The System Failure Analysis Based on Fuzzy Fault Tree for Automobile Logistics Service Supply Chain

Bengang Gong, Xiang Chen, Yunmiao Gui

Abstract

Reducing the system failure rate of logistics service supply chain (LSSC) is the basic guarantee and supporting conditions of LSSC system operational stability. The paper, regarding the automobile logistics service supply chain system composed by logistics service integrators, logistics service providers and car manufacturer as the research object, sets up the fault tree model of the automobile logistics service supply chain system failure, and describes, by the triangular fuzzy number, the probability of basic event failure. Then based on the examples, the paper calculates the confidence interval of automobile logistics service supply chain failure, logistics integrators failure and logistics functions provider failure, and concludes the fuzzy importance sequence of basic event for the logistics service supply chain system failure. Finally, the paper analyzes the reasons for the logistics service supply chain system failure and proposes improvement measures.

Keywords: Automobile Logistics Services Supply Chain; System Failure; Fuzzy Fault Tree Analysis; Fuzzy Importance

1. Introduction

With more and more logistics outsourcing in recent years, various emergencies occur frequently, causing people to show more concern for the supply chain reliability. Yet the key to guaranteeing the reliability of the logistics service supply chain (LSSC) is to reduce the failure rate of the logistics service supply chain system [1-3]. However, few scholars both at home and abroad deal with the failure analysis of LSSC, and few related researches are also involved in the system failure analysis for manufacturing supply chain (MSC) and reliability analysis for LSSC [4, 5]. For instance, Muckstadt et al. proposed to reduce the supply chain system failure method by improving cooperation among the members of supply chain [6]. Kishalay et al. found a solution to the supply chain execution failures under uncertain circumstances by using fuzzy mathematical programming method [7]. Nieuwenhuyse et al. examined the influence factors of logistics service provider’s delivery reliability of two stage service supply chain [8]. Thirumalai et al. studied the effect that the retail supply chain order fulfillment has exerted on the customer’s satisfaction [9].

The above related literature involves little research into the system failure of the automotive LSSC. As we know, automobile LSSC differs from automobile MSC, and the fundamental difference between them is that the former is not an entity facility in the supply chain, but an output of intangible logistics service based on entity facilities. This distinction has fundamentally changed the object and totality of the supply chain. At the same time, the demand uncertainty and the diversity of logistics service make the automobile LSSC stability comparatively weaker, and more easily dissolved and reorganized than the automobile MSC. So the analysis methods of MSC system failure can not meet the needs of system failure analysis for automobile LSSC.

The fault tree analysis is one of the effective methods for system reliability, system failure analysis and prediction [10]. The traditional fault tree analysis, based on the “probability hypotheses and two state hypothesis”, uses precise numerical values to describe the probability of basic events, so it is difficult to deal effectively with uncertainty and fuzziness in the LSSC reliability analysis [11]. Instead, Fuzzy fault tree analysis (FFTA) introduces fuzzy set theory to the fault tree analysis, for those nodes that can’t get the precise values of the probability of the fault occurrence, through the fuzzy theory, think that the probability of bottom event (basic event) is a fuzzy number, and then through the fuzzy operational rule, estimate the fuzzy failure rate of the whole system [12, 13]. For this, the paper will
introduce FFTA to LSSC system failure analysis. Using triangular fuzzy function to describe the probability of the basic event system failure, it will determine the confidence intervals for top event system failure and the basic event fuzzy ranking of logistics service supply chain system failure, based on which, the reasons for the logistics service supply chain system failure will be analyzed and optimization measures proposed too. And related research findings can also provide reference for improving LSSC system structure and determining effectively the system fault diagnosis scheme.

2. Constructing the fault tree of automobile LSSC system failure

2.1 The basic structure of automobile LSSC

Because logistics service type, logistics service quantity and logistics services integrator ability of the demand are different, LSSC patterns vary somewhat, but their essence is consistent. For automobile LSSC, there exist three main enterprises, namely, the logistics demand (automobile MSC enterprise), the functional logistics service provider and the logistics service integrator, and its basic structure is shown in Fig.1 [14-16]. In the operation process of automobile LSSC, the logistics integrator, according to the logistics service demand, firstly arranges logistics service order reasonably, assigning its own enterprises to complete core logistics service, and meanwhile leaving the logistics services beyond its business operation ability to logistics service provider to handle. By the way, logistics integrators and logistics providers are cooperation partners. Besides, automobile MSC node enterprise composed of parts suppliers, hosting distributors / repairs and customers turns into the automotive LSSC logistics demand. And third party logistics company (3PL), the transport fleet, warehousing companies, packaging companies, freight forwarding companies, port terminals, railway companies, airlines and so on constitute functional logistics service providers. These logistics service providers work together, providing efficient, high quality, low-cost logistics services to the automotive MSC [15-17].

![Figure 1. The basic structure of automobile LSSC](image-url)
2.2 Constructing the fault tree of Automobile LSSC system failure

LSSC is a complex, random, fuzzy and unsteady system, and LSSC system fault information is various. Moreover, the probability of fault occurrence is to some extent ambiguous and stochastic. Therefore, with fuzzy fault tree theory to process scientifically and quantitatively fuzzy information about the probability of LSSC failure, the LSSC system failure probability can be calculated. Without loss of generality, let us assume that an Automobile LSSC is composed of 1 logistics service integrator, 1 automobile manufacturing enterprises (logistics service demand side) and 2 functional logistics service providers (transport services, distribution services). We then regard the automobile LSSC system failure as the top event, and analyze the main factors of the automobile LSSC system failure. According to automotive LSSC operating environment, external and internal environment failures are the two main factors of car LSSC system failure, and the automobile LSSC external environmental failure is the system failure caused by the LSSC external environment factors such as natural, economic, social, political, or whatever. Because the probability that the external environment may change is relatively small, and the external environment is difficult to control for the automobile LSSC node enterprise, we here leave alone automobile LSSC external environmental failure factors, and focus on the effect that automobile LSSC internal environment failure has brought on the automotive LSSC system failure.

Automobile LSSC internal environmental failure is the system failure due to unreasonable cooperation among internal member enterprises. Automobile LSSC internal environmental failure is caused by failure of logistics integrator \( T_1 \), failure of functional logistics service provider \( T_2 \) and sluggish information diffusion \( X_1 \), and the relationship among them is the “logic or” (see Fig. 2). The logistics integrator failure is mainly caused by monitoring failures \( T_{11} \) and poor management \( T_{12} \), either of which will lead to the failure of \( T_1 \), and the relationship among them is the “logical or”. The failure of \( T_{12} \) is mainly caused by improperly-handled orders \( T_{12} \) and decision-making mistakes \( T_{12} \), the relationship among them being the “logical or”. Subcontractor failure is mainly caused by transport failure \( T_2 \) and distribution center failure \( T_{22} \), the relationship among them being the “logical or”. Sluggish information diffusion is mainly due to inadequate information flow or out-of-control information monitoring among automobile LSSC node enterprises, which here is directly used as the bottom event of fault tree. Let us analyze the above-mentioned intermediate events layer upon layer with different logical symbols till the basic event. So all the events connected with the logic gate constitute automobile LSSC system failure fault tree, in which the “logical or” means that “As long as only one of lower input events occurs, then the upper output event will necessarily occur”, and “logical and” is “If all the lower input events occur, then the upper output event will occur (see Fig. 2).

3. Basic theory of FFTA method

3.1 Description of fuzzy number

The traditional fault tree analysis is based on probability theory, by which, basic event probability requires a large number of first-hand data as well as precise numerical value to represent. Here the triangular fuzzy function is used to characterize the probability of each basic event and top event of the LSSC system failure. According to the literature [13, 14], when fuzzy number \( A \) is a triangular fuzzy number, the membership function is shown as follows.
Figure 2. The fault tree of Automobile LSSC system failure
where \( m \) is the mean value of \( \overrightarrow{A} \), \( l \) and \( u \) are the left and right parameters of \( \overrightarrow{A} \) (see Fig.3 ). Triangular fuzzy function is a bounded closed fuzzy number. When \( l = u = 0 \), \( \overrightarrow{A} \) is not a fuzzy number, and the distribution of \( l \) and \( u \) is larger, and \( \overrightarrow{A} \) is more ambiguous. Triangular fuzzy function \( \overrightarrow{A} \) can be written as \( \overrightarrow{A}(l, m, u) \), in which sets of \( \lambda \) is shown as follows.

\[
\overrightarrow{A}_\lambda = [(m - l) + l\lambda, (m + u) - u\lambda]
\]  

(2)

**Figure 3.** The membership function of triangular fuzzy number

### 3.2 Analysis of fuzzy importance

Fuzzy importance means the reduced volume of system of fuzzy function state’s fuzzy unreliability when a unit changes from a class of fuzzy fault state to a fuzzy function. For \( n \) basic events, the occurrence probability of basic event \( i \) is fuzzy number, that is \( \overrightarrow{p}_i(l, m, u)(i = 1, 2, \cdots, n) \). This paper uses the median method for fuzzy calculation [18]. As for the triangular fuzzy function shown in Fig.3, suppose \( \overrightarrow{A} = \int_{m-l}^{m} \mu_\lambda(x)dx, \ A = \int_{m-l}^{m+u} \mu_\lambda(x)dx, \ A = A_1 + A_2 \), present a point \( m_\tau \), and make the fuzzy curve divided into two segments of equal area, then call \( m_\tau \) as the median of the triangle fuzzy function. The calculating formula for \( m_\tau \) is shown as follows.

\[
m_\tau = \begin{cases} 
  m + \sqrt{u^2 - ul} & \text{if } u \geq l \\
  m - \sqrt{l^2 - ul} & \text{if } u < l
\end{cases}
\]

(3)

If the fault tree structure function is \( \phi(x_1, x_2, \ldots, x_n) \), and probability of basic event \( x_i \) is triangular fuzzy function \( \overrightarrow{x_i} \), then the top event occurrence probability is still the trigonometric function, written as median \( \overrightarrow{T} = \phi(\overrightarrow{x_1}, \overrightarrow{x_2}, \ldots, \overrightarrow{x_n}) \). Regarding the basic events \( \overrightarrow{T} = \phi(\overrightarrow{x_1}, \overrightarrow{x_2}, \ldots, \overrightarrow{x_{i-1}}, 0, \overrightarrow{x_{i+1}}, \ldots, \overrightarrow{x_n}) \), median is \( m_{\tau_0} \). Then the fuzzy importance degree of the components \( x_i \) is:
If \( T_{ij} \) > \( T_{jk} \), then think that basic events \( i \) is more important than the basic events \( j \), namely, effects of basic events \( i \) on logistics service supply chain system failure are bigger than effects of the basic events \( j \) on logistics service supply chain system failure.

3.3 Basic fuzzy arithmetic operator of FFTA

Because “and / or” structure can be used to represent other logic gate structures, here we only introduce “and gate operator” and “or operator gate”. If there are \( n \) basic events, \( q_i = l_i, m_i, u_i \) \((i = 1,2,\ldots,n)\) is then the probability distribution of the basic event failure probability, which is triangular fuzzy function. Suppose bottom events are independent of each other, then “and gate operator” and “or gate operator” of the fault tree are as follows.

(1) The “and gate” and “or gate” operators of traditional fault tree are as follows:

\[
q_{\text{AND}} = \prod_{i=1}^{n} q_i, \quad q_{\text{OR}} = 1 - \prod_{i=1}^{n} (1 - q_i)
\]

(5)

(2) In Formula (5), \( q_i \) is the exact occurring value of basic events \( i \), so the “and gate operator” and “or gate operators” which have been through the fuzzy means are:

\[
\bar{q}_{\text{AND}} = \langle l_{\text{AND}}, m_{\text{AND}}, u_{\text{AND}} \rangle = \prod_{i=1}^{n} q_i = q_1 \otimes q_2 \otimes q_3 \otimes \cdots \otimes q_n = \prod_{i=1}^{n} [l_i, m_i, u_i],
\]

\[
\bar{q}_{\text{OR}} = \langle l_{\text{OR}}, m_{\text{OR}}, u_{\text{OR}} \rangle = 1 - \prod_{i=1}^{n} (1 - q_i) = 1 - \prod_{i=1}^{n} [1 - l_i, 1 - u_i, 1 - m_i]
\]

(6)

4. Analysis and optimization process of automobile LSSC system failure based on FFTA

Because the operating environment of the automobile LSSC is fairly complex, and involves a large number of entities of interest, and the reasons for failure are in many aspects, there is certainly some randomness and fuzziness for the probability of bottom event. Therefore, considering insufficient statistical data, the paper, by adopting the expert investigation method combined with the theory of fuzzy mathematics, can get triangular fuzzy function method probability distribution of each basic event (see Table 1).

<table>
<thead>
<tr>
<th>basic event</th>
<th>((l, m, u))</th>
<th>basic event</th>
<th>((l, m, u))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(X_1)</td>
<td>((0.00314, 0.04800, 0.00346))</td>
<td>(X_1)</td>
<td>((0.00412, 0.04300, 0.00442))</td>
</tr>
<tr>
<td>(X_2)</td>
<td>((0.00323, 0.03200, 0.00349))</td>
<td>(X_1)</td>
<td>((0.00315, 0.03500, 0.00326))</td>
</tr>
<tr>
<td>(X_3)</td>
<td>((0.00321, 0.03200, 0.00338))</td>
<td>(X_1)</td>
<td>((0.00408, 0.04300, 0.00428))</td>
</tr>
<tr>
<td>(X_4)</td>
<td>((0.00292, 0.02800, 0.00338))</td>
<td>(X_1)</td>
<td>((0.00281, 0.02900, 0.00325))</td>
</tr>
<tr>
<td>(X_5)</td>
<td>((0.00298, 0.02700, 0.00281))</td>
<td>(X_1)</td>
<td>((0.00413, 0.04300, 0.00449))</td>
</tr>
<tr>
<td>(X_6)</td>
<td>((0.00313, 0.03500, 0.00326))</td>
<td>(X_1)</td>
<td>((0.00430, 0.04300, 0.00442))</td>
</tr>
</tbody>
</table>

According to the formula (6) and the structure of fault tree, the following can be calculated: Eight minimum cut sets of the automobile LSSC system fault tree is shown as follows:

\(\{X_1\}, \{X_2, X_3\}, \{X_4\}, \{X_5\}, \{X_6\}, \{X_7\}, \{X_8\}, \{X_9\}, \{X_{10}, X_1\}\). 

The probability possibility distribution of event \( T_1 \): \((0.01319, 0.13532, 0.01359)\).

The probability possibility distribution of event \( T_2 \): \((0.00002, 0.00275, 0.00003)\).
The probability possibility distribution of top event $T : (0.01631, 0.17909, 0.01703)$.

If the probability possibility distribution of top event is $\Phi(x_1, x_2, x_3, ..., x_n) = l, m, u$, the median is credited as $T_m$, then according to the formula (3), (4) we can get a median of the top event $T$ for:

$$Z_T = T_m = m + \sqrt{u^2 - l^2} = 0.18259.$$  

So the median of the basic event $X_i$ is calculated as follows:

$$\bar{P}_i = \Phi(0, x_1, ..., x_n) = (0.01321, 0.15769, 0.01362), \ m_{\bar{P}_i} = m_{10} + \sqrt{u_{10}^2 - l_{10}^2} = 0.17794.$$  

Fuzzy importance of basic event $X_i : s_i = m_{\bar{P}_i} - m_r = 0.00465$.

Similarly, we can get other importance degrees of the basic events, that is:

$$\{X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8, X_9, X_{10}, X_{11}\} = \{0.00465, 0.00722, 0.00722, 0.00859, 0.00389, 0.01389, 0.00918, 0.00918, 0.00130, 0.00130\}.$$  

According to the formula (2) and the probability possibility distribution of top event, we can do $\lambda$ cut set of the probability of top event:

$$\overline{P}_\lambda = [0.16278, 0.17909],$$

$\overline{P}_\lambda$ is an interval number. For $\lambda$ take different values, we can get different confidence intervals for $\overline{P}_\lambda$, as shown in Table 2.

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>Lower limit of $\overline{P}_\lambda$</th>
<th>Upper limit of $\overline{P}_\lambda$</th>
<th>Lower limit of $\overline{P}_\lambda$</th>
<th>Upper limit of $\overline{P}_\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.16278</td>
<td>0.19612</td>
<td>0.01321</td>
<td>0.15769</td>
</tr>
<tr>
<td>0.1</td>
<td>0.1484</td>
<td>0.19442</td>
<td>0.015769</td>
<td>0.1420</td>
</tr>
<tr>
<td>0.2</td>
<td>0.16604</td>
<td>0.19271</td>
<td>0.00859</td>
<td>0.18250</td>
</tr>
<tr>
<td>0.3</td>
<td>0.16767</td>
<td>0.19101</td>
<td>0.00389</td>
<td>0.18079</td>
</tr>
<tr>
<td>0.4</td>
<td>0.16930</td>
<td>0.18931</td>
<td>0.00130</td>
<td>0.17909</td>
</tr>
<tr>
<td>0.5</td>
<td>0.17094</td>
<td>0.18761</td>
<td>0.00130</td>
<td>0.17909</td>
</tr>
</tbody>
</table>

From the above analysis, the following conclusions are obtained.

(1) From Table 2, confidence interval of top event $\overline{P}_\lambda$ can be seen. When $\lambda = 1, \overline{P}_\lambda = 0.17909$, that is, without considering the fuzzy of basic events occurrence probability, probability of LSSC system failure is 17.909%. When $\lambda = 0, \overline{P}_\lambda = [0.16278, 0.19612]$ , it means that considering the fuzzy uncertainty fully, probability of LSSC system failure changes from 16.278% to 19.612%. The results are more consistent with the actual situation. Similarly, we can also calculate the probability of interval integrators failure, which is 12.213%-14.891%, and probability interval of subcontractor failure, which is 2.73%-2.78%.

(2) By the above importance degree of the basic events, we can get the fuzzy importance ranking of each basic event as follows:

$$X_7 > X_6 > X_5 > X_4 > X_3 > X_2 > X_1 > X_5 > X_4 > X_3 > X_2 > X_1 > X_7.$$  

According to fuzzy importance ranking of each basic event in the LSSC system failure tree structure, importance degree of basic event $X_7$ is the biggest, which shows that it has the greatest effect on the system failure. If probability of occurrence of LSSC system failure needs to be reduced, we should first strengthen the supervision and examination of subcontractors. Influence of basic events $X_i$ upon automobile LSSC system failure is just second to the basic events $X_7$, the importance degrees of basic events $X_{10}$ and $X_{11}$ are the smallest in the 11 factors which lead to automobile LSSC failure, suggesting that effect of the two factors on the system failure is the lowest.

(3) Integrating the size of each basic event fuzzy of LSSC system failure with the cut set order, we can summarize an improved scheme to reduce the logistics service supply chain system...
failure probability.) The specific measures are as follows: integrators should first attach great importance to logistics service provider selection and task assignment; second, transport operators must be supervised throughout the whole course, so as to prevent the loss of the whole system caused by insufficient capacity and unreasonable transport mode; finally, logistics integrators also have to improve the defect factor such as orders pile up, monitoring equipment failure, monitoring personnel error, incomplete information, etc.

5. Conclusion

System failure analysis of automobile LSSC is an important research task in LSSC management. Given fault probability of bottom events and intermediate event is difficult to determine precisely, the fuzzy fault tree analysis method is applied to the investigation of the LSSC system failure in this paper. The paper, regarding automobile LSSC structure composed of logistics service integrator, logistics services providers and automobile manufacturers as the research object, combined with the reasons for the failure during automobile LSSC operating process, establishes a fuzzy fault tree model which regards the LSSC system failure orienting towards automobile manufacturer as the top event, and then through the fuzzy fault tree analysis gets confidence interval of the logistics service integrator failure and logistics service provider failure, and finally determines the key factors of the automobile LSSC structural system failure. The results show that the application of fuzzy fault tree analysis method to the diagnosis of automobile LSSC system failure can not only play an important role in cost saving and rapid diagnosis, but also be used to guide the check sequence of the automobile LSSC system fault, providing reference for logistics service supply chain, especially for the coordinated optimization decision-making of automobile LSSC.

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References