Postprint of the Minimal Form Analysis Method for System Functional Structure

Authors: Cui Tiejun, Li Shasha, Wang Laigui

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Abstract

To enable spatial fault tree theory to possess the capability of analyzing discrete reliability data, a method for analyzing the minimal form of system functional structure is proposed based on factor space theory, primarily aimed at understanding the causal relationships and connotations between system functions and component functions. The steps and related definitions of the minimal form method for system functional structure are presented; a background space is constructed using 32 fault states of a system to analyze the inherent relationships between system functions and component functions. Simultaneously, 23 fault states are randomly selected to form a subset of the background space, obtaining the inherent functional relationships. By comparing the differences in the minimal structural forms of the two functional relationships, and based on Boolean algebra, the implicit functional relationship between components is obtained as: the function of component Z3 is identical to the function of Z1 or Z2 or Z1+Z2. Thus, the component equivalence and replacement relationships regarding system reliability are obtained. Additionally, it is shown that the sum of the minimal structural forms of two subsets of the background space does not equal the minimal structural form of the original background space, and the conditions for their equality are provided.

Full Text

Preamble

Simplest Formula Analysis Method of System Function Structure

Tiejun Cui[1,2], Shasha Li[1], Laigui Wang[1]

[1](a. College of Safety Science & Engineering; b. School of Mechanics & Engineering, Liaoning Technical University, Fuxin, Liaoning 123000, China; 2. Tunnel & Underground Structure Engineering Center of Liaoning, Dalian Jiaotong University, Dalian, Liaoning 116028, China)

Abstract: To enable space fault tree theory to analyze discrete reliability data, this paper proposes a simplest formula analysis method for system function structure based on factor space theory. This method is primarily used to understand the causal relationships and connotations between system functions and component functions. The paper presents the procedural steps and relevant definitions of the simplest formula analysis method, using 32 fault states of a system to form a background space for analyzing the inherent relationships between system and component functions. Simultaneously, 23 fault states were randomly selected to form a subset of the background space, yielding the embedded functional relationships. By comparing differences in the simplest structural formulas of these two functional relationships and applying Boolean algebra, the implicit functional relationship between components was obtained: the function of component Z3 is identical to that of Z1 or Z2 or Z1+Z2. This reveals component equivalence and substitution relationships regarding system reliability. Additionally, the sum of the simplest structural formulas from two subsets of the background space does not equal the simplest structural formula of the original background space, and the conditions for their equality are provided.

Keywords: safety science; factor space; space fault tree; functional structure analysis; background relation subset; minimal analytic paradigm

0 Introduction

System design is typically a forward process that begins with overall system functionality and, through functional decomposition, ultimately implements specific components or subsystems. This forward design approach readily satisfies design objectives and accomplishes predetermined functions. However, determining whether the functionally designed system achieves optimal structure remains challenging—considering both functional performance and economic factors. Moreover, if a system' s functional variation patterns are known but the system cannot be opened or its internal structure obtained, replication becomes impossible. These challenges constitute the system function structure analysis problem: understanding the compositional relationship between system functional structure and components when both basic unit functional characteristics and system-level functional features are known. The internal compositional structure may represent an equivalent functional structure rather than the actual physical architecture.

System function structure analysis serves as an effective tool for system identification and understanding, with several scholars conducting research in this area [1-10]. Although these studies achieved good results in various fields, they primarily investigated system function structure through forward analysis, making it difficult to solve the aforementioned problems. Furthermore, system function structure analysis represents a complex reasoning process, with limited related research due to the difficulty for technical engineering scholars to develop a rigorous and feasible logical-mathematical inference system. The authors' earlier proposed system structure inward analysis method also suffered from insufficient rigor and poor logical consistency. Therefore, collaboration between professional scholars and mathematicians is urgently needed to complete this work, which constitutes the primary objective of this paper.

To adapt to the information revolution and big data era, greater focus on intelligent data domains is necessary. In this regard, Professor Peizhuang Wang, an early Chinese scholar, proposed factor space (FS) mathematical theory in 1983, which provides a mathematical foundation for big data analysis and processing. FS has since gained extensive research recognition, with related studies including: background space information compression, FS processing of unstructured data [23], nested structures of factor granular spaces and data cognitive ecosystems [24], evaluation and decision-making theories [25,26], FS and public safety [27], and comprehensive research on algebra, topology, differential geometry, and category theory.

FS theory has achieved significant breakthroughs in intelligent science and big data fields but has not yet integrated into specific scientific technologies. The combination of SFT and FS provides development space for the latter in reliability and fault analysis within safety science. This integration has enabled several studies, including: FS attribute circle definitions and their application in object classification [28], research on system safety classification decision rules considering range attributes [29], coal mine safety situation differentiation methods based on FS [30], and some system reliability analysis research [31]. These studies demonstrate the feasibility of combining FS and SFT.

The authors introduce factor space theory into space fault tree analysis, using factor space concepts to help space fault tree analyze the relationship between system functions and component function embedded in discrete reliability data. This paper proposes a simplest formula analysis method for system function structure to accomplish this task. An example analyzes the simplest structural formulas of a background space and two background space subsets, along with implicit component functional relationships. The conditions under which the sum of the simplest structural formulas from two background space subsets equals that of the original background space are also provided.

1 Space Fault Tree and Factor Space Introduction

To understand how environmental factors affect system reliability, the authors proposed the Space Fault Tree (SFT) theory [11], which posits that systems operate within environments where the fault occurrence probability varies under different conditions due to the properties of basic events or physical components. SFT has three branches: Continuous Space Fault Tree (CSFT), Discrete Space Fault Tree (DSFT), and Inward Analysis of Structural Systems (IASS).

CSFT is a "white box" method that investigates system response behavior under external actions when internal structure and component properties are known. The fundamental concepts of SFT [12] were proposed with reference to classical fault trees, including methods for studying cut set domains and path set domains [13] and factor importance distribution [14]. These concepts have been applied to research on system reliability maintenance methods [15], system reliability decision rule mining [16], and system reliability assessment method optimization [17].

DSFT does not require knowledge of internal system structure or component properties, instead studying system response characteristics to environmental changes—equivalent to a "black box" approach. DSFT definitions and properties [18] were established, followed by research on DSFT construction and fault probability spatial distribution [19]. Fuzzy structural element methods were used to modify characteristic functions, including fuzzy structural element characteristic function construction [20] and SFT conceptualization with fuzzy structural elements.

IASS analyzes and infers internal system structure through system responses to environmental factor changes without knowing the specific internal construction, forming an equivalent pseudo-structure. Research on binary 01-type SFT representation and analysis methods includes item-by-item analysis and classification reasoning methods [21].

Any system possesses specific structure, environment, and function—where structure and environment are internal and external causes, and function is the effect. Adjusting structure to improve function and exploring structure from function represents a complex scientific problem. Factor space theory provides a concise platform for system function structure analysis, requiring only the establishment of a universe of discourse and observation methods for condition and result factors to obtain a set of sample points forming a factor analysis table for function structure analysis.

2 System Function Structure Simplest Formula Method

Given a factor function structure analysis table, the steps to obtain the simplest structural formula for a specified function class are as follows:

The function classes in the factor function structure analysis table are divided into two types: success class T and failure class F. The phase of the function factor g in the last row represents function T or F. The function factor g indicates the object function when object structure factors take different phases. Suppose the factor function analysis table contains M objects u (m = 1, 2, ⋯, M), N structure factors f (n = 1, 2, ⋯, N), and one function factor g, so factors can be uniformly represented as f . The number of phases x for object u under factor f is identical to that of the factor. The phase set of object u is {x } = {x | f (u) = x , n = 1, 2, ⋯, N}, where f (u) represents the phase of object u under factor f . For convenience, the phase set can be rewritten as a phase string x | = x x ⋯x for representation after classification according to T or F. The factor function analysis table can serve as the background space B in factor space analysis, where B = x |~ , n = 1, 2, ···, N and m = 1, 2, ···, M. Let the number of phases in the object phase set be the phase set length .

a) Combine the phases x corresponding to objects u and factors f in the factor function structure analysis table, forming phase sets x | from the phases of the same object u for different factors f —that is, one column of the factor function structure analysis table represents object u .

b) All columns in the factor structure analysis table, i.e., all object phase sets x | , compose the background space B, where B = x |~ , n = 1, 2, ···, N and m = 1, 2, ···, M.

c) Classify objects u into T or F categories based on the function factor g of all phase sets x |~ in background space B.

d) Decompose phases in all phase sets of background space into phases of length = 1. All non-repeating phases appearing in background space compose the screening phase set Γ. Use phases Λ from screening phase set Γ (when > 1, Λ is a phase set) to traverse all phase sets in class F. If these phase sets do not contain phase Λ and class T phase sets contain it, then phase Λ is a structural formula (T) of class T. Delete phase sets containing phase Λ from class T.

e) Set = + 1, where phase set Λ consists of + 1 phases arbitrarily selected from screening phase set Γ. Use phase set Λ to traverse all phase sets in class F. If none contain phase set Λ and class T phase sets contain it, then phase set Λ is a structural formula (T) of class T. Delete phase sets containing phase set Λ from class T.

f) Repeat step e) until all phase sets in class T are deleted.

g) Connect all structural formulas (T) with logical OR "+" to obtain the simplest structural formula (T) of the success class T represented by background space B.

Relevant definitions for factor space, phase set, function structure analysis table, and background space can be found in references [32, 33].

3 System Function Structure Analysis

This analysis uses a system structure analysis example from space fault tree. The example is a switch system Z composed of five components Z , ···, Z . Their functional status is represented by five function factors F = (f , f , f , f , f), where each function factor has a phase space X(f) = {x , x } = {x , x̄ }, j = 1, ···, 5. Here x indicates component Z is operational (通), while x indicates Z is failed (断). The function factor g has phase space X(g) = {T, F}, where T indicates system Z is operational and F indicates system Z is failed. The character set consists of ten characters {x , x̄ , x , x̄ , x , x̄ , x , x̄ , x , x̄ }. Each component has two functional states (F, T), forming 32 phases that compose the universe of discourse U and the background space B, as shown in Table 1 .

In Table 1, the background space is B = x | ~ . The simplest structural formula method is applied to analyze the functional structure of function class T.

Table 1: Functional Structure Analysis Table of 32 Phase Sets

a) The 32 objects form background space B. These 32 phase sets x | ~ are divided into function classes T and F:

T = {x x x x x , x x x x x̄ , x x x x̄ x , x x x̄ x x , x x̄ x x x , x̄ x x x x , x x x x̄ x̄ , x x x̄ x x̄ , x x̄ x x x̄ , x̄ x x x x̄ , x x x̄ x̄ x , x x̄ x x̄ x , x̄ x x x̄ x , x x̄ x̄ x x , x̄ x x̄ x x , x̄ x̄ x x x };

F = {x̄ x̄ x x x , x̄ x x̄ x x , x̄ x x x̄ x , x̄ x x x x̄ , x x̄ x̄ x x , x x̄ x x̄ x , x x̄ x x x̄ , x x x̄ x̄ x , x x x̄ x x̄ , x x x x̄ x̄ , x̄ x̄ x̄ x x , x̄ x̄ x x̄ x , x̄ x̄ x x x̄ , x̄ x x̄ x̄ x , x̄ x x̄ x x̄ , x̄ x x x̄ x̄ }.

b) = 1. In class F phase sets, X | = x̄ x̄ x x x contains phases Λ with = 1: x̄ , x̄ , x , x , x . X | = x̄ x x̄ x x contains phases Λ with = 1: x̄ , x , x̄ , x , x . Decomposing X | and X | and combining = 1 phases without repetition yields screening phase set Γ = {x , x̄ , x , x̄ , x , x̄ , x , x̄ , x , x̄ }. Similarly, decomposing all phase sets in F and combining = 1 phases without repetition yields screening phase set Γ = {x , x̄ , x , x̄ , x , x̄ , x , x̄ , x , x̄ }.

c) = + 1 = 2. In screening phase set Γ = {x , x̄ , x , x̄ , x , x̄ , x , x̄ , x , x̄ }, arbitrarily select two phases to form phase set Λ with = 2. These phase sets compose the screening set Γ without repetition when = 2. Apply step 5) with Γ to screen class F phase sets. The = 2 phase set Λ = x x in Γ does not appear in class F but appears in class T, making Λ a structural formula (T) of class T: (T) = x x . Delete phase sets containing Λ = x x from class T, resulting in T = {x x x x̄ x , x x x̄ x x , x x̄ x x x , x̄ x x x x , x x x x̄ x̄ , x x x̄ x x̄ , x x̄ x x x̄ , x̄ x x x x̄ }. Additionally, = 2 phase set Λ = x x in Γ also does not appear in class F but appears in class T, making it another structural formula (T) = x x of class T. Delete phase sets containing Λ = x x from class T, yielding T = {x x x x̄ x̄ , x x x̄ x x̄ , x x̄ x x x̄ , x̄ x x x x̄ }.

d) = + 1 = 3. In Γ, select = 3 phase set Λ = x x x , which does not appear in class F but appears in class T. Thus phase Λ is a structural formula (T) of class T. Delete phase sets containing Λ = x x x from class T, resulting in T = . T = is the algorithm stopping condition. According to step 7), combining the obtained structural formulas of T yields the simplest structural formula (T)B = x x + x x + x x x , giving the system function structure as Z = Z Z + Z Z + Z Z Z .

Selecting 23 phase sets from the background space forms another background space B = x | ~ (the shaded portion in Table 1). The logical expression for class T phase sets is obtained through OR operations:

T = x x x x x + x x x x x̄ + x x x x̄ x + x x x̄ x x + x x̄ x x x + x̄ x x x x

+ x x x x̄ x̄ + x x x̄ x x̄ + x x̄ x x x̄ + x̄ x x x x̄ + x x x̄ x̄ x + x x̄ x x̄ x + x̄ x x x̄ x + x x̄ x̄ x x + x̄ x x̄ x x + x̄ x̄ x x x , where "+" represents parallel connection and concatenation (e.g., x x x x x) represents series connection. This logical formula constitutes the functional structure expression of system Z.

Applying the same method to background space B B with 23 phase sets:

a) Background space B contains 23 phase sets. Divide these 23 phase sets x | ~ into function classes T and F:

T = {x x x x x , x x x x x̄ , x x x x̄ x , x x x̄ x x , x x̄ x x x , x̄ x x x x , x x x x̄ x̄ , x x x̄ x x̄ , x x̄ x x x̄ , x̄ x x x x̄ , x x x̄ x̄ x , x x̄ x x̄ x , x̄ x x x̄ x };

F = {x̄ x̄ x x x , x̄ x x̄ x x , x̄ x x x̄ x , x̄ x x x x̄ , x x̄ x̄ x x , x x̄ x x̄ x , x x̄ x x x̄ , x x x̄ x̄ x , x x x̄ x x̄ , x x x x̄ x̄ }.

b) = 1. In class F phase sets, X | = x̄ x̄ x x x contains = 1 phases Λ: x̄ , x̄ , x , x , x . X | = x̄ x x̄ x x contains = 1 phases Λ: x̄ , x , x̄ , x , x . Decomposing X | and X | and combining = 1 phases without repetition yields screening phase set Γ = {x , x̄ , x , x̄ , x , x̄ , x , x̄ , x , x̄ }. Similarly, decomposing all phase sets in F and combining = 1 phases without repetition yields screening phase set Γ = {x , x̄ , x , x̄ , x , x̄ , x , x̄ , x , x̄ }.

c) = + 1 = 2. In screening phase set Γ = {x , x̄ , x , x̄ , x , x̄ , x , x̄ , x , x̄ }, arbitrarily select two phases to form = 2 phase set Λ. These compose the screening set Γ without repetition when = 2. Apply step 5) with Γ to screen class F phase sets. The = 2 phase set Λ = x x in Γ does not appear in class F but appears in class T, making Λ a structural formula (T) of class T: (T) = x x . Delete phase sets containing Λ = x x from class T, resulting in T = {x x x x̄ x , x x x̄ x x , x x̄ x x x , x̄ x x x x , x x x x̄ x̄ , x x x̄ x x̄ , x x̄ x x x̄ , x̄ x x x x̄ }. Additionally, = 2 phase set Λ = x x in Γ also does not appear in class F but appears in class T, making it another structural formula (T) = x x of class T. Delete phase sets containing Λ = x x from class T, yielding T = .

The simplest structural formula for T is (T)B = x x + x x + x x , giving the system function structure as Z = Z Z + Z Z + Z Z .

Comparing the functional structures Z = Z Z + Z Z + Z Z Z and Z = Z Z + Z Z + Z Z reveals that background space B = x | ~ provides more detailed system function structure than background space B = x | ~ . This indicates that background space subsets lack constraints on system function structure. If (T)B and (T)B represent systems with identical functional variation characteristics, then x x + x x + x x is equivalent to x x + x x + x x x . Through logical relationships, x is equivalent to {x , x , x + x }, meaning component Z ' s function is identical to that of Z or Z or Z + Z . This functional equivalence relationship enables component replacement or maintenance during system design and operation.

Analyzing the remaining 9 phase sets from Table 1 (excluding the 23 mentioned above) forms B = x | ~ , equivalent to B B, B B = , B B = B.

a) The 9 objects form background space B. Divide these 9 phase sets x | ~ into function classes T and F:

T = {x x x x x , x x x x x̄ , x x x x̄ x };

F = {x̄ x̄ x x x , x̄ x x̄ x x , x̄ x x x̄ x , x̄ x x x x̄ , x x̄ x̄ x x , x x̄ x x̄ x }.

b) = 1. In class F phase sets, X | = x̄ x̄ x x x contains = 1 phases Λ: x̄ , x̄ , x , x , x . X | = x̄ x x̄ x x contains = 1 phases Λ: x̄ , x , x̄ , x , x . Decomposing X | and X | and combining = 1 phases without repetition yields screening phase set Γ = {x , x̄ , x , x̄ , x , x̄ , x , x̄ , x , x̄ }. Similarly, decomposing all phase sets in F and combining = 1 phases without repetition yields screening phase set Γ = {x , x̄ , x , x̄ , x , x̄ , x , x̄ , x , x̄ }. Phase x does not appear in class F nor in class T, so it is not a structural formula.

c) = + 1 = 2. In screening phase set Γ = {x , x̄ , x , x̄ , x , x̄ , x , x̄ , x , x̄ }, arbitrarily select two phases to form = 2 phase set Λ. These compose the screening set Γ without repetition when = 2. Apply step 5) with Γ to screen class F phase sets. The = 2 phase set Λ = x x in Γ does not appear in class F but appears in class T, making Λ a structural formula (T) of class T: (T) = x x . Delete phase sets containing Λ = x x from class T, resulting in T = .

The simplest structural formula for T is (T)B = x x , giving the system function structure as Z = Z Z .

This example demonstrates that when B B, B B, B B = , B B = B, (T)B (T)B + (T)B , i.e., x x + x x + x x x x x + x x + x x + x x . The simplest structural formulas obtained from subsets of a background space do not necessarily equal the sum of the original background space' s structural formula, though equality can occur depending on how all phase sets or samples are partitioned. If a background space subset contains multiple = 1 phases with different states, it can produce a simplest structural formula with more "+"terms, indicating richer embedded information (e.g., B). If a background space subset contains only single-state = 1 phases, the resulting simplest structural formula carries less information (e.g., B). Based on this analysis, if a background space is partitioned into two subsets satisfying B B, B B, B B = , B B = B, and B and B contain identical phase sets including all = 1 phase states, then (T)B = (T)B + (T)B . This shows the strict conditions required for the simplest structural formulas from several background space subsets to equal that of the complete background space.

4 Conclusion

This paper presents a simplest formula analysis method for system function structure regarding system reliability. The method primarily analyzes the relationship between component functions and system functions through discrete system reliability data, obtaining simplest structural formulas under different background space conditions—that is, the simplest system function structures—and further identifying component functional relationships under different background spaces. The paper provides method procedures, relevant definitions, and theorems, offering an effective approach for discrete data processing in space fault trees. This extends factor space theory' s application in safety science while providing an effective method for space fault tree discrete data processing.

Using 32 reliability data points to form background space B with 32 phase sets, the method yields the simplest structural formula (T)B = x x + x x + x x x . Randomly selecting 23 phase sets to form background space subset B yields (T)B = x x + x x + x x . The remaining 9 phase sets form background space subset B , yielding (T)B = x x . This demonstrates that background space subsets lack constraints on system function structure. Comparing (T)B and (T)B reveals that x is equivalent to {x , x , x + x }, meaning component Z ' s function is identical to that of Z or Z or Z + Z . Furthermore, analysis using two background space subsets shows that when B B, B B, B B = , B B = B, (T)B (T)B + (T)B , i.e., x x + x x + x x x x x + x x + x x + x x . The conditions for (T)B = (T)B + (T)B when partitioning the background space into subsets are provided.

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Note: Figure translations are in progress. See original paper for figures.