Availability allocation through importance measures

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Abstract

Purpose – To define availability importance measures in order to calculate the criticality of each component or subsystem from the availability point of view and also to demonstrate the application of such importance measures for achieving optimal resource allocation to arrive at the best possible availability.

Design/methodology/approach – In this study the availability importance measures of a component are defined as a partial derivative of the system availability with respect to the component availability, failure rate, and repair rate. Analyses of these measures for a crushing plant are performed and the results are presented. Furthermore, a methodology aimed at improving the availability of a system using the concept of importance measures is identified and demonstrated by use of a numerical example.

Findings – The availability importance measure of a component/subsystem is an index which shows how far an individual component contributes to the overall system availability. The research study indicates that the availability importance measures could be applied in developing a strategy for availability improvement. The subsystem/component with the largest value of importance measure has the greatest effect on the system availability.

Research limitations/implications – The result of availability improvement strategy is demonstrated using only a hypothetical example.

Practical implications – Using availability importance measures will help managers and engineers to identify weaknesses and indicate modifications which will improve the system availability.

Originality/value – This paper presents the concept of availability importance measure for a component/subsystem. It also introduces some availability importance measures based on failure rate, mean time between failures (MTBF), and repair rate/mean time to repair (MTTR) of a component /subsystem. The concept of importance measures is used to prioritise the components or subsystems for the availability improvement process.

Keywords Mean time between failures, Mean time to repair

Paper type Research paper

Introduction

The most important performance measures for repairable system designers and operators are system reliability and availability. Improvement of system availability has been the subject of a large volume of research and articles in the area of reliability. Availability and reliability are good evaluations of a system's performance. Their values depend on the system structure as well as the component availability and reliability. These values decrease as the component ages increase; i.e. their serving times are influenced by their interactions with each other, the applied maintenance policy and their environments (Samrout *et al.*, 2005). The main requirements for the operation of complex systems are usually specified in terms of cost and availability and/or reliability, or equivalently in terms of mean time between failure (MTBF) and/or mean time to repair

(MTTR) under a cost constraint. These requirements have to be taken into consideration in the system design stage in order to determine the appropriate reliability and availability of each of the system's components (Elegbede and Adjallah, 2003). In a simplistic sense, there are some issues to be resolved during the development of an availability improvement or optimization process in design and operation phases, such as: where it is best to attempt improvements in availability; and how to affect improvements in availability when the areas which merit attention have been identified. Finding appropriate answers to these questions can be quite difficult and the solutions to the many problems which result in loss of availability are frequently not obvious.

A number of researchers have investigated the theoretical problem of availability allocation and optimisation using different techniques and methods, e.g. Painton and Campbell (1995); Castro and Cavalca (2002; 2003); Elegbede and Adjallah (2003); Chiang and Chen (2006). The availability allocation problems are mainly dealt with considering the criticality of reliability and maintainability characteristics of the system at component level. Therefore, it is useful to consider reliability and maintainability importance measures for improving the existing availability characteristics. The concept of importance measures came from the perception that in any orderly arrangement of components in a system, some of the components are more important than others in providing certain system characteristics. Component importance analysis is a key part of the system reliability quantification process. It enables the weakest areas of a system to be identified and indicates modifications which will improve the system reliability and maintainability (Beeson and Andrews, 2003). Several component importance measures have been developed in the reliability area, e.g. Aven (1986), Boland and El-Neweihi (1995), Andrews and Beeson (2003), Zio and Podofillini (2003), Cassady *et al.* (2004); as Birnbaum (1969) first introduced mathematical concept of the importance measures. The main objectives of this study are to define some availability importance measures in order to find the criticality of each component or subsystem form availability point of view, and identify a methodology which aims to allocate resources for the availability optimisation applying the concept of availability importance measures.

This paper is organized as follows. Part 2 introduces availability importance measures and application of those importance measures for different types of configurations and a real case study of a crushing plant is presented. Part 3 defines the availability improvement strategy by use of the concept of importance measures for resource allocation and a numerical example of a parallel-series system is applied to demonstrate the proposed approach. In part 4, the conclusions of this paper are provided. In this study we assumed the following:

· The system is composed of n s-independent components.

· Failure rate and repair rate of components and subsystems are known.

· All the components are repairable. The repair of components makes them as good as new.

· Each component, subsystem, and system has two states: working or failed.

Availability importance measures
When assessing a system, its performance depends upon its components. Some components have major influences on system reliability and availability than others. In

order to evaluate the importance of different aspects of a system, a set of importance measurements including Structure Importance, Birnbaum Component Importance, Reliability Criticality Importance, Upgrading Function, Operational Criticality Importance, and Restore Criticality Index (Leemis, 1995, Frickes and Trivedi, 2003, Wang *et al.* 2004) are widely used in engineering practices. According to Beeson and Andrews (2003), component reliability importance measure is defined as the probability that component i is critical to system failure. One of the most widely used reliability importance indices is Birnbaum's component importance (Frickes and Trivedi, 2003). The reliability importance of a component can be determined based on the failure characteristics of the component and its corresponding positioning in the system. The reliability importance of component i, I_R^i, in a system of n components is given by:

$$I_R^i = \frac{\partial R_s(t)}{\partial R_i(t)} \qquad (1)$$

where $R_S(t)$ is the system reliability and $Ri\ (t)$ is the component reliability.

By using the same concept in the case of system availability performance, some availability importance measures are defined by Barabady (2005) and can be used as a guideline in developing an improvement strategy. Availability importance measure enables the weakest areas of a system to be identified and indicates modifications which will improve the system availability. Efforts to improve availability can be concentrated on those components whose contributions indicate that by upgrading them, the maximum improvement in system availability can be achieved. Availability importance measure is a function of time, the failure and repair characteristics or MTBF and MTTR parameters, and the system structure. Availability importance measure (I_A^i) assigns a numerical value between 0 and 1 to each subsystem or component, with the value 1 signifying the highest level of importance. The availability importance of component i in a system of n components is given as follows:

$$I_A^i = \frac{\partial A_s}{\partial A_i} \qquad (2)$$

where A_S is the system availability and Ai is the component availability.

Availability importance measure shows the effect of the availability of subsystem or component i on the availability of the whole system. The subsystem or component with the largest value has the greatest effect on the availability of the whole system. It is useful to obtain the value of the availability importance measure of each component in the system prior to deploying resources toward improving the specific components. This is carried out to determine which component needs to be improved in order to achieve the maximum effect from the improvement effort. If the availability of the system needs to improve, then efforts should first be concentrated on improving the subsystem that has the largest effect on the availability of the system. The availability of a system is a function of failure rate and repair rate characteristics or Mean MTBF and MTTR parameters, which mean other sets of importance measures can be defined as:

- availability importance measure based on the failure rate or MTBF; and
- availability importance measure based on the repair rate or MTTR.

Availability importance measure based on the failure rate/MTBF shows the effect of the failure rate/MTTR of component i on the availability of the whole system, and the failure rate/MTBF of the component with the largest value has the greatest effect on the availability of the whole system. It can be calculated by equation (3) or (4).

$$I^i_{A,\lambda_i} = -\frac{\partial A_s}{\partial \lambda_i} = -\frac{\partial A_s}{\partial A_i} \times \frac{\partial A_i}{\partial \lambda_i} \tag{3}$$

where λ_i represents the failure rate of component i.

$$I^i_{A,MTBF_i} = \frac{\partial A_s}{\partial MTBF_i} = \frac{\partial A_s}{\partial A_i} \times \frac{\partial A_i}{\partial MTBF_i} \tag{4}$$

Availability importance measure based on the repair rate/MTBF shows the effect of the repair rate/MTTR of component i on the availability of the whole system, and the repair rate of the component with the largest value has the greatest effect on the availability of the whole system. It can be calculated by equation (5) or (6).

$$I^i_{A,\mu_i} = \frac{\partial A_s}{\partial \mu_i} = \frac{\partial A_s}{\partial A_i} \times \frac{\partial A_i}{\partial \mu_i} \tag{5}$$

where μ_i represents the repair rate of component i.

$$I^i_{A,MTTR_i} = -\frac{\partial A_s}{\partial MTTR_i} = -\frac{\partial A_s}{\partial A_i} \times \frac{\partial A_i}{\partial MTTR_i} \tag{6}$$

Application of availability importance measures to a series system
Consider a system which consists of n s-independent subsystems connected in series and which fails when at least one of its components fails. The steady-state availability for a series-system is the product of the component availabilities (Ebeling, 1997; Pham, 2003).

$$A_s = \prod_{i=1}^{n} A_i = \prod_{i=1}^{n} \frac{MTBF_i}{MTBF_i + MTTR_i} = \prod_{i=1}^{n} \frac{\mu_i}{\mu_i + \lambda_i} \tag{7}$$

Availability importance measures for component i of a series system is given by:

$$I^i_A = \frac{\partial A_s}{\partial A_i} = \prod_{\substack{k=1 \\ k \neq i}}^{n} A_k \tag{8}$$

Equation 8 shows that the availability of a component doesn't affect on the availability importance measure of that component. The priority in terms of increased availability of the system should be assigned to component i which is the component with the minimum availability estimate. Different types of availability importance measures based on availability characteristics for such system can be calculated by following equations.

$$I^i_{A,MTBF_i} = \frac{\partial A_s}{\partial A_i} \frac{\partial A_i}{\partial MTBF_i} = A_s \times \frac{MTTR_i}{MTBF_i(MTTR_i + MTBF_i)} \qquad (9)$$

$$I^i_{A,MTTF_i} = -\frac{\partial A_s}{\partial A_i} \frac{\partial A_i}{\partial MTTR_i} = A_s \times \frac{1}{(MTTR_i + MTBF_i)} \qquad (10)$$

$$I^i_{A,\lambda_i} = -\frac{\partial A_s}{\partial A_i} \frac{\partial A_i}{\partial \lambda_i} = A_s \times \frac{1}{(\lambda_i + \mu_i)} \qquad (11)$$

$$I^i_{A,\mu_i} = \frac{\partial A_s}{\partial A_i} \frac{\partial A_i}{\partial \mu_i} = A_s \times \frac{\lambda_i}{\mu_i(\lambda_i + \mu_i)} \qquad (12)$$

Application of availability importance measures to a parallel system
Consider a system which consists of n independent subsystems connected in parallel and which works when at least one of its components works. The steady-state availability of a parallel-system is given by (Ebeling, 1997):

$$A_s = \prod_{i=1}^{n} A_i = \prod_{i=1}^{n} \frac{MTBF_i}{MTBF_i + MTTR_i} = \prod_{i=1}^{n} \frac{\mu_i}{\mu_i + \lambda_i} = 1 - \prod_{i=1}^{n} \left(1 - \frac{\mu_i}{\mu_i + \lambda_i}\right) \quad (13)$$

Availability importance measure for component i of the system is given as follows:

$$I^i_A = \frac{\partial A_s}{\partial A_i} = 1 - \prod_{\substack{k=1 \\ k \neq i}}^{n} (1 - A_k) \qquad (14)$$

Equation 14 shows that the availability of a component doesn't affect on the availability importance measure of that component. The priority in term of increase availability of the system should be assigned to component i which is the component with the maximum availability estimate. Different types of availability importance measures based on availability characteristics for such system can be calculated by following equations.

$$I^i_{A,MTBF_i} = \frac{\partial A_s}{\partial A_i} \frac{\partial A_i}{\partial MTBF_i}$$

$$= 1 - \prod_{\substack{k=1 \\ k \neq i}}^{n} (1 - A_k) \times \frac{MTTR_i}{MTBF_i(MTBF_i + MTTR_i)} \times A_i \qquad (15)$$

$$I^i_{A,MTTR_i} = -\frac{\partial A_s}{\partial A_i}\frac{\partial A_i}{\partial MTTR_i}$$

$$= 1 - \prod_{\substack{k=1 \\ k \neq i}}^{n} (1-A_k) \times \frac{1}{(MTBF_i + MTTR_i)} \times A_i \qquad (16)$$

$$I^i_{A,\lambda_i} = -\frac{\partial A_s}{\partial A_i}\frac{\partial A_i}{\partial \lambda_i} = 1 - \prod_{\substack{k=1 \\ k \neq i}}^{n} (1-A_k) \times \frac{1}{(\lambda_i + \mu_i)} \times A_i \qquad (17)$$

$$I^i_{A,\mu_i} = \frac{\partial A_s}{\partial A_i}\frac{\partial A_i}{\partial \mu_i} = 1 - \prod_{\substack{k=1 \\ k \neq i}}^{n} (1-A_k) \times \frac{\lambda_i}{\mu_i(\lambda_i + \mu_i)} \times A_i \qquad (18)$$

Application of availability importance measures to a Series-parallel system
Consider a system which consists of n independent subsystems connected in series, and each subsystem consists of m component in parallel, the steady-state availability for a series-parallel system is given by equation (19).

$$A_s = \prod_{K=1}^{n}\left(1 - \prod_{l=1}^{m}(1-A_{kl})\right) = \prod_{K=1}^{n}\left(1 - \prod_{i=1}^{m}(1 - \frac{MTBF_{kl}}{MTBF_{kl}+MTTR_{kl}})\right) \qquad (19)$$

Availability importance measure for component ij of the system is given by:

$$I^{ij}_A = \frac{\partial A_s}{\partial A_{i,j}} = \prod_{\substack{k=1 \\ k \neq i}}^{n}\left(1 - \prod_{l=1}^{m}(1-A_{kl})\right) \times \left(1 - \prod_{\substack{l=1 \\ l \neq j}}^{m} A_{il}\right) \qquad (20)$$

Equation 20 shows that the availability of a component doesn't affect on the availability importance measure of that component. The priority in term of increase availability of the system should be assigned to component ij, which is the component with the maximum availability importance measure. Different types of availability importance measures based on availability characteristics for such system can be calculated by following equations.

$$I_{A,MTBF_{ij}}^{ij} = I_A^{ij} \times \frac{MTTR_{ij}}{MTBF_{ij}(MTBF_{ij} + MTTR_{ij})} \times A_{ij} \qquad (21)$$

$$I_{A,MTTR_{ij}}^{ij} = I_A^{ij} \times \frac{1}{(MTBF_{ij} + MTTR_{ij})} \times A_{ij} \qquad (22)$$

$$I_{A,\lambda_{ij}}^{ij} = I_A^{ij} \times \frac{1}{(\lambda_{ij} + \mu_{ij})} \times A_{ij} \qquad (23)$$

$$I_{A,\mu_{ij}}^{ij} = I_A^{ij} \times \frac{\lambda_{ij}}{\mu_{ij}(\lambda_{ij} + \mu_{ij})} \times A_{ij} \qquad (24)$$

An illustrative case study
To illustrate the concept of importance measures, we use a case study of a crushing plant in Jajarm Bauxite mine of Iran. The crushing plant is divided into six subsystems that work in series system which means the crushing plant is in working state if all subsystems work. The best-fit distributions for all subsystem of the crushing plant are calculated using Weibull $++6$ software based on historical data form the period of one year. Table I shows the best-fit distributions for time between failures data and time to repair data for all subsystems of the crushing plant.

The availability importance measures for all subsystems are calculated and tabulated in Table II by use of equations 2, 4, and 6. The availability importance measure I_A^i shows that the SCRCS and COCS subsystems have more influence on the availability of the whole system. As a result, improvement in the availability of the SCRCS and COCS will cause the greatest increase in the system availability.

Comparing $I_{A,MTBF_i}^i$ and $I_{A,MTTR_i}^i$ can determine whether the MTBF or MTTR of component i has more influence on the availability of the crushing plant. In this case study, if the availability of the crushing plant needs to be improved, the efforts should be primarily concentrated on increasing the availability of the SCRCS and COCS. In addition, it is better to pay more attention to the MTTR of SCRCS and also MTTR of COCS subsystem; because the effect of MTTR of them on the availability of the whole system is about 13 and 16 times respectively greater than the corresponding effect of the MTBF of both subsystem which is indicated by a comparison of $I_{A,MTBF_i}^i$ and $I_{A,MTTR_i}^i$. However, the investment requirements to decrease the MTTR may be much grater than those requirements to increase the MTBF. Cost trade-off is essential for making final decision.

Availability improvement process using importance measures
Availability is an important characteristic of a repairable system. When the availability of a system is low, efforts are needed to improve it. The question of how to meet an availability goal for a system arises when the estimated availability is inadequate. This then becomes a reliability and availability allocation problem at the component level. Reliability and availability engineers are often called upon to make decisions as to whether to improve a certain component or components in order to

Sub-system	Best-Fit	Time between failures Parameters	Best-Fit	Time to repair data Parameters
PCRCS (Primary Crusher)	Weibull 3 P	Beta = 1.34, Eta = 78.6, Gamma = 3.873	Lognormal	Mean = 0.4638, Std = 0.922
SCRCS (Secondary Crusher)	Weibull 3 P	Beta = 1.115, Eta = 78.96, Gamma = 8.931	Lognormal	Mean = 0.720, Std = 1.515
PSCCS (Primary Screen)	Lognormal	Mean = 3.37, Std = 1.142	Weibull 2 P	Beta = 1.4998, Eta = 1.5843
SSCCS (Secondary Screen)	Lognormal	Mean = 3.868, Std = 1.101	Lognormal	Mean = 0.10, Std = 1.021
COCS (Conveyer Subsystem)	Lognormal	Mean = 3.18, Std = 0.841	Lognormal	Mean = 0.154, Std = 1.1157
FECS (Feeder Subsystem)	Exponential 2P	Lambda = 0.0057, Gamma = 24.80	Exponential 2P	Lambda = 1.039, Gamma = 0.159

Table I.
Best-fit distribution and their parameters for TBF and TTR data sets

achieve better results. There are two ways to improve the availability of a repairable system:

(1) reduce the failure rate of the component in question or, in other words, increase the mean time between failures; and/or

(2) improve the repair rate of the system, structure or component (SSC), or, in other words, reduce the mean down-time.

Figure 1 and Figure 2 show how to maximize the availability of the SSC through decreasing the failure rate and also decreasing the time needed to restore the SSC.

Any improvement in the availability of a system is associated with the requirement of additional efforts and cost. Therefore, it is essential to use methods or techniques for availability allocation amongst various components/subsystems of a system with the minimum efforts and cost. As a result, many studies have been performed to improve and optimise the availability of a system through different methods and techniques,

Sub-system	I_A^i	$I_{A,MTBF_i}^i$	$I_{A,MTTR_i}^i$
PCRCS	0.829	0.00033	0.01024
SCRCS	0.866	0.00068	0.00874
PSCCS	0.826	0.00040	0.01395
SSCCS	0.818	0.00016	0.00900
COCS	0.854	0.00139	0.02201
FECS	0.808	0.00002	0.00401

Table II.
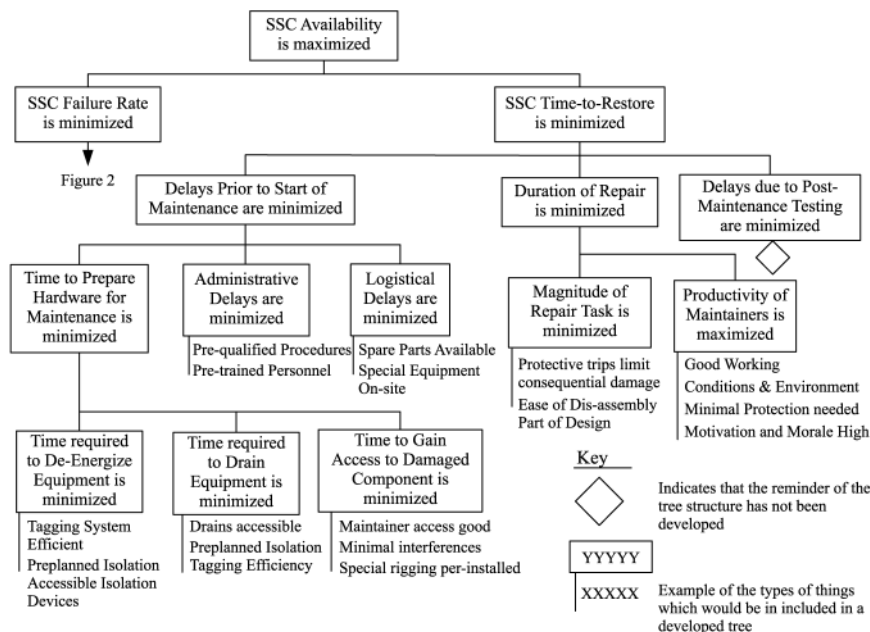Availability importance measures for all subsystems of the crushing plants

Source: Adapted from IAEA (2001)

Figure 1.
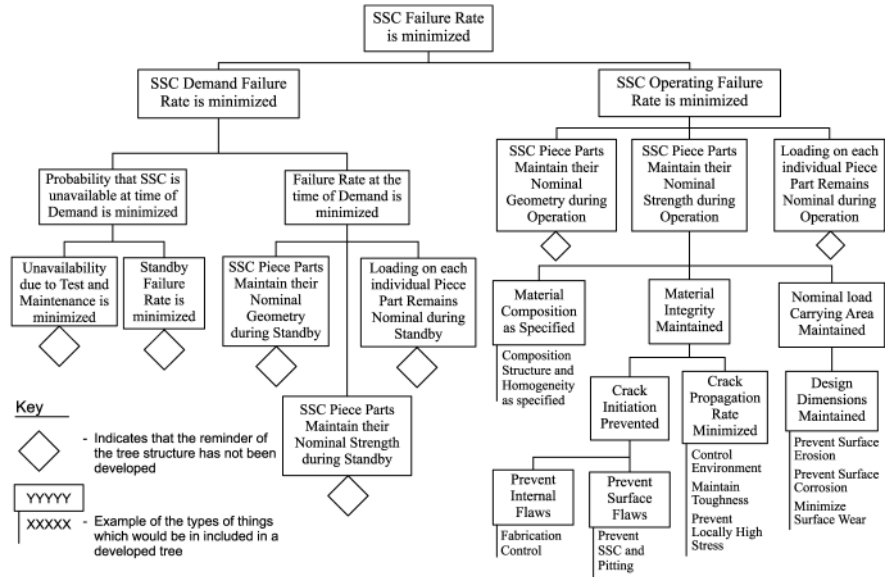Contributors to SSC unavailability, down-time rate

Figure 2.
Contributors to SSC
unavailability, failure rate

Source: Adapted from IAEA (2001)

e.g. Murty and Naikan (1995), Owens *et al.* (2006), and Chiang and Chen (2006). Some optimisation methods to redundancy allocation problems are applied by Castro and Cavalca (2002). The genetic algorithm (Holland, 1975) is a search method which is analogous to biological evolution and reproduction that have selected by Painton and Campbell (1995), Castro and Cavalca (2003), Elegbede and Adjallah (2003) to solve availability allocation problems and other reliability optimisation problems. In most cases, the problem of availability allocation and optimisation can be defined as a multi-objective optimisation problem which aims to maximize system availability and minimize system cost. In these studies, specifically in genetic algorithm, complex mathematic expressions for modelling are used. Generally, the availability importance measures of components should be used during the design or evaluation of systems to determine which components or subsystems have the greatest importance for the availability of the system. This part suggests an approach for the allocation of resources and availability optimisation using the concept of importance measures which are mentioned in part 2 and the approach suitability is demonstrated using numerical example. The main motivation for applying the concept of availability importance measures is due to its easiness to understand as it uses the criticality of components for resource allocation and availability optimisation purposes. Furthermore, the model is quantitative approach. With the assistance of importance measures, the components that merit additional research and development to improve their availabilities can be identified; therefore, the greatest gain is achieved in the system availability. Those components with high importance could prove to be candidates for further improvements. In the present research, it is found that the availability improvement process could be implemented by following three steps:

(1) identification of an ordered list of candidates for the availability improvement process.

(2) identification of effective changes or remedial actions for each candidate, which will either reduce its failure frequency or reduce its time required to restore a component.

(3) justification and prioritization of the actions for each candidate on the basis of cost-benefit comparisons.

In step one an ordered list of candidates for availability improvement can be identified by using of the availability importance measure, but this measure does not provide more information about those candidates. Therefore, in step two the availability importance measure based on failure rate and the availability importance measures based of repair rate for each component must be calculated. Comparing these two importance measures shows which of the two factors, the failure rate or the repair rate of each component, has more influence on the availability of the whole system. In other words, this comparison will show whether the availability improvement should be based on reducing the failure rate or increasing the repair rate of critical components or subsystems.

To find the final strategy for the availability improvement process (step 3) the cost trade-off is essential. When the availability of the system is less, it needs to be improved using the special budget C. The question is how to manage improvement efforts and which component or components, if improved, will give better results. This question can be answered through the following procedure. The cost needed to reduce the failure rate which denoted by$\Delta C_{\lambda i}$ and the cost needed to improve the repair rate that denoted by$\Delta C_{\mu i}$ can be calculated by equations (25) and (26).

$$\Delta C_{\lambda_i} = \frac{\partial C}{\partial \lambda_i} \times \Delta \lambda_i \tag{25}$$

$$\Delta C_{\mu_i} = \frac{\partial C}{\partial \mu_i} \times \Delta \mu_i \tag{26}$$

$\frac{\partial C}{\partial \lambda_i}$ and $\frac{\partial C}{\partial \mu_i}$ explain the variation of the availability improvement cost with respect to the failure rate and the repair rate of component i, respectively.

If budget C is spent on improving the repair rate for the critical components the repair rate will increase as$\Delta \mu_i$:

$$\Delta \mu_i = \frac{\Delta C_{\mu_i}}{\frac{\partial C}{\partial \mu_i}} = \frac{C}{\frac{\partial C}{\partial \mu_i}} \tag{27}$$

Therefore, the availability will increase as$\Delta A_{s,\mu_i}$which can be calculated by:

$$\Delta A_{s,\mu_i} = I^i_{A,\mu_i} \times \Delta \mu_i = \frac{\partial A_s}{\partial \mu_i} \times \frac{C}{\frac{\partial C}{\partial \mu_i}} \tag{28}$$

If the budget is spent on reducing the failure rate of the critical component, the failure rate will be decreased as$\Delta \lambda_i$:

$$\Delta \lambda_i = \frac{\Delta C_{\lambda_i}}{\frac{\partial C}{\partial \lambda_i}} = \frac{C}{\frac{\partial C}{\partial \lambda_i}} \tag{29}$$

Therefore, the availability will be increased as $\Delta A_{s,\lambda_i}$ which can be calculated by:

$$\Delta A_{s,\lambda_i} = I^i_{A,\lambda_i} \times \Delta \lambda_i = \frac{\partial A_s}{\partial \lambda_i} \times \frac{C}{\frac{\partial C}{\partial \lambda_i}} \tag{30}$$

By comparing $\Delta A_{s,\lambda_i}$ and $\Delta A_{s,\mu_i}$ the strategy can be identified. If there are some restrictions, the budget can be spent on both increasing the repair rate and decreasing the failure rate. We then allocate a fraction f of the budget for decreasing the failure rate and the remaining fraction $1\text{-}f$ for increasing the repair rate. And hence the availability improvement can be calculated by:

$$\Delta A_{s,\lambda_i,\mu_i} = \frac{\partial A_s}{\partial \lambda_i} \times \frac{fC}{\frac{\partial C}{\partial \lambda_i}} + \frac{\partial A_s}{\partial \mu_i} \times \frac{(1-f)C}{\frac{\partial C}{\partial \mu_i}} \tag{31}$$

Illustrative numerical example

To illustrate the model, we made the simple example system which is illustrated in Figure 3 with the same assumptions as those given in Part 2. Table III shows the failure rate and repair rate of all the components. It also shows the cost needed to change the failure rate and repair rate of each component based on the failure rate of component 1. For example, the cost needed to change the failure rate of component 2 and 3 is about 30 per cent and 90 per cent of the cost which is needed to decrease the failure rate of component 1, respectively.
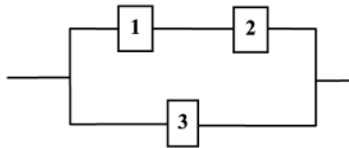

Figure 3.
A simple system

Component	Failure rate	Repair rate	$\frac{\partial C}{\partial \lambda_i} / \frac{\partial C}{\partial \lambda_1}$	$\frac{\partial C}{\partial \mu_i} / \frac{\partial C}{\partial \lambda_1}$
1	0.007	0.018	1	0.3
2	0.0214	0.05	0.26	0.5
3	0.0175	0.03	0.8	0.6

Table III.
Failure and repair rates of all the components

Component	I^i_A	I^i_{A,λ_i}	I^i_{A,μ_i}	$\frac{\Delta A_{s,\lambda_i}}{\Delta A_{s,\lambda_1}} \frac{\Delta A_{s,\lambda_i}}{\Delta A_{s,\lambda_1}}$	$\frac{\Delta A_{s,\mu_i}}{\Delta A_{s,\mu_1}}$
1	0.258	7.430	2.890	1.000	1.296
2	0.265	2.602	1.114	1.347	0.300
3	0.496	6.592	3.846	1.109	0.863

Table IV.
Availability importance measures for all the components

Based on equation 2, 3, and 5 the availability importance measures for all components are calculated and tabulated in Table IV. The availability importance measure (I_A^i) indicates that component 3 has more influence on the availability of the whole system and therefore, improvement in the availability of component 3 will cause the greatest increase in the system availability. By comparing I_{A,λ_i}^i and I_{A,μ_i}^i can determine whether the repair rate or the failure rate has more influence on the availability of the system. In the example studied, if the availability of the system needs to be improved, the effort should first be concentrated on increasing the availability of component 3. In addition, it is better to pay more attention to the failure rate of component 1, because the effect of this failure rate on the availability of the whole system is about 2 times greater than the corresponding effect of the repair rate, which is indicated by a comparison of I_{A,λ_i}^i and I_{A,μ_i}^i.

By using equations 28 and 30, the final decision in the availability improvement process can be identified. From Table II it is found that it is better to focus one's efforts and finances on reducing the failure rate of component 2 and increasing the repair rate of component 1. In this way the availability of the system will increase more than by using other strategies with the same effort and cost.

Conclusions

In this research study some availability importance measures are defined and a method for availability allocation and optimisation of system's availability using the concept of availability importance measures is proposed. In the case of a system's availability performance, availability importance measures could be used as a guideline in developing a strategy for availability improvement. It is useful to obtain the value of the availability importance measure for each component in the system prior to deploying resources toward improving the specific components.

References

Andrews, J.D. and Beeson, S. (2003), "Birnbaum's measures of component importance for noncoherent systems analysis", *IEEE Transactions on Reliability*, Vol. 52 No. 2, pp. 213-9.

Aven, T. (1986), "On the computation of certain measures of importance of system components", *Microelectron Reliab*, Vol. 26 No. 2, pp. 279-81.

Barabady, J. (2005), "Improvement of system availability using reliability and maintainability analysis", Licentiate thesis, Luleå University of Technology, Luleå, available at: http://epubl.ltu.se/1402-1757/2005/92/LTU-LIC-0592-SE.pdf.

Beeson, S. and Andrews, J.D. (2003), "Importance measures for non-coherent-system analysis", *IEEE Transactions on Reliability*, Vol. 52 No. 3, pp. 301-10.

Birnbaum, Z.W. (1969), "On the importance of different component in a multi-component system", in Krishaniah, P.R. (Ed.), *Multivariate Analysis*, Vol. 11, Academic Press, New York, NY.

Boland, P.J. and El-Neweihi, E. (1995), "Measures of component importance in reliability theory", *Computers & Operations Research*, Vol. 22 No. 4, pp. 455-63.

Cassady, R.C., Pohl, E.A. and Song, J. (2004), "Managing availability improvement efforts with importance measures and optimization", *IMA Journal of Management Mathematics*, Vol. 15 No. 2, pp. 161-74.

Castro, H.F. and Cavalca, K.L. (2002), "Reliability optimization of redundant system", *SAE Technical Papers*, Vol. 1 No. 1, pp. 1-9.

Castro, H.F. and Cavalca, K.L. (2003), "Availability optimization with genetic algorithm", *International Journal of Quality and Reliability Management*, Vol. 20 No. 7, pp. 847-63.

Chiang, C-H. and Chen, L-H. (2006), "Availability allocation and multi-objective optimization for parallel-series systems", *Reliability Engineering and System Safety*, available at: www.scincedirect.com (in press).

Ebeling, C.E. (1997), *An Introduction to Reliability and Maintainability Engineering*, McGraw-Hill, New York, NY.

Elegbede, C. and Adjallah, K. (2003), "Availability allocation to repairable systems with genetic algorithms: a multi-objective formulation", *Reliability Engineering and System Safety*, Vol. 82 No. 3, pp. 319-30.

Frickes, M.F. and Trivedi, K.S. (2003), "Importance analysis with Markov chains", *Proceedings of the 49th Annual Reliability and Maintainability Symposium, Tampa, FL, 27-30 January*, pp. 89-95.

Holland, J.H. (1975), *Adaptation in Natural and Artificial System: An Introduction with Application to Biology, Control and Artificial Intelligence*, University of Michigan Press, Ann Arbor, MI.

Leemis, L.M. (1995), *Reliability: Probabilistic Models and Statistical Methods*, Prentice Hall, Englewood Cliffs, NJ.

Murty, A.S.R. and Naikan, V.N.A. (1995), "Availability and maintenance cost optimization of a production plant", *International Journal of Quality & Reliability Management*, Vol. 12 No. 2, pp. 28-35.

Owens, J., Miller, S. and Deans, D. (2006), "Availability optimization using spares modeling and the six sigma process", *Annual Reliability and Maintainability Symposium*, pp. 636-40.

Painton, L. and Campbell, J. (1995), "Genetic algorithms in optimization of system reliability", *IEEE Transaction on Reliability*, Vol. 44 No. 2, pp. 172-8.

Pham, H. (2003), "Steady-state series-system availability", *IEEE Transactions on Reliability*, Vol. 52 No. 2, pp. 146-7.

Samrout, M., Yalaoui, F., Chatelet, E. and Chebbo, N. (2005), "New methods to minimize the preventive maintenance cost of series-parallel systems using ant colony optimization", *Reliability Engineering and System Safety*, Vol. 89 No. 3, pp. 346-54.

Wang, W., Loman, J. and Vassiliou, P. (2004), "Reliability importance of components in a complex system", *Proceedings of the Annual Reliability and Maintainability Symposium, International Symposium on Product Quality and Integrity*, pp. 6-11.

Zio, E. and Podofillini, L. (2003), "Importance measures of multi-state components in multi-state systems", *International Journal of Reliability, Quality and Safety Engineering*, Vol. 10 No. 3, pp. 289-310.

Further reading

International Atomic Energy Agency (IAEA) (2001), *Reliability Assurance Programme Guidebook for Advanced Light Water Reactors*, IAEA, Vienna.

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