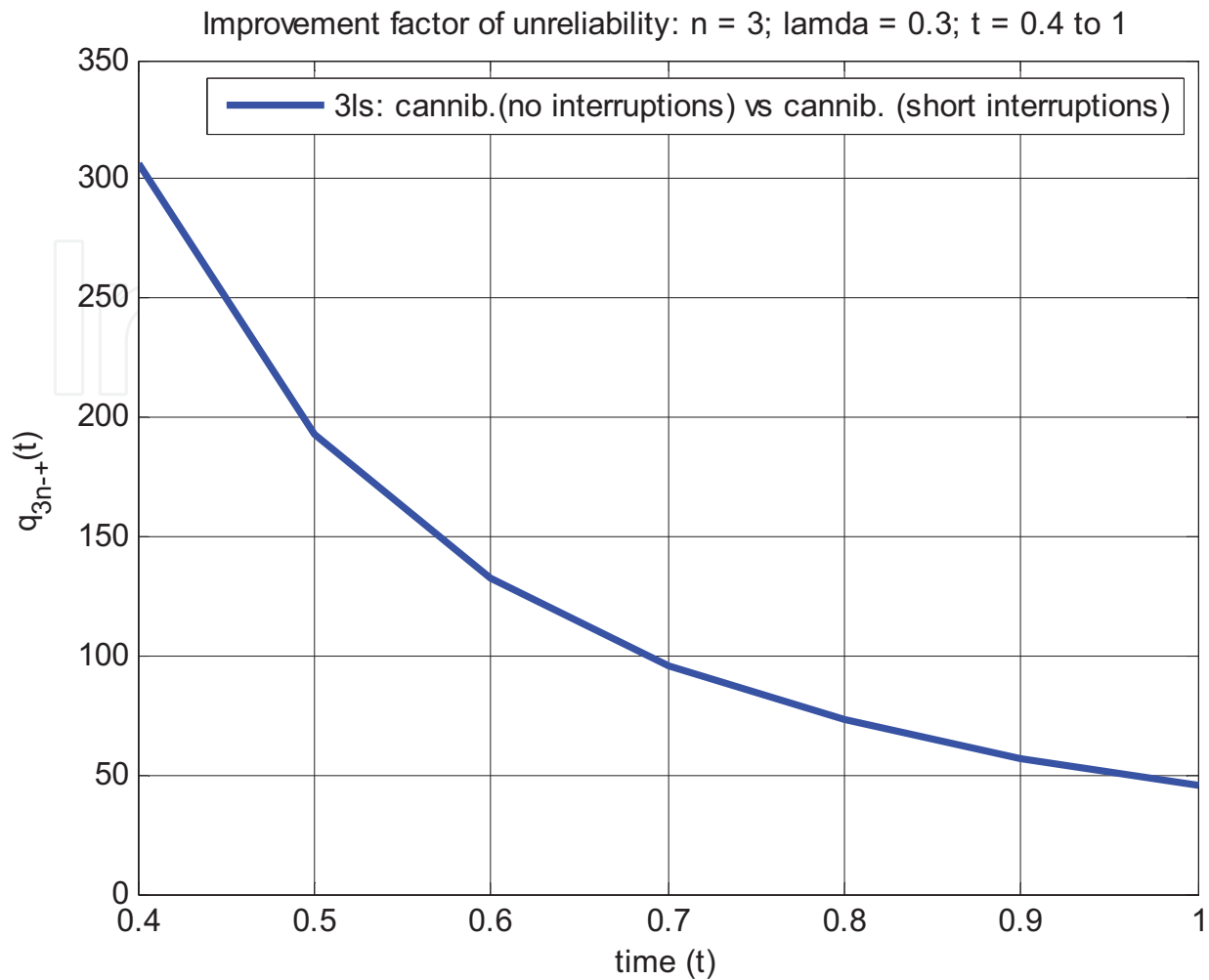
Figure 8. Improvement factor of unreliability for a three-line system (comparison of a system with cannibalization when no short interruptions to the system are allowed and that with cannibalization when short interruptions to the system are allowed).

3.5. k-Line system

Now consider k-identical lines of series-connected components in a similar manner to the two-line system. Now, we compute $Pr(X \geq t)$ for three cases [7, 8]: (Section 3.5.1) when no cannibalization is allowed at all (just k-lines of n-series parallel-connected components) (Section 3.5.2), when no short interruptions to the system are allowed (cannibalization is made possible here as we are using the operable components of the failed line as spares, as reflected in Eq. (16)) and (Section 3.5.3) when short interruptions to the system are allowed (i.e. when cannibalization is allowed).

3.5.1. No cannibalization is allowed at all (just k-lines of n-series parallel-connected components)

The formula for $Pr(X \geq t)$ (i.e. the probability of survival) is written as follows:

$$S_{kn}^{nc}(t) = Pr(X \geq t) = 1 - (1 - e^{-n\lambda t})^k \tag{15}$$

3.5.2. No short interruptions to the system are allowed (i.e. cannibalization is made possible here by operable components of the failed lines which are used as spares)

Cannibalization can still be done here. Indeed, when one line fails, we can use $n - 1$ spares for the system of $k - 1$ lines. When the $n - 1$ non-failed components are exhausted, then no cannibalization can be done. The formula is written as follows:

$$S_{kn}^-(t) = Pr(X \geq t)$$

$$= e^{-kn\lambda t} + \int_0^t \left\{ kn\lambda e^{-kn\lambda x} \left(\sum_{i=0}^{n-1} e^{-(k-1)n\lambda(t-x)} \frac{\left((k-1)n\lambda(t-x)\right)^i}{i!} \right. \right.$$

$$\left. \left. + \int_0^{t-x} \frac{\left((k-1)n\lambda\right)^n}{(n-1)!} y^{n-1} e^{-(k-1)n\lambda y} S_{(k-1)n}^-(t-x-y) dy \right) \right\} dx \qquad (16)$$

where $e^{-kn\lambda t}$ in the first term in Eq. (16) means that all k-lines have survived (i.e. by the law of total probability); the integral corresponds to the probability that one line failed and then the remaining $k - 1$ lines survived with $n - 1$ spares, and $kn\lambda e^{-kn\lambda x} dx$ means the density of the first failure of kn components. Then with $k - 1$ lines with $n - 1$ spares and the nth failure with intensity $(k - 1)\lambda$ will 'ruin' it and one line will be left and no further failures. $S_{(k-1)n}^-(t - x)$ is recurrent from the probability of survival (at time $t - x$) of the system with $k - 1$ lines when no short interruptions to the system are allowed (i.e. cannibalization is made possible here as we are using the operable components of the failed line as spares).
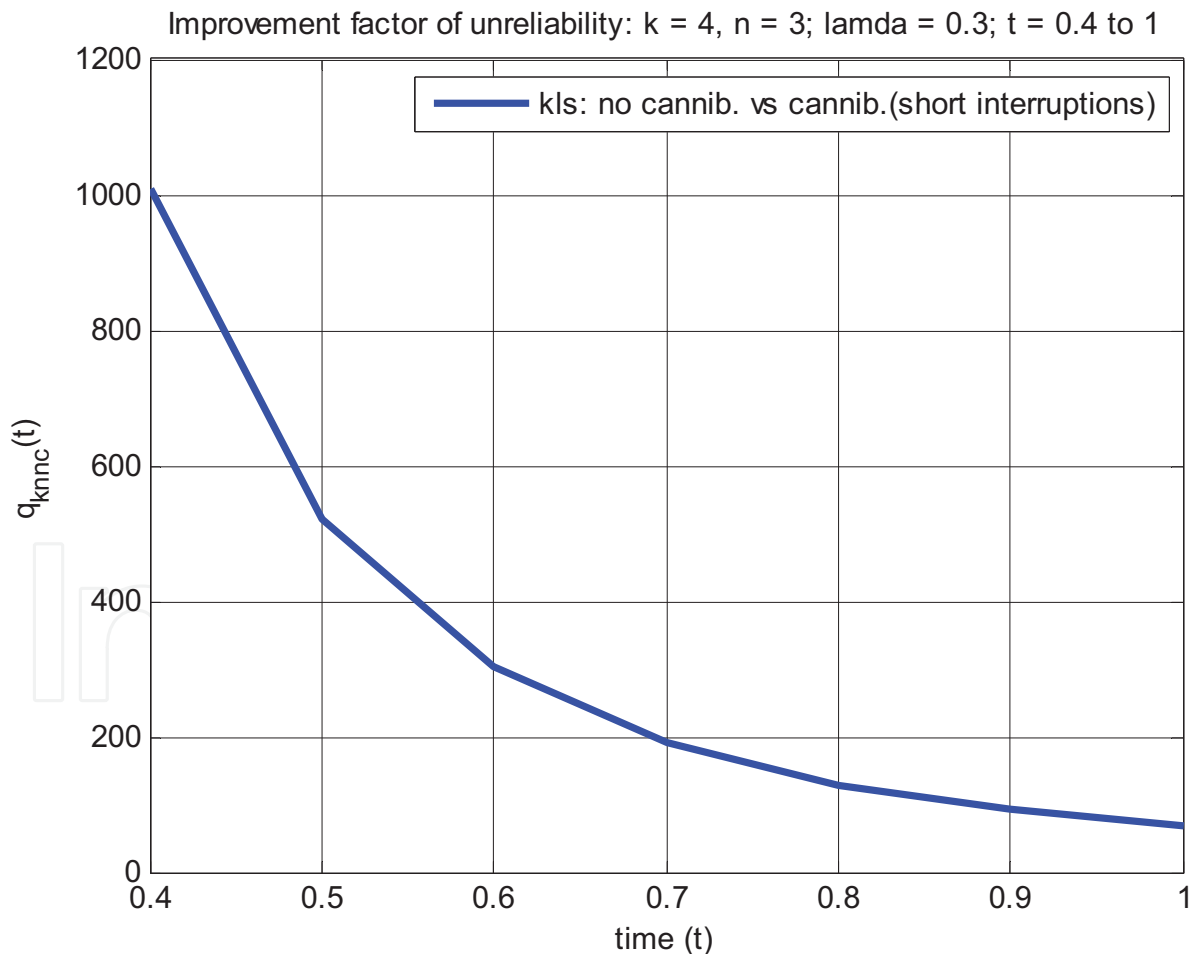
3.5.3. Short interruptions to the system are allowed (i.e. cannibalization is allowed but it was made possible in b) by operable components of the failed lines which are used as spares)

The $k - 1$ stage cannibalization goes. When the first line fails, the time for replacing the failed component of the $k - 1$ remaining lines is allowed. $n - 1$ non-failed components of the failed line can be used to maintain the $k - 1$ remaining lines. When these components are exhausted and one of the $k - 1$ lines fails, the $n - 1$ non-failed components of the failed line can be used as spares for the remaining operable lines. The process is repeated until one (line) remains, and the time for replacing the failed component of this remaining line (if one has a spare) is not allowed. The corresponding cannibalization formula for $Pr(X \geq t)$ is written as follows:

$$S_{kn}^+(t) = Pr(X \geq t)$$

$$= e^{-kn\lambda t} + \int_0^t \left\{ kn\lambda e^{-kn\lambda x} \left(\sum_{i=0}^{n-1} e^{-(k-1)n\lambda(t-x)} \frac{\left((k-1)n\lambda(t-x)\right)^i}{i!} \right. \right.$$

$$\left. \left. + \int_0^{t-x} \frac{\left((k-1)n\lambda\right)^n}{(n-1)!} y^{n-1} e^{-(k-1)n\lambda y} S_{(k-1)n}^+(t-x-y) dy \right) \right\} dx \qquad (17)$$

where $e^{-kn\lambda t}$ in the first term in Eq. (17) means that all k-lines have survived; the integral corresponds to the probability that one line failed and then the remaining $k-1$ lines survived with $n-1$ spares; $kn\lambda e^{-kn\lambda x}\,dx$ means the density of the first failure of kn components, and $S^{+}_{(k-1)n}(t-x)$ is the probability of survival (at time $t-x$ of the system with $k-1$ lines when short interruptions to the system are allowed. Then with $k-1$ lines with $n-1$ spares and the nth failure with intensity $(k-1)\lambda$ will 'ruin' it and one line will be left and no further failures. Thus, Eq. (17) is a recurrent relationship.

Again, we can compare probabilities with and without cannibalization. More usefully, we compare probabilities of failures. Hence, we compute the improvement factor of unreliability for the k-line system (i.e. that for no cannibalization and cannibalization with and without short interruptions) as $q^{nc}_{kn}(t) = \frac{1 - S^{nc}_{kn}(t)}{1 - S^{(+)}_{kn}(t)}$ and $q^{-\,+}_{kn}(t) = \frac{1 - S^{-}_{kn}(t)}{1 - S^{+}_{kn}(t)}$ as depicted in **Figures 9** and **10**, respectively.

Figure 9. Improvement factor of unreliability for a k-line system (comparison of a system with no cannibalization and that with cannibalization when short interruptions to the system are allowed).
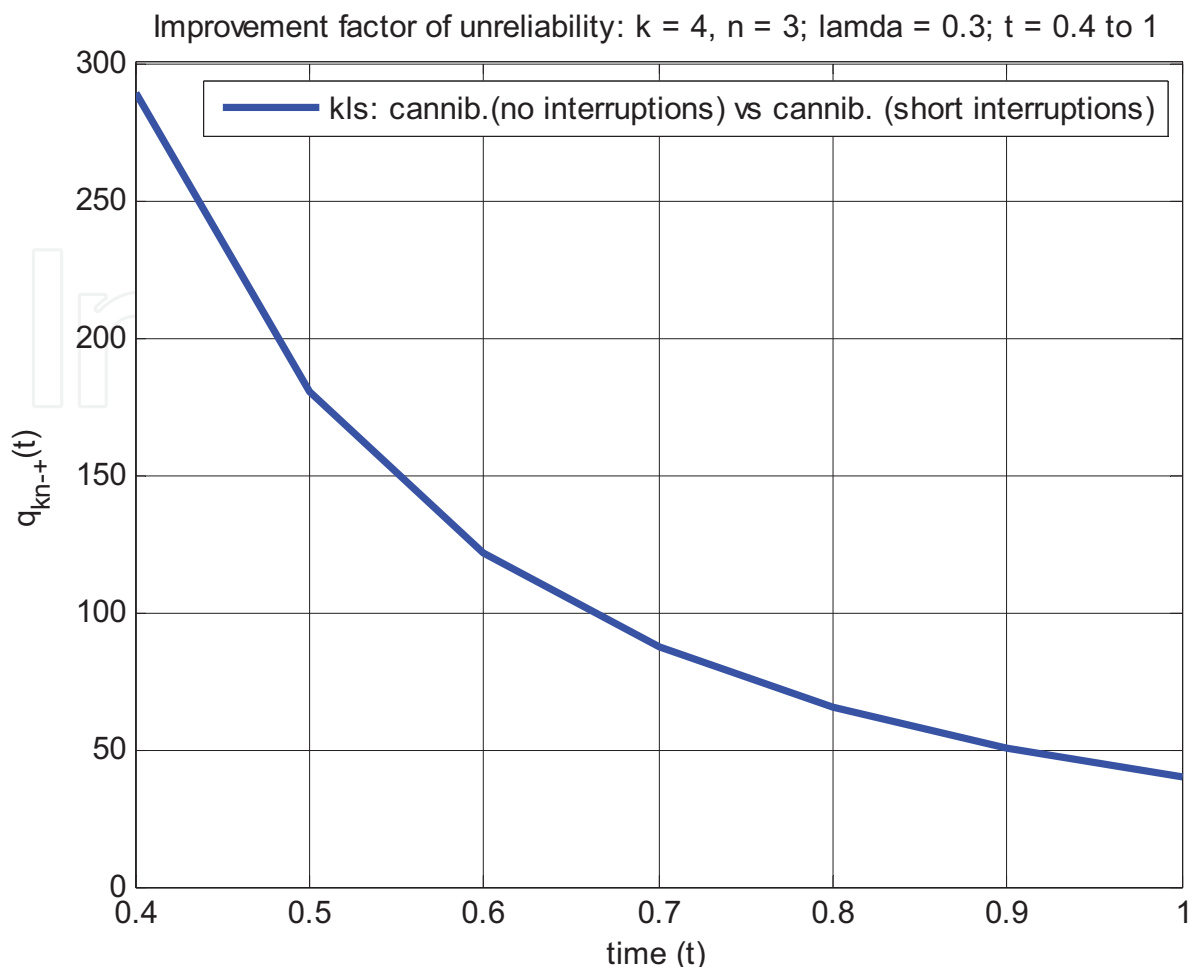
Figure 10. Improvement factor of unreliability for a *k*-line system (comparison of a system with cannibalization when no short interruptions to the system are allowed and that with cannibalization when short interruptions to the system are allowed).

3.6. Computation results

Figures 6–10 show the improvement factors of unreliability for the two-line system, three-line system and *k*-line system, respectively. We are looking at reliable systems, where the survival functions should be close to 1. For illustrative purposes, we choose the values of the failure rate and time accordingly. Therefore, it is more effective to compare unreliability of the systems with no cannibalization (i.e. $1 - S_{kn}^{nc}(t)$) and with cannibalization (i.e. with and without short interruptions) (i.e. $1 - S_{kn}^{+}(t)$ and $1 - S_{kn}^{-}(t)$). The improvement factor of unreliability is obtained by dividing the unreliability of the said system without cannibalization (worse quantity) by that of the said system with cannibalization (without short interruptions) (better quantity) and thus is larger than one. This is then compared to that obtained by dividing the unreliability of the said system with cannibalization with short interruptions (worse quantity) by that of the said system with cannibalization (without short interruptions) (better quantity). It can be seen from **Figures 6–10** that the improvement factors of unreliability of the systems in which cannibalization is allowed are better than in those in which it is prohibited.

From simulation results of **Figures 6–10**, it can also be shown that very larger values lead to asymptotically equivalent system performance levels.

4. Conclusions

In this chapter, we have explored strategies to mitigate the unfavourable effects that cannibalizations have on the costs of maintaining systems of equipment and also on the morale of maintenance personnel. The methodologies developed in this chapter, at least, can be used to (1) ascertain those cannibalizations that are appropriate, (2) start implementation of goals to reduce cannibalization and (3) enlist actions to be taken in order for cannibalization reduction goals to be met.

We also presented a combined analytic and simulation model of a two-line, three-line and k-line system when cannibalization is not allowed and when cannibalization is allowed (with and without short interruptions to the system). It is clear from the analytic and simulation results that cannibalization can substantially increase the reliability of the systems where it is allowed. The improvement factor of unreliability obviously exists in systems where cannibalization is not allowed as compared to those in which cannibalization is allowed. Moreover, the improvement factor is larger when we have two-stage cannibalization (short interruptions) than without them.

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