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Xujie JIA
Lirong CUI
Liudong XING

NEW INSIGHTS INTO RELIABILITY PROBLEMS FOR SUPPLY CHAINS MANAGEMENT BASED ON CONVENTIONAL RELIABILITY MODEL

NOWE SPOJRZENIE NA PROBLEMY ZWIĄZANE Z NIEZAWODNOŚCIĄ W ZARZĄDZANIU ŁAŃCUCHAMI DOSTAW Z PUNKTU WIDZENIA TRADYCYJNEGO MODELU NIEZAWODNOŚCI

The paper aims to find the relationship between conventional reliability and supply chain reliability, and introduce and adapt conventional reliability models to the field of supply chains, expanding the horizon of solving supply chain reliability problems. Based on a comprehensive literature review, the paper summarizes definitions of reliability in supply chain systems and presents reliability system structures and reliability indexes for supply chains. Relationship and differences between conventional reliability and supply chain reliability are shown. Illustrative examples such as the supply chain reliability problem in China are provided to show how to convert a supply chain reliability problem into a conventional reliability problem and then solve it using reliability techniques in conventional reliability.

Keywords: *supply chain management, conventional reliability, supply chain reliability, reliability system structures, reliability indexes.*

Celem artykułu jest znalezienie związku między niezawodnością w ujęciu tradycyjnym a niezawodnością łańcuchów dostaw, a także wprowadzenie i dostosowanie tradycyjnych modeli niezawodności do badań nad łańcuchami dostaw, co pozwoli na rozszerzenie możliwości rozwiązywania problemów dotyczących niezawodności tych ostatnich. W oparciu o obszerny przegląd literatury, w artykule przedstawiono pokrótce definicje niezawodności w systemach łańcucha dostaw oraz omówiono struktury systemów niezawodnościowych i wskaźniki niezawodności dla łańcuchów dostaw. Pokazano zależności i różnice między niezawodnością w rozumieniu tradycyjnym a niezawodnością łańcucha dostaw. Przedstawiono przykład problemu niezawodności łańcucha dostaw zaczerpnięty z realiów chińskich, ilustrujący jak można przekształcić problem niezawodności łańcucha dostaw w tradycyjny problem niezawodnościowy, a następnie rozwiązać go za pomocą technik niezawodnościowych stosowanych w tradycyjnej analizie niezawodności.

Słowa kluczowe: *zarządzanie łańcuchami dostaw, niezawodność w ujęciu tradycyjnym, niezawodność łańcucha dostaw, struktury systemu niezawodności, wskaźniki niezawodności.*

1. Introduction

Supply chain systems are an integral part of most of modern business. As supply chain systems play a more critical role in business success and society, consequences of any unreliable behavior become increasingly severe in terms of cost, effort and time. Thus, high reliability is an essential attribute for a successful supply chain system in today's competitive environment. Numerous research efforts have been expended in studying supply chair reliability and related optimization problems.

To quantify reliability of supply chain systems, one research stream focuses on models that describe elements and activities of supply chain systems. For example, Bundschuh et al. built an integrated inbound supply chain model with many potential suppliers for products [7]. Wang et al. developed statistical spatial modeling techniques to approximate store location and capacity constraints [43]. Hsu & Li presented a supply chain network model to study the reliability evaluation [11]. Zhou et al. proposed hazard rate models for early detection of reliability problems [48]. Mettler et al. developed an intelligent supply chain design for non-hierarchical manufacturing networks [28]. Brumnik et al. presented a Markov chain model for estimating biometric system reliability in supply chain management [5]. Chen et al. built a common cause failure model between suppliers and manufacturers [8]. Li et al. presented a supply disruption risk model to study impacts of decision sequence on reliability enhancement with supply disruption risks [18]. There are also other models such as the simulation model [39], economic model [9], stochastic model [40], link-capacity model [41], deterministic model [42], multi-stage supply chain model [3], supply chain operations reference (SCOR) model [13], network equilibrium model [44], and etc.

Reliability metrics are important in the study of supply chain reliability. Reliability metrics may be expressed as, for example, failure free operating time, failure rate, or mean time between specified events such as failure, replacement or overhaul [30]. Considerable research efforts have been devoted to evaluating system reliability using different reliability metrics [10, 12, 21, 45]. Thomas proposed a reliability interference theory method for quantifying reliability of contingency logistics systems [37]. Nieuwenhuyse & Vandaele estimated the delivery reliability for the lot splitting policy using an approximation method [26]. Liu et al. proposed an adjacency matrix of the meta-graph method to analyze structural reliability and integrated-capacity reliability [22]. Graph-theory based methods such as GO-methodology and petri nets were proposed for studying the supply chain reliability [19, 32]. Bottani & Rizzi studied selection problems of suppliers and products based on an adapted multi-criteria approach

[4]. Lam & Ip adopted a spanning tree approach to get the reliability of a supply chain collaborative network [16]. Jia & Cui introduced the Copula method and studied the reliability of dependent supply chain systems [14]. Zhao et al. analyzed reliability of apparel supply chains based on the state space method [47]. Ohmori & Yoshimoto showed the management of supply chain disruption risks by the network reliability method [27]. Lukinskiy et al. proposed a formal conceptual apparatus for the supply chain reliability evaluation [23]. Other methods on supply chain reliability include, for example, the self-assessment method [6], uncertainty evaluation method [25], and Fuzzy theory based method [17].

Considerable research efforts have also been expended in the problem of reliability optimal design for supply chain management. To get superior results, analytical hierarchy analysis (AHA) and conjoint analysis are often used. AHA takes pair-wise comparisons while conjoint analysis uses rating or ranking methods [34]. There are also some research results based on other methods. For example, Quigley & Walls used Shapley's value to support trading of reliability metrics across a supply chain by minimizing the cost of the combined suppliers' reliability programmers [30]. Snyder & Daskin used mixed integer programming methods to minimize the increase in transportation costs under various failure scenarios [35]. Sohn & Choi developed a fuzzy quality function deployment model to design specification and improve the supply chain management reliability [36]. Other research works in reliability optimal design for supply chain management can be found in Balan et al. [2], Liao & Rittscher [20] , Zaitzev & Bochazev [46], Madadi et al. [24], and Torabi et al. [38].

While many research efforts have been made for analyzing supply chain reliability, it still lacks a universal authority definition. Moreover, as structures of supply chain systems appear to be different from and more complicated than structures of conventional product-based systems, indexes and methods of supply chain reliability should be distinct from those of product-based reliability. This paper investigates the relationship and differences between the supply chain reliability and the conventional reliability, leading to some insights on how to model the supply chain reliability based on models and techniques of the conventional reliability. Based on the investigation, the paper also suggests some topics and directions that may be interesting in the further study.

Remaining parts of this paper are organized as follows. In Section 2, definitions of reliability for supply chain systems are summarized. In Section 3 we present reliability system structures for supply chain and some reliability indexes. Section 4 shows the relationship between conventional system reliability and supply chain reliability. Section 5 focuses on reliability problems in supply chains and discussions on their solution methodology. Illustrative examples are also provided to demonstrate the application of the proposed methodology. Section 6 are the applications, and some concluding remarks and extensions for further research are provided in Section 7.

2. Reliability definitions for supply chain systems

In general, reliability is defined as the probability that an item will perform a required function under stated environment and operational conditions for a stated period of time [1, 31]. Reliability in supply chains is developed from the conventional reliability concept. However, currently the supply chain reliability still lacks a universal authority definition. Below list some existing definitions for the supply chain reliability (SCR).

(1) The probability of the chain meeting mission requirements to provide the required supplies to the critical transfer points within the system [37].
(2) The ability to meet the logistic performance expectations of customers [33].
(3) The quality & reliability of products required by the customers [36].
(4) Delivery reliability [15, 29]: measures the supplier's ability to predictably complete processes as promised. It is measured by perfect order fulfillment and demonstrates the degree to which a supplier is able to serve its customers within the promised delivery time.
(5) Suppliers' ability to be completed in supply chain systems [49].

Some researchers also give definitions of service reliability [43] for supply chains. For a service reliability at location x it is defined as:

$$v(x) \equiv P\{\text{transportation time} < \text{specified time}\} .$$

While the supply-chain system reliability has been developed from the product-based system reliability, there exist both difference and similarity between them as demonstrated by the above definitions.

The adoption of the supply chain reliability definition is decided by the system model and needs of the system manager. It can be one of the definitions mentioned above when applicable, or some extension of one definition above based on the special feature of the considered system.

3. Reliability system structures for supply chains

There are some typical structures in conventional reliability, such as series system, parallel system, k -out-of- n .The supply chain systems can also be described by these structure models. As discussed below, the reliability factors of supply chain systems, in general, are more complicated than those of product-based reliability systems.

There are two major kinds of reliability models for supply chains: chain structure (Fig. 1) and network structure (Fig. 2).

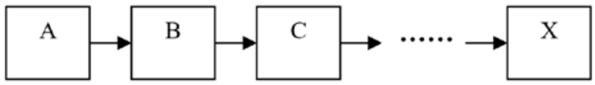

Fig. 1. Chain structure

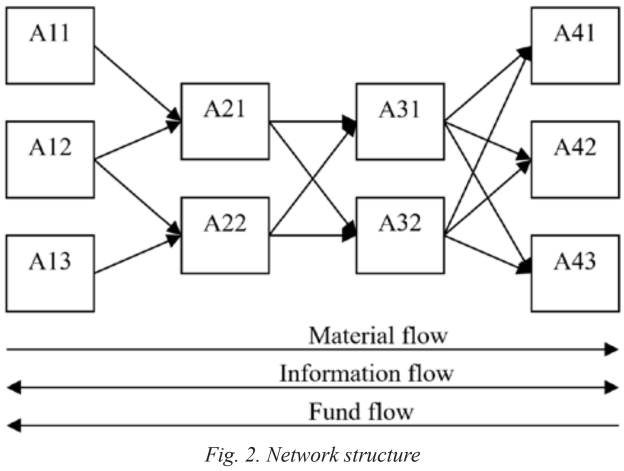

Fig. 2. Network structure

Regardless of the structure, a supply chain system is composed of nodes and links. Each node can be one of enterprises, suppliers or customers in the supply chain. Each link represents the relationship between enterprises, suppliers and customers. There are material flows, fund flows, information flows etc. in a supply chain. In general, a supply chain system is complicated in structure, linkage, flow, etc., which leads to the complexity of supply chain reliability problems.

The reliability of each node depends on factors on which customers focus. For example, the following definitions are related to different types of flows.

Material-flow-based consideration of nodes [37]:

(1) $P\{\text{supply} > \text{demand}\}$

(2) $P\{\text{conformity supply} > \text{demand}\}$

(3) $P\{\text{conformity supply} > \text{demand} | \text{within a specified time interval}\}$

Fund-flow-based consideration of nodes:

(1) $P\{\text{money arrives before goods sent out}\}$

(2) $P\{\text{paid unit cost} \geq \text{market unit price}\}$

The node reliability can also be defined in terms of order form, quality of goods, delivery in time, storage etc.

The reliability of each link is related to factors, such as natural factors (road, weather, transportation reliability, transportation cost, etc.), business relationship, and political situation, etc.

4. Relationship between conventional reliability and supply chain reliability

The differences between conventional reliability and supply chain reliability are listed as follows:

(1) The reliability definitions are different at both the system and component levels.

(2) Systems are different from network point of view; the focus of supply chain reliability may be flows of material, fund and information or combination of them. In most situations, the links/nodes have some capacity constraints, which is different from conventional reliability.

(3) The independence is lost in supply chain reliability in general, which makes the reliability problems complex.

The similarities between conventional reliability and supply chain reliability are as follows:

(1) Most reliability techniques in conventional reliability can be used in supply chain reliability, from the point of view of product life cycle.

(2) Most reliability indexes, such as reliability, availability, dependability, mean time to the first failure, etc., are applicable to supply chain systems.

5. Representative reliability problems in supply chains and illustrative examples

The SCR problems discussed in literature include: delivery reliability, structure reliability, performance reliability, reliability optimal design, importance of nodes in supply chain. Following are some examples to illustrate the SCR problems, and how to solve the supply chain reliability problems using reliability techniques in conventional reliability.

5.1. Series supply chain system

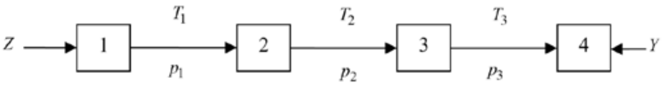

Fig. 3. Series supply chain system

System description:

(1) As Fig. 3 shows, the original supply amount is Z, and the final customer 4 needs the amount of goods Y (Fig. 3).

(2) Suppliers 1, 2 and 3 take time durations T_i $(i = 1,2,3)$ to transport the amount Z of some kind of goods successively. At the corresponding transportation stages there are successful rates p_i or loss rates (proportion) $1 - p_i$, $0 \leq p_i \leq 1$, $(i = 1,2,3)$.

(3) All quantities Z, Y, T_1, T_1, T_3 are non-negative random variables. T_1, T_1, T_3 are dependent with each other and all p_i are independent with each other.

The supply chain system success criterion is: the conformity goods amount required by the final customer can be met within the specified time t.

Solution:

Based on the success criterion, the supply chain system reliability can be formulated as:

$$R(t) = P\{T_1 + T_2 + T_3 \leq t \ \& \ p_1 p_2 p_3 Z \geq Y\}.$$

According to assumption (3):

$$R(t) = P\{T_1 + T_2 + T_3 \leq t\} P\{p_1 p_2 p_3 Z \geq Y\},$$

the dependence among T_1, T_1, T_3 can be modeled using the copula method from the conventional reliability. A N-dimensional copula is a distribution function on $[0,1]^N$ with standard uniform marginal distributions. Reserve the notation $C(U) = C(u_1, \ldots, u_N)$ for the multivariate distribution functions which are copulas. Hence C is a mapping of the form $C : [0,1]^N \to [0,1]$ i.e. a mapping of the unit hypercube into the unit interval [50]. Specifically, $C(F_1(t), F_2(t), F_3(t)) = F(T_1, T_1, T_3)$ is the Copula of T_1, T_1, T_3, and the density Copula function is $c(F_1(t), F_2(t), F_3(t)) = \dfrac{\partial^n C(u_1, u_2, u_3)}{\partial u_1 \partial u_2 \partial u_3}$.

Thus the reliability of the example supply chair system is evaluated as:

$$\begin{aligned} R(t) &= P\{T_1 + T_2 + T_3 \leq t\} P\{p_1 p_2 p_3 Z \geq Y\} \\ &= C(F_1(t), F_2(t), F_3(t)) \int_0^\infty [1 - F_Z(\frac{y}{p_1 p_2 p_3})] dG_Y(y). \end{aligned} \quad (1)$$

The mean time to the first failure of this example supply chain system is:

$$\begin{aligned} MTTF &= \int_0^\infty R(t) dt \\ &= \int_0^\infty \left\{ C(F_1(t), F_2(t), F_3(t)) \int_0^\infty [1 - F_Z(\frac{y}{p_1 p_2 p_3})] dG_Y(y) \right\} dt. \end{aligned} \quad (2)$$

If we assume that the successful rates at corresponding stages are related to the corresponding transportation durations, then the situation becomes more difficult.

For example:

$$p_i(t) = \begin{cases} c_i, & t \leq t_i;\ 0 < c_i < 1, \\ 1, & \text{otherwise.} \end{cases}, \text{ or } p_i(t) = \begin{cases} a_i t, & t \leq t_i; \\ 1, & \text{otherwise.} \end{cases}, \ i = 1,2,3.$$

In this case, we have:

$$\begin{aligned} R(t) &= P\{T_1 + T_2 + T_3 \leq t \ \& \ p_1 p_2 p_3 Z \geq Y\} \\ &= \iiint_{u_1 + u_2 + u_3 \leq t} \{[\int_0^\infty (1 - F_Z(\frac{y}{p_1(u_1) p_2(u_2) p_3(u_3)})) dG_Y(y)] c(F_1(t), F_2(t), F_3(t)\} du_1 u_2 u_3. \end{aligned}$$

(3)

It is clear that when the transportation successful rates depend on the transportation durations, there is an optimal problem in which the suppliers should choose the optimal transportation durations to make the supply chain reliability maximal.

6. Applications

China has established a developed logistics network system. It is important to study the reliability of the system because any reliability related problems could result in certain serious consequence, such as significant damage to property or inconvenience for people's life. Consider a supple chain system illustrated in Fig. 4. The suppliers are in Guangzhou, Shenzhen and Shanghai and they supply the goods to Beijing. Once a supplier cannot supply enough material to the factory, the supplier is in the failed state. The supply chain system is in the working state if and only if at least 2 suppliers are in the working state.

Fig. 4. A supply chain system in mainlan China

The problem can be converted to a conventional reliability problem, particularly, a 2-out-of-3: G reliability system. The state of the system is the number of the failed suppliers. For a k -out-of- n : G system, if the n suppliers are independent and identically distributed, then the reliability of the supply chain is:

$$R_{k/n}^{I}(t)=\sum_{j=k}^{n} C_n^j P\{X_{j+1},\dots,X_n \le t \le X_1,\dots,X_j\}$$
$$=\sum_{j=k}^{n} C_n^j R^j(t)(1-R(t))^{n-j}.$$

Let X_1, X_2, X_3 denote the lifetime of the 3 suppliers in Guangzhou, Shenzhen and Shanghai, respectively. All the suppliers are in good states in the beginning. Suppose the functions of X_1, X_2 and X_3 are $F_1=1-e^{-t}$, $F_2=1-e^{-2t}$ and $F_2=1-e^{-3t}$, respectively. Then the reliability of the example system is:

$$R_{2/3}^{I}(t)=e^{-3t}+e^{-4t}+e^{-5t}-2e^{-6t}. \tag{4}$$

If the suppliers are dependent with each other, then we apply the copula method from the conventional reliability to model the dependence among the suppliers.

First we calculate the reliability of a dependent k -out-of- n : G system. There are j suppliers randomly chosen from $X_1, X_2, \dots, X_n$ in the m -th and let $X_m^1,\dots,X_m^j$ denote the lifetime of them, where $m=1,2,\dots,C_n^j$. The distributions of $X_m^1,\dots,X_m^j$ are $F_m^1(t),\dots,F_m^j(t)$ respectively. Their copula of $X_m^1,\dots,X_m^j$ is $C_m^j(F_m^1,\dots,F_m^j)$. The remain parts' lifetime of the n suppliers are denoted by $Y_m^1,\dots,Y_m^{n-j}$ and their copula is $C_m^{*n-j}(F^{*1}{}_m(t),\dots,F_m^{*n-j}(t))$, shorted as $C_m^{*n-j}(t)$.

For $X_n^{(\min)}=\min(X_1,X_2,\dots,X_n)$, the reliability of $X_n^{(\min)}$ is:

$$R_{\min}(\min(X_1,X_2,\dots,X_n))$$
$$=P(\min(X_1,X_2,\dots,X_n)>t)=P(X_1>t,\cdots,X_n>t)=\sum \operatorname{sgn}(F)\ C_n(F),$$

where $\operatorname{sgn}(F)$ is 1 if n is even, and -1 if n is odd.

For $X_n^{(\max)}=\max(X_1,X_2,\dots,X_n)$, the reliability is:

$$R_{\max}(X_1,X_2,\dots,X_n)$$
$$=P(\max(X_1,X_2,\dots,X_n)>t)=1-P(\max(X_1,X_2,\dots,X_n)<t)$$
$$=1-P(X_1<t,\dots,X_n<t)=1-C(X_1,X_2,\dots,X_n)=1-C_n$$

For a k -out-of- n : G system, if the m -th j parts in the n components are in working state, and the others are failed, then the reliability is:

$$R_m^j(t) = P\{\max(Y_m^1,\dots,Y_m^{n-j}) \le t,\ \min(X_m^1,\dots,X_m^j) > t\}$$
$$= P\{\max(Y_m^1,\dots,Y_m^{n-j}) \le t\} - P\{\max(Y_m^1,\dots,Y_m^{n-j}) \le t,\ \min(X_m^1,\dots,X_m^j) \le t\}$$
$$= C_m^{*n-j}(t) - C(\max,\min)(C_m^{*n-j}(t),\ {}_m^jR_S^C(t)).$$

So the reliability of a k -out-of- n : G system is:

$$R_{k/n}=\sum_{j=k}^{n}\sum_{m=1}^{C_n^j}\{R_m^j(t)\}. \tag{5}$$

Then for the 2-out-of-3: G supply chain system, take three-dimensional Clayton copula $C_1^{Cl}(u_1,u_2,u_3)=(u_1^{-1}+u_2^{-1}+u_3^{-1}-2)^{-1}$ to model the dependence among the suppliers. Based on Eq. (5), the reliability of the supply chain system is:

$$R_{2/3}^{D}(t)$$
$$=e^{-2t}-\left\{(1-e^{-t})^{-1}+(1-e^{-3t})^{-1}-1\right\}^{-1}+\left\{(1-e^{-t})^{-1}+(1-e^{-2t})^{-1}+(1-e^{-3t})^{-1}-2\right\}^{-1}. \tag{6}$$

Based on Eq. (4) and (6), curves of the reliability for the dependent supply chain system $R_{2/3}^{D}(t)$ and independent supply chain system $R_{2/3}^{I}(t)$ are shown in Fig. 5.

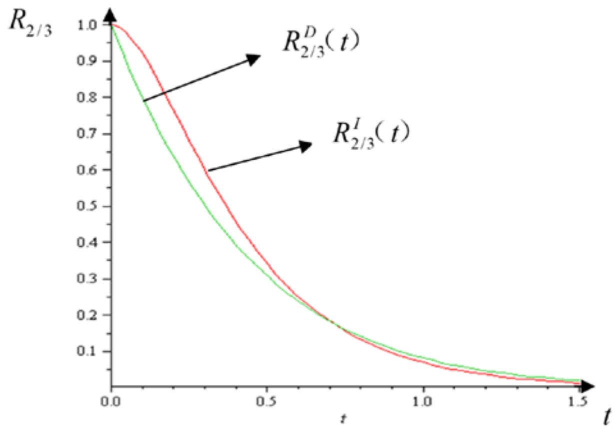

Fig. 5. Comparing curves for $R_{2/3}^{D}(t)$ and $R_{2/3}^{I}(t)$

So for the supply chain shown in Fig. 4, the reliability of the supply chain when the three suppliers are independent is shown as the curve $R_{2/3}^{I}(t)$, and is shown as the curve $R_{2/3}^{D}(t)$ when they are dependent. In the beginning, the reliability when the suppliers are dependent is lower than that when they are independent, while after sometime t , the dependent case is higher.

7. Conclusion and further research

Supply chain management raises some new problems in the reliability discipline, which are generally more difficult than the problems we faced in the conventional product-based reliability problems. As demonstrated through examples, techniques and methods in the conventional reliability can be adapted to solve the supply chain reliability problems. We try to find the relationship between conventional reliability and supply chain reliability, and introduce and adapt conventional reliability models to the field of supply chain. The paper summarizes definitions of reliability in supply chain systems and presents reliability system structures and reliability indexes for supply chains. Relationship and differences between conventional reliability and supply chain reliability are shown. The following topics or directions may be interesting for further study:

(1) The development of new supply chain reliability models, including node models and link models.
(2) A universal framework or guideline for supply chain reliability
(3) Availability and dependability definition and modeling in supply chain systems.
(4) Modeling reliability for various supply chain systems, such as contingency operation supply chain, industry product supply chain, food supply chain, etc.
(5) Expanding the conventional reliability thinking, technique and methods to analyze the supply chain reliability.

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Xujie JIA
School of Science, Minzu University of China, Beijing, China. 100081
Electrical& Computer Engineering Department, University of Massachusetts, Dartmouth, MA 02747, USA

Lirong CUI
School of Management & Economics, Beijing Institute of Technology, Beijing, China, 100081

Liudong XING
School of Mechanical and Electrical Engineering, University of Electronic Science and Technology of China, Chengdu, China, 611731
Electrical & Computer Engineering Department, University of Massachusetts, Dartmouth, MA 02747, USA

E-mails: jiaxujie@126.com, lirongcui@bit.edu.cn, lxing@umassd.edu