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Innovative Applications of O.R.

Connectivity modeling and optimization of linear consecutively connected systems with repairable connecting elements

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ABSTRACT

Linear consecutively connected systems (LCCSs) are systems containing a linear sequence of ordered nodes. Connection elements (CE) characterized by diverse connection ranges, time-to-failure and time-to-repair distributions are allocated to different nodes to provide the system connectivity, i.e., a connection between the source and sink nodes of the LCCS. Examples of LCCSs abound in practical applications such as flow transmission systems and radio communication systems. Considerable research efforts have been expended in modeling and optimizing LCCSs. However, most of the existing works have assumed that CEs either are non-repairable or undergo a restrictive minimal repair policy with constant repair time. This paper makes new technical contributions by modeling and optimizing LCCSs with CEs under corrective maintenance with random repair time and different repair policies (minimal, perfect, and imperfect). The characteristics of CEs can depend on their location because the distance between adjacent nodes and conditions of CE operation and maintenance at different nodes can be different, which further complicates the problem. We first propose a discrete numerical algorithm to evaluate the instantaneous availability of each CE. A universal generating function based method is then implemented for assessing instantaneous and expected system connectivity for a specific CE allocation. As the CE allocation can have significant impacts on the system connectivity, we further define and solve the optimal CE allocation problem, whose objective is to find the CE allocation among LCCS nodes maximizing the expected system connectivity over a given mission time. Effects of different parameters including repair efficiency, mission time and repair time are investigated. As illustrated through examples, optimization results can facilitate optimal decisions on robust design and effective operation and maintenance managements of LCCSs.

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1. Introduction

In many industrial systems (e.g., flow transmission, radio communication, sensor monitoring, satellite communication), a set of nodes is deployed in a linearly ordered manner with connection elements (CEs) being allocated to some of the nodes to accomplish a specific function or mission task. These systems are referred to as linear consecutively connected systems (LCCSs) (Levitin, 2005; Zuo & Liang, 1994). The purpose of the CE in LCCSs is to provide connectivity between its hosting node and a certain number of subsequent nodes along the sequence specified by its connection range. The overall functionality of an LCCS is to provide a connection between its source (the first) node and destination (the last) node.

The model of LCCSs was first introduced in (Hwang & Yao, 1989) as a generalized model of consecutive-k-out-of-n: F systems (Chang & Hwang, 2003; Eryılmaz, 2013; Eryilmaz & Tutuncu, 2009). Due to its abundant applications in various industries, considerable research efforts have been dedicated to the reliability analysis of LCCS for both binary-state and multi-state cases (Hwang & Yao, 1989; Levitin, 2001; Levitin, Xing, & Dai, 2015; Zuo & Liang, 1994). In the case of heterogeneous CEs with non-identical characteristics (e.g., time-to-failure distribution, repair time distribution, connection range), different CE allocations can lead to different LCCS performance (Levitin, 2003a; Malinowski & Preuss, 1996). Thus the optimization problem of CE allocation arises. Many studies actually showed that the performance of an LCCS can be significantly improved through the optimal CE allocation to the system nodes (Levitin, 2003b; Peng, Xie, Ng, & Levitin, 2012). Recently, the optimal CE allocation problem has been solved for LCCSs subject to phased-mission requirements, which involve distinct connection

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tasks between different source and destination nodes performed in multiple mission phases (Levitin, Xing, & Dai, 2013). During these phases, the system elements may be subject to diverse environment conditions and stress levels, causing dynamics in their failure behaviors (Feyzioğlu, Altınel, & Özekici, 2008). In (Levitin, Xing, & Yu, 2014), effects of common-cause failures were further incorporated into the modeling and optimization of phased-mission LCCSs, where multiple CEs can fail due to a shared root cause (Hajeeh, 2011). Additional recent developments in LCCSs have been made to extend the model by allowing different types of gaps (disconnected nodes) in the system functionality. For example, the LCCS in (Levitin, Xing, & Dai, 2015b; Yu, Yang, & Zhao, 2015) can tolerate a limited number of single-node gaps; the LCCS in (Xiang, Levitin, & Dai, 2012) can tolerate a certain size of gap window (i.e., consecutive gaps); the LCCS in (Levitin, Xing, Ben-Haim, & Dai, 2015a; Yu, Yang, Peng, & Zhao, 2016) allows combined constraints of total number of single-node gaps and size of consecutive gaps.

To the best of our knowledge, the existing works on LCCSs have mostly assumed non-repairable CEs for the system modeling and optimization with exception that CEs undergoing the minimal repair policy with constant repair time were addressed in (Peng et al., 2012). In practice, the repair time can be random due to factors such as availability and distance of manpower and repair facilities, variations of ambient conditions and readiness level of standby equipment. Moreover, the minimal repair policy where a failed CE is restored to an “as bad as old” condition is restrictive. A more general repair model covering different degrees of repair efficiency is desirable. Particularly, there exist three different degrees respectively corresponding to the minimal repair, perfect repair, and imperfect repair policies (Kijima, 1989; Lindqvist, 2006; Yañez, Joglar, & Modarres, 2002). Under the minimal repair policy adopted in (Peng et al., 2012), the effective age of a repaired element is the same as that right before the repair action. Under the perfect repair policy, the effective age of a repaired element is simply reduced to 0. In other words, the failed element after the repair can be restored to an “as good as new” condition. Under the imperfect repair policy, the effective age of a repaired element is reduced by a certain amount depending on the type or efficiency of the repair. At this case, the failed element is restored to some condition between the minimal and perfect repair policies.

In this paper, we make new contributions by considering LCCSs with heterogeneous repairable CEs having random repair time and the general repair policy covering the minimal, perfect, and imperfect repairs. Following definitions of the generic LCCS model, system performance indices and problems addressed (Section 2), a discrete numerical algorithm is first proposed to estimate the instantaneous availability of each repairable CE (Section 3). A universal generating function (UGF) based method is then suggested for evaluating the defined system performance indices (instantaneous and expected system connectivity) for a particular CE allocation (Section 4). The optimal CE allocation problem is further solved, which aims to find the CE allocation maximizing the expected LCCS connectivity over a given mission time (Section 5). Applications of the proposed methodology to effective operation and maintenance managements of LCCSs are also demonstrated through examples (Section 6).

Acronyms

cdf	cumulative distribution function
CE	connecting element
CEAP	CE allocation problem
GA	genetic algorithm
ILC	instantaneous LCCS connectivity
LCCS	linear consecutively connected system
pdf	probability density function
pmf	probability mass function
UGF	universal generating function (u-function)

Nomenclature

I	number of nodes that can contain CEs in the considered LCCS system
K	total number of CEs
τ	time horizon or mission time
$L_n(t)$	index of the most remote node that can be reached by operating CEs located at nodes 1,…,n at time t
s	CE allocation function that maps index of node i to index $s(i)$ of CE located at this node
$a(t,s)$	instantaneous LCCS connectivity
$A(\tau,s)$	expected LCCS connectivity over system mission time τ
$s(i)$	index of CE located at node i
$\zeta_{s(i)}(t)$	hazard rate of CE $s(i)$
$\pi_{s(i)}$	repair efficiency coefficient of CE $s(i)$ ranging from 0 to 1
$G_i(t)$	random connection range of CE located at node i
$J_{i,k}$	maximal number of failures of CE k located at node i during the time horizon
$p_{i,k}(t)$	instantaneous availability of CE k located at node i
$\langle T_j, X_j\rangle$	event when the jth failure of a CE occurs at time T_j and the CE spends time X_j in an operation mode before the failure
$Q_j(t,x)$	function representing joint distribution of random variables T_j and X_j for a CE
$f_{i,k}(t)$, $F_{i,k}(t)$	*pdf*, *cdf* of lifetime for CE k located at node i
$\psi_{i,k}(t)$,$\Psi_{i,k}(t)$	pdf, cdf of repair time for CE k located at node i
$g_{i,k}$	connection range of operating CE k located at node i
$\eta_{i,k}$, $\beta_{i,k}$	scale, shape parameters of Weibull time-to-failure distribution for CE k located at node i
$D_{i,k}$	random repair time for CE k located at node i
$d_{i,k}^{\min}$,$d_{i,k}^{\max}$	minimal, maximal possible realizations of $D_{i,k}$
$\mu_{i,k}$, $\sigma_{i,k}$	mean, standard deviation for truncated normal distribution of $D_{i,k}$

2. LCCS model and problem description

There are $I+1$ consecutive locations (nodes) in the LCCS considered with the first node being the source, the last being the sink node. K connecting elements (CEs) are available and should be allocated in K out of I non-sink nodes (any nodes except the last node) to provide connection between the source and sink nodes. The CEs are characterized by specific connection range, time-to-failure and time-to-repair distributions. As the distance between adjacent nodes and conditions of CE operation and maintenance at different nodes can differ, the characteristics of the CEs depend on their location. For example, the distance of nodes hosting CEs from service centers affects the repair time distributions of the CEs. The repair time for CE k can also depend on availability and efficiency of the repair manpower and equipment. Thus it is assumed that for any CE k located at node i, the repair time is randomly distributed in the interval $[d_{i,k}^{\min}, d_{i,k}^{\max}]$. The *cdf* $\Psi_{i,k}(t)$ of the random repair time is known and such that $\Psi_{i,k}(t)=0$ for $t<d_{i,k}^{\min}$ and $\Psi_{i,k}(t)=1$ for $t>d_{i,k}^{\max}$. Each CE has two states, operation or failure. The connection range of CE k located at node i, when operating, is represented by $g_{i,k}$.

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