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RESEARCH ARTICLE

Research on Judgment and Solving Strategy of Flow Problems in Complex Engineering Systems

JIANHUI ZHANG[1], **JIANYONG LI**[1], **XUEJIE PU**[1], **AND XUERUI WANG**[2]

[1]National Engineering Research Center for Technological Innovation Method and Tool, School of Mechanical Engineering, Hebei University of Technology, Tianjin 300130, China

[2]Treolica (Tianjin) Company Ltd., Tianjin 300467, China

Corresponding authors: Jianhui Zhang (zhjh@hebut.edu.cn) and Jianyong Li (lijianyong5285@163.com)

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ABSTRACT Frequent processes of mutual transfer and transformation generally take place between the material flow, the energy flow, and the information flow in complex engineering systems, and complex coupling relationships exist between the different flows. Abnormal coupling of flows will cause flow problems, which can easily lead to the failure of the system functions. To address these problems, in this study, the starting point has been taken as the change in the attributes and types of the study flow, the attributes of the flows have been categorized, and a flow transfer and transformation model, oriented to the flow problem analysis has been proposed. Secondly, based on the analysis of the effect of the attribute changes of flows in complex engineering systems on the generation of flow problems, an innovatively introduced information processing mathematical tool, the polychromatic sets theory, has been used to explore and determine the flow problems existing in complex engineering systems. Further, depending on the different manifestations of flow problems, three solution strategies have been proposed. Finally, the process model of the flow problem judgment and a solution strategy for complex engineering systems has been constructed. The feasibility of the process model has been verified by considering the engineering case of the tubular feeding machine (TFM) system of a large-scale integrated marine resource survey ship.

INDEX TERMS Complex engineering system, polychromatic sets, flow problem judgment, solving strategy, tubular feeding machine (TFM) system.

I. INTRODUCTION

Owing to the integration of a variety of high-tech industries, complex engineering systems consist of a variety of structures, advanced design levels, and high research and development investment costs. They have become the core system that constitutes the pillar industry equipment of the national economy [1]. Complex engineering systems involve multiple disciplines, multiple methods, and other fields. And their functional characteristics are generated by the integration of many subsystems, each of which has its own physical process, and the total function of the system is realized through the interaction between subsystems [2]. With the material flow, energy flow, and information flow as the basic factors constituting the ecosystem [3], the transfer and transformation of multiple flows are also carried out in the interaction among subsystems of the complex engineering systems, and they participate in the function realization of the system [4], [5].

In the process of mutual transmission and transformation, various flows in the system have complex mutual interactions and coupling relationships [4], [6]. Changes in the attributes and types of some flows sometimes have abnormal effects on other flows, thus, resulting in the generation of flow problems [7]. This might lead to many problems in the operation of the system, such as function weakening, function failure, or strange working conditions. Hence, it is necessary to deeply analyze and determine the flow problems that exist in complex engineering systems and study the corresponding

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solution strategies, which will help in realizing the optimization, improvement, and innovation of complex engineering systems [5].

This study presents a strategy for determining and solving flow problems in complex engineering systems. Firstly, starting from the study of the effect of flow properties and the changes in the types of flows on other flows, and combined with the transfer and transformation process of flows, a flow problem analysis and discovery method for complex engineering systems has been proposed in this study. Depending on the specific forms and types of flow problems, the corresponding flow-problem-solving strategies have been proposed. Finally, a process model for the determination and solution strategy of a complex engineering system flow problem has been constructed, which provides the corresponding methods and key technologies for the judgment and solution of the system flow problem. Further, the model has been verified by performing a case study.

The remainder of this paper has been organized as follows: Section II reviews the studies on the transmission of flow in a system, the synergy of the flow in the system, the construction of the flow analysis model, and methods of mining and solving the flow problem in the system. Section III introduces the main contents of the proposed process model, including the flow analysis, judgment of the flow problem in a complex engineering system, and the solving strategy for the flow problem. Section IV describes the verification of the effectiveness of the process model done by performing a case study. The conclusions of the research and the future research plan have been discussed in Section V and Section VI respectively.

II. RELATED WORKS

At present, a few studies have been done on the determination and solving strategies of flow problems in complex engineering systems, mainly from the point of view of the following aspects: the transfer and synergy of flow (matter, energy, and information) in the system, the construction of a flow analysis model, and mining and solving flow problems in a given system.

A. TRANSFER AND SYNERGY OF FLOWS

The following works have conducted flow (material, energy, and information) transfer analysis: Andersen and Hyman [8] analyzed the consumption patterns of material flow and energy flow in the US steel industry and established a corresponding consumption model, which can provide guidelines for simulating the material and energy consumption in the steelmaking process. Johansson and Söderström [9] studied the consumption of material and energy in the steel refining process and proposed improvement measures based on the integration of material flow and energy flow to reduce CO_2 emissions.

Studies have been conducted on the synergy of flows. Long [10] studied the coordination mechanism of material flow, energy flow, and information flow in a large-scale system from the perspective of interdisciplinary research and put forward the flow characteristics of these three types of flows in the system, thereby improving the efficiency of the system and realizing the global optimization of the system. Zheng et al. [11] developed a coordination method to improve the material flow and energy flow of the system from the perspective of information flow and proposed a collaborative optimization model based on information flow to facilitate the efficient execution of steel production.

B. FLOW ANALYSIS MODEL

Constructing a flow analysis model that can express the mutual transfer and transformation relationship between different types of flow, the generation mechanism of flow problems, etc., can facilitate the study of flows with defects in the system and the corresponding flow problems. Earlier, the construction of the flow analysis model, namely, the functional structure model, was done by Pahl and Beitz in Germany [4], in which the total function was decomposed into a set of functions accompanied by energy flow, material flow, and signal flow, and this was a generally recognized flow model. The flow analysis model can be used to analyze the existing flow problems in the system [7], [12], but the model construction is relatively cumbersome. Ran et al. [13] used the polychromatic sets theory to model the workflow process and established a unified hospital workflow model based on polychromatic sets graphs, which promoted the rationalization of the dynamic resource allocation of the hospital. The polychromatic sets theory uses the concept of "contour" to abstract and generalizes concepts such as properties, attributes, characteristics, and parameters of objects in actual systems [14]. As a mathematical tool for information processing, it has more advantages than other modeling tools such as Petri nets and unified modeling language (UML) [13], [15]. In addition, this theory is also widely used in the reverse design for remanufacturing (RDfRem) method [16], unmanned aerial vehicle (UAV) route planning application [17], product information model construction [18], the design improvement of the electric multiple unit (EMU) bogie system [19], and many other fields. Therefore, an increasing amount of attention is being paid to the modeling of complex engineering systems using the polychromatic sets theory and the research on the system innovative design. However, no research has been done on the application of the polychromatic sets theory to the flow problem in complex engineering systems.

C. MINING AND SOLVING FLOW PROBLEMS

The following studies have been done on the methods of mining and solving flow problems: TRIZ master Litvin [20] proposed a flow analysis tool to analyze the material flow, energy flow, and information flow in the product system, which can mine and analyze the possible defects in these flows. Ikovenko [21] classified flow defects into flow operation defects and flow distribution defects, and the former cause the decline of system functions or increase the cost. Sun and Ikovenko suggested that the main purpose of flow analysis is to find the bottleneck or stagnation area of the flow that causes the problem [22]. On this basis, Zhao et al. [5] proposed a solution measure of the flow evolution law to eliminate the flow bottlenecks and stagnant areas. Wang et al. [12] divided flow problems into four types: flow loss, excessive flow, flow retention, and flow deterioration, and proposed to use the extension theory to determine the flow problems and use TRIZ tools to solve the flow problems. Xi [23] clarified the coupling relationship between parameters in a complex electromechanical system based on the flow analysis and solved the functional coupling problem existing in the system design. Wang [7] proposed the concept of flow threshold to describe the system flow problem and used the solution strategy of flow evolution to solve the flow problem.

III. METHODS

A. FLOW ANALYSIS

1) THE CONCEPT OF FLOW ANALYSIS

The functional realization of complex products is closely related to the flow. A function is the carrier of a flow, which converts an input flow into an output flow. A flow is the object of the action of the function, which connects the function elements to form a certain function and goal and has the characteristics of flow and transfer [4]. Analyzing the system from the perspective of the flow in a complex engineering system is a new type of problem-exploring method. It is the key to solving the faults in complex engineering systems by digging deeply into the relationship between the mutual transfer, transformation, and evolution between the internal flows of the system, to explore the generation mechanism of flow problems, and to propose the solution measures for them.

Flow analysis was first proposed by TRIZ masters Simon Litvin and Alex Lyubomirskiy, and it has become an important part of modern TRIZ [5]. The modern TRIZ theory defines flow as the movement of materials, energy, and information in a system [6] and regards flow analysis as one of the tools for analyzing the problem. Some researchers believe that the flow analysis of a system must combine the functions of the system components and make full use of the resources available in the system and the super-system [7], [20], [24]. Therefore, based on the functional analysis [25], [26], [27] and resource analysis in the TRIZ theory [24], the establishment of a flow problem analysis model that is suitable for the system flow analysis [7] is the prerequisite for determining the system flow problem.

2) ANALYSIS OF THE ATTRIBUTES OF THE FLOW

The attributes of a flow are considered to be the different properties and connections of the flow of materials, energy, and information that are transmitted and transformed within a system. The manifestation of an internal flow in a complex engineering system is essentially determined by the attributes of the flow [12]. Interaction between the different types of flows and system components and the mutual transmission and transformation between different flows change the attributes and types of the flow. Therefore, the flow problem is essentially a functional defect caused by the negative effect of the attributes and the change in the type of the flow on other normal flows during the process of transmission, which hinder multiple flows from working together [12]. Therefore, the study of flow attributes and types in complex engineering systems is the basis for determining the problem of the types of flows in complex engineering systems. Cao [28] believed that different types of flow have different attributes and established the flow attributes set without giving the specific content of the flow attributes. In a study by Zhao et al. [5], the attributes of flow were classified into different types, but the differences between them were not considered. Therefore, by comprehensively considering the content of the above-mentioned studies, in this study, the different attributes of the (material, energy, and information) flow in the system have been classified, as shown in Figure 1.

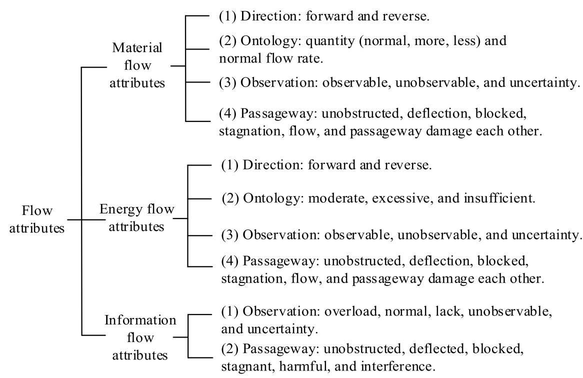


FIGURE 1. Classification of different types of flow attributes.

3) PROCESS OF CONSTRUCTING THE FLOW TRANSFER AND TRANSFORMATION MODEL

A concise flow transfer and transformation model has been proposed in this study, as shown in Figure 2, and the meaning of the model symbols has been given in Table 1. The model uses the system elements and the corresponding functions as the nodes, the flow as the edges, and arrows to indicate the direction of flow in order to express the transfer and transformation of flows in the system. In the model, S represents the system component, and F represents the function realized by the component. The model only reflects the transfer and transformation of the system flow and can express the flow in the system simply and clearly. The flow analysis model and the flow problem determination model have been discussed separately, which is helpful for the designer to establish the flow analysis model clearly and avoid differences in the model construction caused by subjective judgment.

Therefore, based on the functional analysis of the complex engineering system and combining the resource analysis with the flow analysis, the construction process of the system

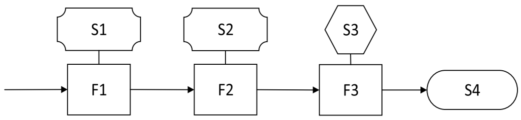


FIGURE 2. **Schematic of the flow transfer and transformation model.**

TABLE 1. **Symbols used in the schematic of the flow transfer and transformation model.**

Symbol	Name	Classification
	Component	Node symbol
	Function	Node symbol
	Super-system	Node symbol
	System target	Node symbol
	Flow	Connection symbol
	Bearing connection	Connection symbol

flow transfer and transformation model has been obtained, as shown in Figure 3, which can be divided into seven steps.

Step 1: Select a complex engineering system.

Step 2: Decompose the function of the system.

Step 3: Analyze the resources of the system to obtain the material resources, energy resources, and information resources of the system.

Step 4: Carry out the flow analysis of the system to determine the material flow, energy flow, and information flow of the system.

Step 5: Take the system components and functions as the nodes (the bearing connection symbols are used between the components and the functions) and the flows as the edges, and establish the flow transfer and transformation models of material flow, energy flow, and information flow, respectively.

Step 6: Check whether the model construction is complete; otherwise, go to Step 3. If yes, go to the next step.

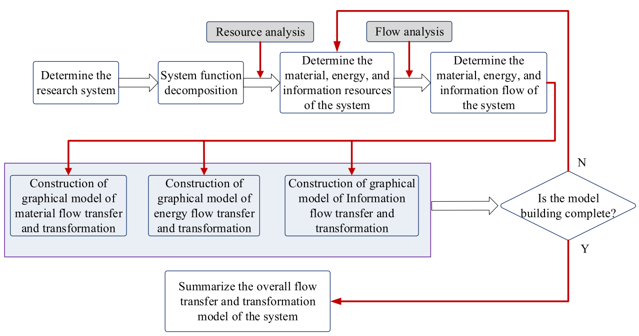


FIGURE 3. **Flowchart of the process of constructing the flow transfer and transformation model for a system.**

Step 7: Summarize and obtain the overall flow transfer and transformation model of the system.

B. JUDGMENT OF FLOW PROBLEMS IN A COMPLEX ENGINEERING SYSTEM

It can be seen from the flow attributes analysis that the flow problems in a complex engineering system are essentially influenced by other flows in the process of their transfer and transformation, and their attributes change. Therefore, in this study, the starting point has been taken as the attributes analysis of the flow, and the theory of polychromatic sets has been used to determine the flow problems in the system.

1) CONCEPTS RELATED TO POLYCHROMATIC SETS

The polychromatic sets theory has been formed by combining fuzzy mathematics, mathematical logic, and matrix knowledge on the basis of a traditional set [13], [15], [16], [17], [18], [19]. The polychromatic sets are mainly composed of six components, as given in Equation (1).

$$PS = (A, F(A), F(\mathrm{a}), [A \times F(A)], [A \times F(a)], [A \times A(F)]) \tag{1}$$

where A represents an element in the set, $F(a)$ represents the individual color of the element in the geometry, and $F(A)$ is the uniform coloring of the object. $[A \times F(a)]$ is the individual coloring of all elements, $[A \times F(A)]$ represents the relationship between the uniform color and the individual color, $[A \times A(F)]$ represents the composition of all elements that guarantees the existence of all uniform colors in the polychromatic sets.

In order to facilitate the judgment of flow problems in a complex engineering system, Zhao [6] proposed the concept of flow threshold $(Flow\,\{Attributes\,(F)\})$, i.e., to judge the flow problem depending on the range of the flow attributes. Based on this, the Boolean matrix, $[A \times F(a)]$, of the individual coloring of all elements in a multi-color set was established, as shown in Equation (2).

$$\|C_{ij}\|_{A,F(a)} = AXF(a) = \begin{array}{c} \begin{matrix} f_1 & \cdots & f_j & \cdots & f_q \end{matrix} \\ \begin{bmatrix} c_{11} & \cdots & c_{1j} & \cdots & c_{1q} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ c_{i1} & \cdots & c_{ij} & \cdots & c_{iq} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ c_{n1} & \cdots & c_{nj} & \cdots & c_{nq} \end{bmatrix} \end{array} \begin{matrix} a_1 \\ \cdots \\ a_i \\ \cdots \\ a_n \end{matrix}$$

$$\begin{cases} C_{ij} = 1, \quad if\ a_i \in Attributes(f_i), \\ f_i = F(a_i) \end{cases} \tag{2}$$

2) APPLICATION OF POLYCHROMATIC SETS IN THE JUDGMENT OF FLOW PROBLEMS IN COMPLEX ENGINEERING SYSTEMS

In a complex engineering system, the a set of research objects, $A = \{a_1, a_2, \cdots a_n\}$, is the set of material flow in the system, B is the set of energy flow in the system, and C is the set of information flow in the system. The attributes of the flow are colored as $F(a)$, $F(b)$, and $F(c)$, respectively.

a: SETS OF ATTRIBUTES FOR THE DIFFERENT FLOWS IN THE SYSTEM

The attribute elements of material flow, energy flow, and information flow are not completely identical. Thus, based on the attribute division of convection in literature [17], the different attributes of various flows are further distinguished, and a set of attributes of different flows is established as follows:

The set of attributes for the material flow is given by

$$F(a) = \left\{ \begin{array}{l} D(F(a_1), F(a_2)), N(Q(F(a_3), F(a_4), \\ F(a_5)), F(a_6)), O(F(a_7), F(a_8), F(a_9)), \\ P(F(a_{10}), F(a_{11}), F(a_{12}), F(a_{13}), F(a_{14})) \end{array} \right\} \quad (3)$$

where $F(a_1)$: forward, $F(a_2)$: reverse, $F(a_3)$: normal, $F(a_4)$: more, $F(a_5)$: less, $F(a_6)$: normal flow rate, $F(a_7)$: observable, $F(a_8)$: unobservable, $F(a_9)$: uncertainty, $F(a_{10})$: unobstructed, $F(a_{11})$: deflection, $F(a_{12})$: blocked, $F(a_{13})$: stagnation, and $F(a_{14})$: flow and passageway damage each other.

The set of attributes for the energy flow is given by

$$F(b) = \left\{ \begin{array}{l} D(F(b_1), F(b_2)), N(F(b_3), F(b_4), \\ F(b_5)), O(F(b_6), F(b_7), F(b_8)), \\ P(F(b_9), F(b_{10}), F(b_{11}), F(b_{12}), F(b_{13})) \end{array} \right\} \quad (4)$$

where $F(b_1)$: forward, $F(b_2)$: reverse, $F(b_3)$: moderate, $F(b_4)$: excessive, $F(b_5)$: insufficient, $F(b_6)$: observable, $F(b_7)$: unobservable, $F(b_8)$: uncertainty, $F(b_9)$: unobstructed, $F(b_{10})$: deflection, $F(b_{11})$: blocked, $F(b_{12})$: stagnation, and $F(b_{13})$: flow and passageway damage each other.

The set of attributes for the information flow is given by

$$F(c) = \left\{ \begin{array}{l} O(F(c_1), F(c_2), F(c_3), F(c_4), F(c_5)), P(F(c_6), \\ F(c_7), F(c_8), F(c_9), F(c_{10}), F(c_{11})) \end{array} \right\} \quad (5)$$

where $F(c_1)$: overload, $F(c_2)$: normal, $F(c_3)$: lack, $F(c_4)$: unobservable, $F(c_5)$: uncertainty, $F(c_6)$: unobstructed, $F(c_7)$: deflection, $F(c_8)$: blocked, $F(c_9)$: stagnation, $F(c_{10})$: harmful, and $F(c_{11})$: interference.

b: CONTOUR MATRIX OF MATERIAL FLOW

According to the classification of convection types in the literature [18], taking the material flow as an example, a unified polychromatic set of flow types is established, which contains eight types of flow coloring, as follows:

$$\begin{aligned} F(A) &= \left\{ \begin{array}{l} F_1(A), F_2(A), F_3(A), F_4(A), \\ F_5(A), F_6(A), F_7(A), F_8(A) \end{array} \right\} \\ &= \left\{ \begin{array}{l} F_1, F_2, F_3, F_4, \\ F_5, F_6, F_7, F_8, \end{array} \right\} \end{aligned} \quad (6)$$

where $F_1(a)$: normal flow, $F_2(a)$: insufficient flow, $F_3(a)$: excessive flow, $F_4(a)$: harmful flow, $F_5(a)$: stagnant flow, $F_6(a)$: deflected flow, $F_7(a)$: lengthy flow, and $F_8(a)$: conflicting flow.

The contour matrix $[A \times F(a)]$ of the relationship between the different flows and their attributes is:

$$\|C_{ij}\|_{A,F(a)} = AXF(a) = \begin{array}{c} \begin{array}{ccccc} f_1 & \cdots & f_7 & \cdots & f_{14} \end{array} \\ \left[\begin{array}{ccccc} c_{11} & \cdots & c_{17} & \cdots & c_{1,14} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ c_{i1} & \cdots & c_{i7} & \cdots & c_{i,14} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ c_{n1} & \cdots & c_{n7} & \cdots & c_{n,14} \end{array} \right] \end{array} \begin{array}{c} a_1 \\ \cdots \\ a_i \\ \cdots \\ a_n \end{array} \quad (7)$$

The contour matrix $[A \times F(A)]$ that represents the division of different flow types is:

$$\|D_{ij}\|_{A,F(a)} = AXF(A) = \begin{array}{c} \begin{array}{ccccc} F_1 & \cdots & F_4 & \cdots & F_8 \end{array} \\ \left[\begin{array}{ccccc} d_{11} & \cdots & d_{14} & \cdots & d_{1,8} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ d_{i1} & \cdots & d_{i4} & \cdots & d_{i,8} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ d_{n1} & \cdots & d_{n4} & \cdots & d_{n,8} \end{array} \right] \end{array} \begin{array}{c} a_1 \\ \cdots \\ a_i \\ \cdots \\ a_n \end{array} \quad (8)$$

Depending on the attributes of the flow, a set matrix of flow attributes and flow types can be established as follows:

$$[F(a) \times F(A)] = \begin{array}{c} \begin{array}{ccccc} F_1 & \cdots & F_4 & \cdots & F_8 \end{array} \\ \left[\begin{array}{ccccc} g_{11} & \cdots & g_{14} & \cdots & g_{1,8} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ g_{71} & \cdots & g_{74} & \cdots & g_{7,8} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ g_{14,1} & \cdots & g_{14,4} & \cdots & g_{14,8} \end{array} \right] \end{array} \begin{array}{c} f_1 \\ \cdots \\ f_7 \\ \cdots \\ f_{14} \end{array} \quad (9)$$

Because the sets $F(a)$ and $F(A)$ are known, the numerical value in the matrix $[F(a) \times F(A)]$ of flow attributes and flow types are constant. The construction of the contour matrix of the material flow and its flow attributes is shown in Table 2. The energy flow and information flow contour matrices are similar to that of the material flow.

3) JUDGMENT OF THE MATERIAL FLOW PROBLEMS

From Equations (7) and (9), it can be seen that $[A \times F(a)]$ is a $14 \times n$ matrix and $[F(a) \times F(A)]$ is an 8×14 matrix. Therefore, the matrix $[A \times F(A)]$ can be obtained by matrix operation. The "*" symbol denotes the conjunctive XNOR operation, and the specific operation is shown in Equation (10).

$$\begin{aligned} &[A \times F(a)] * [F(a) \times F(A)] \\ &\quad = [A \times F(A)] \\ &\quad \times \begin{array}{c} \begin{array}{ccccc} f_1 & \cdots & f_7 & \cdots & f_{14} \end{array} \\ \left[\begin{array}{ccccc} c_{11} & \cdots & c_{17} & \cdots & c_{1,14} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ c_{i1} & \cdots & c_{i7} & \cdots & c_{i,14} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ c_{n1} & \cdots & c_{n7} & \cdots & c_{n,14} \end{array} \right] \end{array} \begin{array}{c} a_1 \\ \cdots \\ a_i \\ \cdots \\ a_n \end{array} \end{aligned}$$

TABLE 2. Contour matrix of flow attributes and flow types (The key determinants have been marked by red color in the matrix).

F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	
1	1	1	1	1	1	1	0	f_1
0	0	0	0	0	0	0	1	f_2
1	0	0	1	0	1	1	1	f_3
0	0	1	0	0	0	0	0	f_4
0	1	0	0	0	0	0	0	f_5
1	0	0	1	0	1	1	0	f_6
1	1	1	1	0	1	1	1	f_7
0	0	0	0	1	0	0	0	f_8
0	0	0	0	0	0	0	0	f_9
1	1	1	1	0	1	1	1	f_{10}
0	0	0	0	0	1	0	0	f_{11}
0	0	0	0	0	0	1	0	f_{12}
0	0	0	0	1	0	0	0	f_{13}
0	0	0	1	0	0	0	0	f_{14}

$$* \begin{array}{c} \begin{matrix} F_1 & \cdots & F_4 & \cdots & F_8 \end{matrix} \\ \begin{bmatrix} g_{11} & \cdots & g_{14} & \cdots & g_{1,8} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ g_{71} & \cdots & g_{74} & \cdots & g_{7,8} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ g_{14,1} & \cdots & g_{14,4} & \cdots & g_{14,8} \end{bmatrix} \end{array} \begin{matrix} f_1 \\ \cdots \\ f_7 \\ \cdots \\ f_{14} \end{matrix}$$

$$= \begin{array}{c} \begin{matrix} F_1 & \cdots & F_4 & \cdots & F_8 \end{matrix} \\ \begin{bmatrix} h_{11} & \cdots & h_{14} & \cdots & h_{1,8} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ h_{i1} & \cdots & h_{i4} & \cdots & h_{i,8} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ h_{n1} & \cdots & h_{n4} & \cdots & h_{n,8} \end{bmatrix} \end{array} \begin{matrix} a_1 \\ \cdots \\ a_i \\ \cdots \\ a_n \end{matrix} \quad (10)$$

Here, $h_{11} = (c_{11} \odot g_{11}) \wedge (c_{12} \odot g_{21}) \wedge \ldots \wedge (c_{1,14} \odot g_{14,1})$, $h_{12} = (c_{11} \odot g_{12}) \wedge (c_{12} \odot g_{22}) \wedge \ldots \wedge (c_{1,14} \odot g_{14,2})$, $\ldots h_{1k} = (c_{11} \odot g_{1k}) \wedge (c_{12} \odot g_{2k}) \wedge \ldots \wedge (c_{1,14} \odot g_{14,k})$, "$\odot$" is the symbol for the XNOR operation, and "$\wedge$" is the symbol for the conjunction operation.

Using Equation (10), the relationship between the element "flow" and the flow type in the research object set A can be obtained when determining the problem flows. The problem flows judgment process for the energy flow, and information flow is similar to that of material flow problems judgment process.

C. SOLVING STRATEGY FOR THE FLOW PROBLEMS OF A COMPLEX ENGINEERING SYSTEM

After judging the problem flows in the complex engineering system, it is necessary to combine the specific manifestation of the problem flows in an actual operation in order to determine the bad conditions caused by the flow problems and to solve the flow problems. A previous study by research team [7] proposed that the problem flows in complex engineering systems can be classified into seven types, namely, insufficient flow, excessive flow, harmful flow, stagnant flow, deflected flow, lengthy flow, and conflicting flow. Different problem flows correspond to different flow problems, and the mapping relationship between them has been established, as shown in Table 3.

This study considers solving the flow problem in local as well as global dimensions. Considering that the primitive model of extenics theory adopts the combination of an object (O), characteristic (C), and value (V) as the primitive unit to describe things, it can easily and accurately describe any problem [29]. Therefore, firstly, the extenics theory has been proposed to solve the flow problems; for flow problems that cannot be solved by applying the extenics theory, by considering the diversity of the solution methods of the flow evolution rules, they have been used to continue to solve the flow problems. The extenics solution strategy and the flow evolution rules solution strategy use the resources and flows inside and outside the complex engineering system to make partial improvements to the system to achieve system improvement and innovation. Furthermore, in this study, the prediction of the overall future improvement direction of the system from a macro perspective has also been put forth, and a technology-driven evolutionary solution strategy has been proposed to promote the improvement and innovation of the system as a whole in the desired direction.

TABLE 3. The mapping relationship between problem flows and flow problems.

Problem flows		Flow problems
Insufficient flow	→	Insufficient effect
Excessive flow	→	Over-effect
Harmful flow	→	Exacerbation
Stagnant flow	→	Retention
Deflected flow	→	Deflection
Lengthy flow	→	Verbosity
Conflicting flow	→	Conflict effect

1) EXTENICS SOLUTION STRATEGY

The relationship of an object in the extenics has the characteristics of composability, decomposability, and scalability. An object can be combined with another object to form a new object. Alternatively, an object can be decomposed into multiple other objects, which allows the new object to have characteristics that the original object does not have, thereby providing the possibility to solve system problems. In addition, the nature of an object that can be expanded or reduced can also provide the possibility of solving problems [30].

a: INSUFFICIENT FLOW

When a certain material, energy, or information flow in the system has an insufficient effect on another flow, the expandable characteristics of the primitives in the extenics are used to increase the insufficient effect.

Any primitive can be expanded under certain conditions, i.e., for $B = (O, c, v)$, under certain conditions, ℓ, there must be a real number $\alpha(\alpha > 0)$ such that $\alpha B = (\alpha O, c, \alpha v)$. When $\alpha > 1$, the primitive B can be expanded to αB. Here, αO represents an object O whose magnitude is αv.

b: EXCESSIVE FLOW

When a certain material, energy, or information flow in the system has an excessive effect on another flow, the contractible characteristics of the primitives in the extenics are used to reduce the excessive effect.

Any primitive can be reduced under certain conditions, i.e., for $B = (O, c, v)$, under certain conditions, ℓ, there must be a real number $\alpha(\alpha > 0)$ such that $\alpha B = (\alpha O, c, \alpha v)$. When $0 < \alpha < 1$, it can be reduced to αB based on B.

c: HARMFUL FLOW

When a certain material, energy, or information flow in the system has a harmful effect on another flow, the combinable and decomposable characteristics of primitives in the extenics are used to add primitives to counteract the harmful effects or to decompose the primitives to eliminate the harmful effects.

Given a primitive $B_1 = (O_1, c_1, v_1)$, there is at least one primitive $B_2 = (O_2, c_2, v_2)$, such that B_1 and B_2 can be combined into B, and B_2 is a combinable primitive of B_1. As expressed by Equation (11), the primitive B, formed by combining B_1 and B_2 using primitives, can have normal effects on other flows in the system.

$$\begin{aligned} B &= B_1 \oplus B_2 \\ &= \begin{cases} (O_1, c_1 \oplus c_2, v_1 \oplus v_2) = \begin{bmatrix} O_1, c_1, v_1 \\ c_2, v_2 \end{bmatrix}, \\ \quad \text{when} \quad O_1 = O_2, c_1 \neq c_2 \\ (O_1 \oplus O_2, c_1, v_1 \oplus v_2), \\ \quad \text{when} \quad O_1 \neq O_2, c_1 = c_2 \\ \begin{bmatrix} O_1 \oplus O_2, c_1, v_1 \oplus c_1(O_2) \\ c_2, c_2(O_2) \oplus v_2 \end{bmatrix}, \\ \quad \text{when} \quad O_1 \neq O_2, c_1 \neq c_2 \end{cases} \end{aligned} \tag{11}$$

Any primitive can be decomposed into multiple primitives based on certain conditions, i.e., if we set $B = (O, c, c(O))$, then under certain conditions, ℓ, for a certain feature, c, $(O, c, c(O))//(\ell)\{(O_1, c, c(O_1)), (O_2, c, c(O_2)), \cdots, (O_m, c, c(O_m))\}$ is denoted as $B//\{B_1, B_2, \cdots, B_m\}$, where $B_i = (O_i, c, c(O_i))(i = 1,2 \cdots, m)$. B_i can be used as the separated part of the harmful effect and the remaining part can have a normal effect on other flows in the system.

d: CONFLICTING FLOW

The conflicting flows existing in the system generally have two manifestations. One is that the flow is affected by the reverse flow while the flow is functioning normally, resulting in the generation of a flow conflict. The other is that due to the influence of the environment and the channel, the direction of flow changes during the process of flowing, resulting in conflicts with the flow itself. For the first case, it is necessary to find the established condition, ℓ, and the coefficient $0 < \alpha < 1$, and adopt the expansion and contraction effect of the extenics theory to reduce the conflicting flow under the condition ℓ, in order to eliminate the conflicting flows. In the second case, it is necessary to find the actual reason that causes the change in the flow direction and adjust the flow carrier based on the actual problem in order to eliminate the conflicting flows.

2) FLOW EVOLUTION RULES SOLUTION STRATEGY

As given in Table 3, insufficient flow is classified into a flow with defective conductivity and a flow with defective utilization rate [5]. The essence of the deflected flow and lengthy flow is that the conductivity of the flow is defective, and thus the solution measures of the defective conductivity of the flow can be used to solve the problem. Stagnant flow could be considered to be a defect of the flow conductivity or the utilization rate. Therefore, the problem of flow retention can be solved by improving the flow conductivity and increasing the utilization rate of the flow. Excessive flow and conflicting flow often produce undesirable effects in their results. Thus, they can be classified as harmful flows for processing.

After G.S. Altshuller first proposed the "Law of Minimizing Energy Conductivity" [31]., his student Igor Gridnev further promoted and perfected this rule and formed the flow evolution rules [32]. In the solution strategy of the flow evolution rules, 14 improvement measures to improve the flow conductivity, 9 measures to improve the utilization rate, and 18 improvement measures to reduce or eliminate the harmful effects of the flow were described [5]. In summary, the mapping between the seven flow problems listed in Table 3 and the solution strategy in the flow evolution rule was established, and the results are given in Table 4.

The process of solving the flow problem based on the flow evolution law essentially involves solving the corresponding problem flow. As shown in Figure 4, seven problem flows are used to represent the problems existing in a complex engineering system in a unified manner, and subsequently, the problem flows are converted into flows with defective conductivity, flows with defective utilization rate, and flows with harmful effects. The solution measures in the flow evolution law are used to solve the flow problems.

3) TECHNOLOGY-DRIVEN EVOLUTION SOLUTION STRATEGY

Upgrades in complex engineering systems will inevitably lead to changes in the internal flow of the system. The extenics solution strategy and the flow evolution rules solution

TABLE 4. Flow evolution rules solution strategy.

Problem flows		Solution measures
Excessive flow	→	18 improvement measures to reduce or eliminate the harmful effects of the flow
Insufficient flow	→	14 improvement measures to improve the flow conductivity
	→	9 measures to improve the utilization rate
Harmful flow	→	18 improvement measures to reduce or eliminate the harmful effects of the flow
Conflicting flow	→	18 improvement measures to reduce or eliminate the harmful effects of the flow
Deflected flow	→	14 improvement measures to improve the flow conductivity
Lengthy flow	→	14 improvement measures to improve the flow conductivity
Stagnant flow	→	14 improvement measures to improve the flow conductivity
		9 measures to improve the utilization rates

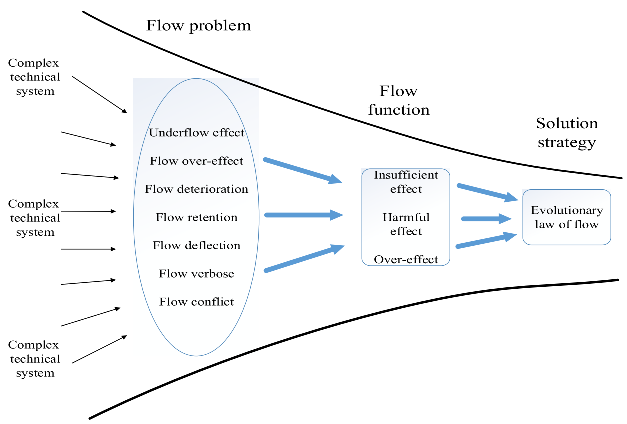


FIGURE 4. Schematic showing the process of the flow evolution rules solution strategy.

strategy analyze the changes in the subsystem or the local structure to improve the problematic flow in order to transform it into a normal flow and achieve normal functions. Based on the partial improvement of the system, the TRIZ theory proposes nine product technology evolution laws and multiple technology evolution routes [33], which can be used to predict the future development direction of the system and realize improvement and innovation of the entire system or its subsystem. Because technological evolution will inevitably lead to essential changes in the utilization or attributes of the flows in the system [34], based on the above two solution strategies and combined with the analysis of the types and attributes of the flow, a technology-driven evolution approach has been proposed in this study, as summarized in Table 5.

TABLE 5. Technology-driven evolution solution strategy.

Evolution scheme	Description of scheme	Scheme route
scheme 1	Improve the level of idealization	1–1 Improve the functional conversion of the output flow 1–2 Reduce useless flow
scheme 2	Eliminate imbalances between flows	2–1 Improve flow utilization
scheme 3	Dynamic growth to meet the needs of new performance, new environmental conditions, and new functions	3–1 Evolution to continuously changing system flows 3–2 Evolution to adaptive flow 3–3 Evolution to fluid or field
scheme 4	Evolve to complex flows	4–1 Increase the diversity of flow
scheme 5	Toward flow evolution under microscopic systems	5–1 Under the condition of meeting normal functions, replace the original flow carrier with a smaller flow carrier
scheme 6	Increase the integrity of the flow	6–1 Integrity Route (Reduction of human intervention route)
scheme 7	Shorten the energy flow path length	7–1 Number of stages with less energy transfer 7–2 Increase the controllability of energy flow
scheme 8	Increase the controllability of the flow	8–1 Increase the adjustable flow
scheme 9	Increase the coordination of the flow	9–1 Adopt function-time dynamics process

D. PROCESS MODEL CONSTRUCTION FOR THE JUDGMENT AND SOLVING STRATEGY OF FLOW PROBLEMS IN COMPLEX ENGINEERING SYSTEM

Based on the above analysis, a process model for the judgment and solution strategy of flow problems in the complex engineering system has been established, which consists of 2 stages and 14 steps.

Phase 1: Judgment of the flow problems in a complex engineering system.

Step 1: Select the complex engineering system and perform its functional decomposition.

Step 2: Determine the material resources, energy resources, and information resources based on the resource analysis of the system.

Step 3: Analyze the flow of the system to determine the material flow, energy flow, and information flow of the system.

Step 4: By constructing the material flow, energy flow, and information flow transfer and transformation models, generate the total flow transfer and transformation model of the system by summarizing.

Step 5: Build a personal coloring set, $F(a)$, of flow attributes and a contour matrix, $[F(a) \times F(A)]$, of flow attributes and flow types.

Step 6: Establish a set, A, of research objects (flows).

Step 7: Based on the personal coloring set, $F(a)$, of the flow attributes, establish the contour matrix, $[A \times F(a)]$, of the flow and its attributes.

Step 8: Based on the contour matrix, $[F(a) \times F(A)]$, of the flow attributes and flow types, obtain the contour matrix, $[A \times F(A)]$, of the flow and the flow types by performing conjunctive and XNOR operations on the matrices.

Step 9: Determine the flow problems existing in the system based on the contour matrix, $[A \times F(A)]$, and judge whether the extraction process of the flow problems is perfect or not.

Step 10: Summarize and get a list of the flow problems.

Phase 2: Solving the flow problems.

Step 11: Depending on the actual project needs, choose to adopt a partial system improvement or overall system optimization.

Step 12: Adopt the extenics theory solution strategy and the flow evolution rules solution strategy in turn for the local improvement of the system. After the solution of either of the solution strategies is completed, choose to either adopt another solution strategy and judge whether the flow problem is solved.

Step 13: For the overall system optimization, adopt the technology-driven evolution to analyze and judge whether the solution process is comprehensive.

Step 14: Obtain the total solution scheme by summarizing the above solutions.

The process for the judgment of the flow problem and the solution strategy model for the complex engineering system are shown in Figure 5.

IV. ENGINEERING CASE

A. PROJECT BACKGROUND OVERVIEW

As the key equipment for resource exploration drilling rig automation, the tubular feeding machine (TFM) can realize the functions of a pick-up drilling tool and a lay-down drilling tool. At present, many such equipment are being used at well sites [35]. The TFM considered in this study is a device used for ocean-going ship platform operation, which is used for transporting pipes and materials from the pipe storage area (PSA) to the drill floor (DF) of a large-scale integrated marine resources survey ship and vice versa. The pipe from the PSA is placed on the TFM by a crane, and the TFM transports it to the operating well. Using the centralizer arm, the TFM can also straighten the pipe to the center of the well (WC) for easy connection.

B. PROJECT ANALYSIS

1) THE FUNCTION AND COMPOSITION OF THE SYSTEM

The function of the TFM system involves transporting tubulars and materials from the PSA to the DF and vice versa.

The TFM system and the super-system include the following components: S1 (skate), S2 (rail), S3 (roller), S4 (shuttle), the skate driving system (S5 (skate driving motor), S6 (gear 1), S7 (gear 2), S8 (drag chain), S9 (encoder 1)), the shuttle drive system (S10 (encoder 2), S11 (shuttle driving motor), S12 (slave sprocket), S13 (sprocket), S14 (chain)), the centralizer arm assembly system (S15 (holding rod), S16 (finger), S17 (main arm), S18 (auxiliary arm)), the hydraulic system (S19 (holding rod cylinder), S20 (finger cylinder), S21 (main arm cylinder), S22 (auxiliary arm cylinder)), the action object of the TFM system, S23 (pipe), and the information recipient, S24 (manipulator).

Figure 6 shows the components that make up the TFM system. Figure 6(a) shows the components of the entire system, the components of the centralizer arm assembly, and the components of the shuttle drive system, whereas Figure 6(b) shows the components of the skate drive system.

2) WORKING PRINCIPLE

The working process of the TFM system is divided into two processes: the pick-up operation and the lay-down operation. Figure 7 shows a schematic of the pick-up operation. During this operation, a crane is used to place the pipe slowly on the TFM system, control the skate to move forward, and send the pipe to the WC. Subsequently, the shuttle moves forward, the threaded end (male thread) of the pipe is lifted, and the flange end (female thread) follows the shuttle. Then, the secondary arm of the centralizer arm is opened, and after the pipe tool touches the finger, the main arm is controlled to lift. The auxiliary lifting system helps the pipe to the WC and uses the holding rod to fine-tune the pipe to the buckle. Finally, the fingers are opened, the holding rod and the main arm are retracted, and the skate is evacuated from the DF.

The sequence of the lay-down operation is the exact opposite of the pick-up operation and thus will not be described again. As shown in Figure 8, at a certain instance of the lay-down operation, the centralizer arm is extended, the finger and the holding rod work together, and the flange end (female thread) of the pipe is put into the shuttle.

C. FLOW ANALYSIS OF THE TFM SYSTEM

1) FUNCTIONAL DECOMPOSITION OF THE TFM SYSTEM

Based on the total function of the TFM system, the functional decomposition of the system has been done as shown in Figure 9.

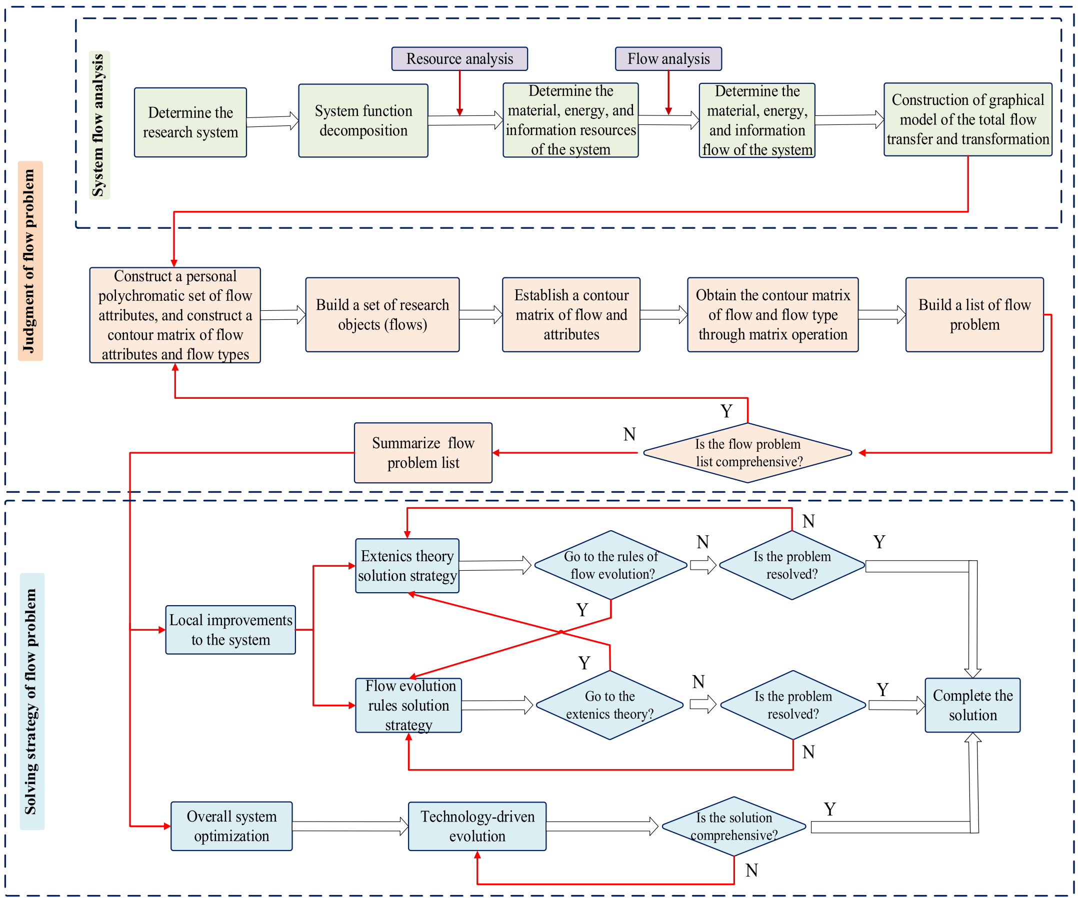


FIGURE 5. Process model for the judgment of the flow problem and the solution strategy for a complex engineering system.

TABLE 6. Resource analysis of the TFM system.

Resource classification	Resource list
Material resources	system components, power and hydraulic lines, system support frame, pipes
Energy resources	electric energy, thermal energy, mechanical energy, gravitational potential energy, magnetic field energy, joule heat
Information resources	pipes transport effect, pipes clamping effect, pipes installation effect, and running effect of encoder programming

2) RESOURCE ANALYSIS OF THE TFM SYSTEM

Analyze the resources of the TFM system, as classified as given in Table 6.

TABLE 7. Flow analysis of the TFM system.

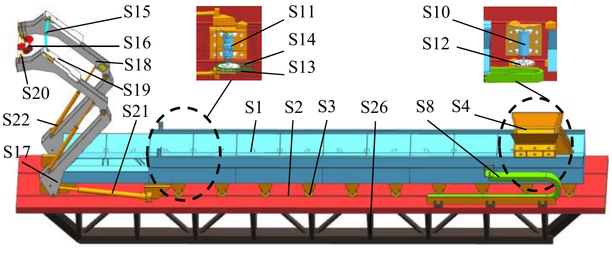
Flow classification	The flow of the system
Material flow	pipes
Energy flow	electric energy, thermal energy, mechanical energy, gravitational potential energy, magnetic field energy, joule heat
Information flow	pipes transport effect, pipes clamping effect, pipes installation effect, and running effect of encoder programming

3) FLOW ANALYSIS

Depending on the results of the resource analysis of the system, the flow analysis of the TFM system has been done, as given in Table 7.

4) CONSTRUCTION OF A GRAPHICAL MODEL OF FLOW TRANSFER AND TRANSFORMATION IN THE TFM SYSTEM

Based on the resource analysis and flow analysis of the TFM system, a schematic model of the material flow transfer and transformation of the TFM system is obtained, as shown in



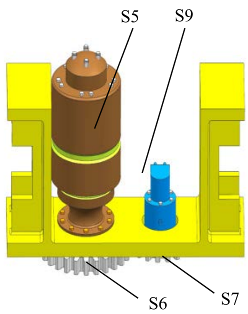


FIGURE 6. **The main components of the TFM system. (a) shows the components of the centralizer arm assembly and the components of the shuttle drive system, whereas (b) shows the components of the skate drive system.**

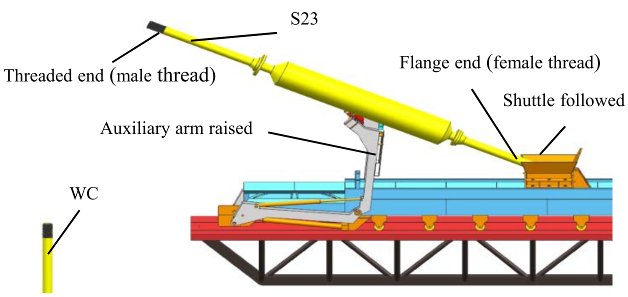


FIGURE 7. **Schematic showing a typical pick-up operation.**

Figure 10. The process of model establishment in the case of energy flow and information flow transfer and transformation is similar to that for the material flow. The material flow, energy flow, and information flow transfer and transformation graphical model of the system is synthesized, and the overall transfer and transformation graphical model of the TFM system is obtained, as shown in Figure 11.

D. JUDGMENT OF THE TFM SYSTEM FLOW PROBLEM

Based on the flow analysis of the TFM system, the existing flows, namely, the material flows: $A = \{a_1, a_2, a_3, a_4, a_5\}$, the energy flows: $B = \{b_1, \cdots, b_{28}\}$, and the information flows: $C = \{c_1, c_2, c_3, c_4, c_5\}$ in the system are determined.

Taking energy flow as an example and combined with the application feedback of the company on the TFM system, the flow problem judgment process of the TFM system is as follows:

Step 1: Construct a contour matrix, $[B \times F(b)]$, of the relationship between the energy flow and its attributes. Its calculation results have been given in Table 8.

Step 2: Construct a contour matrix, $[F(b) \times F(B)]$, of the energy flow attributes and flow types. The calculation results thus obtained have been given in Table 9.

Step 3: The contour matrix $[B \times F(B)]$ of the energy flow and the flow types can be calculated using Equation (9), and the results thus obtained have been given in Table 10.

By analyzing the data given in Table 10, it has been found that the energy flow, b_9, is a stagnant flow; b_{14} is an insufficient flow, b_{16}, b_{17}, and b_{18} are excessive flows; b_{19}, b_{21}, b_{22}, b_{25}, and b_{26} are conflicting flows.

Step 4: Similar to the judgment of the energy flow problem described in the previous three steps, the judgment results for the flow problem of material flow and information flow can be obtained. Combined with the singular working conditions encountered by the enterprise during actual operations, the actual manifestation of the flow problems is obtained, as given in Table 11.

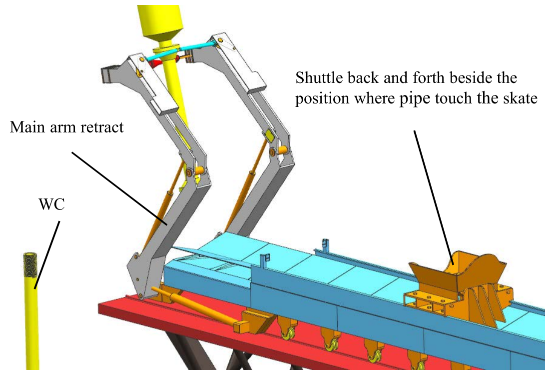


FIGURE 8. **Schematic showing a typical lay-down operation.**

E. SOLUTION OF THE FLOW PROBLEMS

Based on the manifestations of the main flow problems of the TFM system listed in Table 11, 11 flow problems were classified into four different forms of expressions to solve the problems, namely b_9, b_{14}, b_{16}-b_{17}-b_{18}, b_{19}-b_{21}-b_{22}-b_{25}-b_{26}, c_4. Due to limitations on the length of the article, taking the flow problems b_{19}-b_{21}-b_{22}-b_{25}-b_{26} as an example, the three methods of using the extenics theory, the flow evolution rules, and the technology-driven evolution were used to solve the flow problem in order to find the optimal solution idea of the flow problem and guide the innovative design of the TFM system.

1) EXTENICS SOLUTION

The analysis of the flow conflict problem generated by b_{19}-b_{21}-b_{22}-b_{25}-b_{26} has been described in this subsection. When the centralizer arm is extended without load, the main arm cylinder pushes the main arm to extend, and the auxiliary

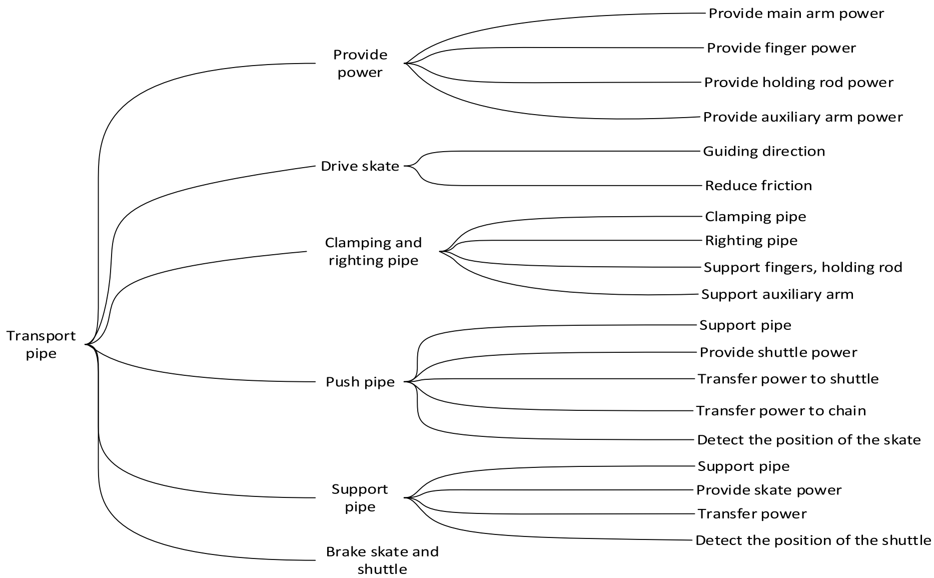


FIGURE 9. Functional decomposition of the TFM system.

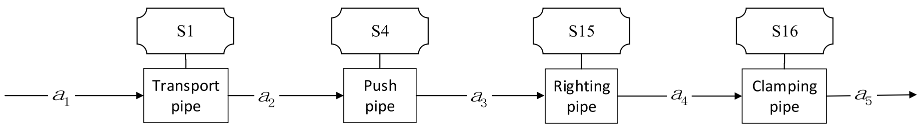


FIGURE 10. Material flow transfer and transformation model for the TFM system.

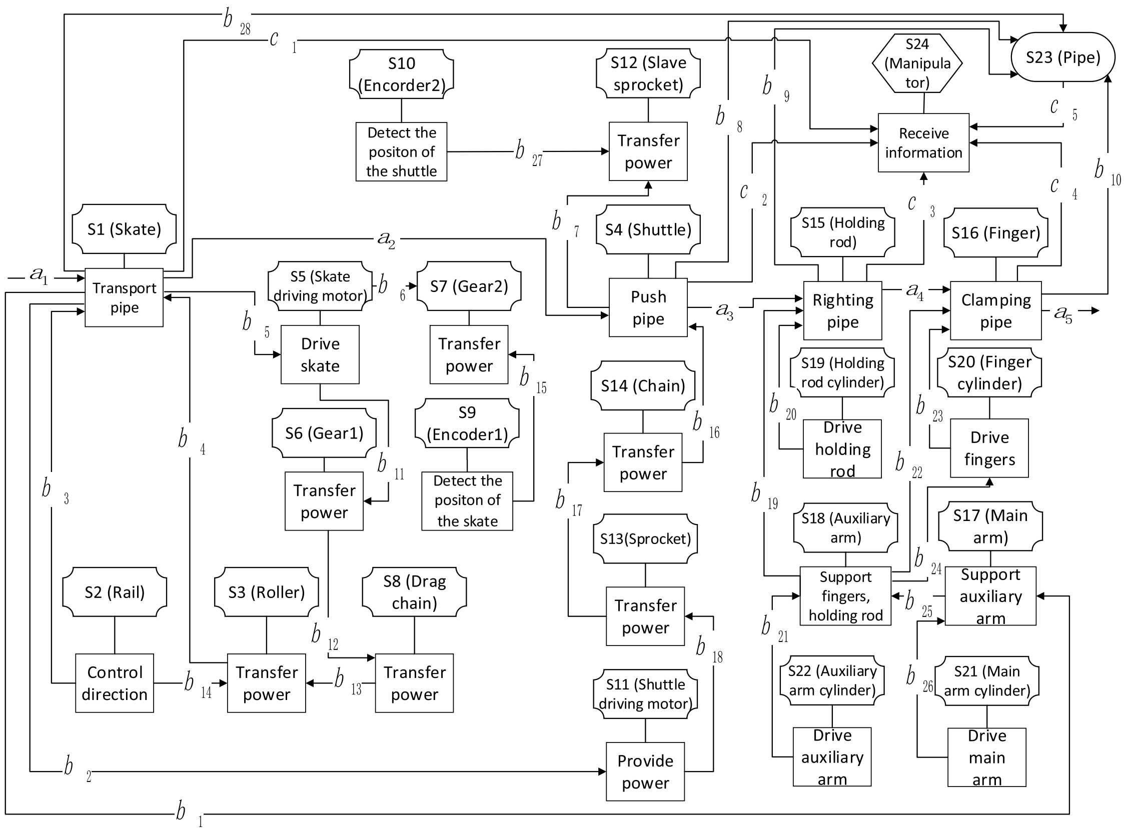


FIGURE 11. The complete model of flow transfer and transformation for the TFM system.

arm cylinder pushes the auxiliary arm to extend. If the speed is too fast, due to the inertia of the centralizer arm, when the cylinder starts to push and when the limit position is braked, the direction of the force of the cylinder

TABLE 8. Contour matrix of the relationship between the energy flow and its attributes (The key determinants have been marked by red color in the matrix).

f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}	f_{11}	f_{12}	f_{13}	
1	0	1	0	0	1	1	0	0	1	0	0	0	b_1
1	0	1	0	0	1	1	0	0	1	0	0	0	b_2
1	0	1	0	0	1	1	0	0	1	0	0	0	b_3
1	0	1	0	0	1	1	0	0	1	0	0	0	b_4
1	0	1	0	0	1	1	0	0	1	0	0	0	b_5
1	0	1	0	0	1	1	0	0	1	0	0	0	b_6
1	0	1	0	0	1	1	0	0	1	0	0	0	b_7
1	0	1	0	0	1	1	0	0	1	0	0	0	b_8
0	0	0	0	0	0	0	1	0	0	0	0	1	b_9
1	0	1	0	0	1	1	0	0	1	0	0	0	b_{10}
1	0	1	0	0	1	1	0	0	1	0	0	0	b_{11}
1	0	1	0	0	1	1	0	0	1	0	0	0	b_{12}
1	0	1	0	0	1	1	0	0	1	0	0	0	b_{13}
1	0	1	0	1	0	1	0	0	1	0	0	0	b_{14}
1	0	1	0	0	1	1	0	0	1	0	0	0	b_{15}
1	0	0	1	0	1	1	0	0	1	0	0	0	b_{16}
1	0	0	1	0	1	1	0	0	1	0	0	0	b_{17}
1	0	0	1	0	1	1	0	0	1	0	0	0	b_{18}
0	0	1	0	0	0	1	0	0	1	0	0	0	b_{19}
1	0	1	0	0	1	1	0	0	1	0	0	0	b_{20}
0	0	1	0	0	0	1	0	0	1	0	0	0	b_{21}
0	0	1	0	0	0	1	0	0	1	0	0	0	b_{22}
1	0	1	0	0	1	1	0	0	1	0	0	0	b_{23}
1	0	1	0	0	1	1	0	0	1	0	0	0	b_{24}
0	0	1	0	0	0	1	0	0	1	0	0	0	b_{25}
0	0	1	0	0	0	1	0	0	1	0	0	0	b_{26}
1	0	1	0	0	1	1	0	0	1	0	0	0	b_{27}
1	0	1	0	0	1	1	0	0	1	0	0	0	b_{28}

on the centralizer arm will suddenly change, causing flow conflicts; thus, leading to the obvious shaking of the centralizer arm. This problem can be expressed in extension canonicalization as:

$R_{b19+b21+b22+b25+b26}$ = (The mechanical energy of the cylinder of the centralizer arm, mechanical energy, conflicting).

Therefore, the characteristic of scalability of the primitive element in the extenics theory can be applied to improve the positive effect of the support force of the centralizer arm, eliminate the reverse effect, and propose the following solution: A set of springs are added between the skate and the main arm cylinder and inside the main arm cylinder. When the centralizer arm starts to operate or reaches the limit position,

TABLE 9. **Contour matrix of the energy flow attributes and the flow types (The key determinants have been marked by red color in the matrix).**

F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	
1	1	1	1	0	1	1	0	f_1
0	0	0	0	0	0	0	1	f_2
1	0	0	1	0	1	1	1	f_3
0	0	1	0	0	0	0	0	f_4
0	1	0	0	0	0	0	0	f_5
1	1	1	1	0	1	1	1	f_6
0	0	0	0	1	0	0	0	f_7
0	0	0	0	0	0	0	0	f_8
1	1	1	1	0	0	1	1	f_9
0	0	0	0	0	1	0	0	f_{10}
0	0	0	0	0	0	1	0	f_{11}
0	0	0	0	1	0	0	0	f_{12}
0	0	0	1	0	0	0	0	f_{13}

the elastic force of the spring is opposite to the opening direction of the arm, and thus the flow conflict caused by the energy flow in the limit position is weakened and the jittering caused by the impact force is eliminated when the centralizer arm is at the limit position.

Figure 12 shows a schematic of the design of the spring at the retraction limit position, and Figure 13 shows a schematic of the design of the spring at the extension limit position.

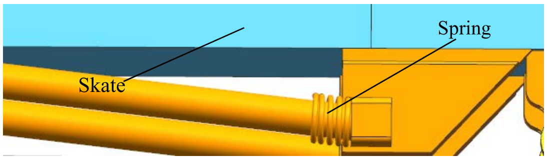


FIGURE 12. **Design of the spring in the retraction limit position.**

2) FLOW EVOLUTION RULES SOLUTION

By analyzing the channel of the energy flow b_{19}-b_{21}-b_{22}-b_{25}-b_{26} causing the flow conflict problem, it was found that the problem can be solved by changing the flow channel to avoid the conflicting area. 18 improvement measures for reducing or eliminating the harmful effect of the flow in the flow evolution law [5] were adopted, and the fifth item was selected to increase the length of the flow. The specific measures were as follows: another set of centralizer arms (forearms) and forearm cylinder was added to the auxiliary arm to form a reverse z-shaped centralizer arms structure, which could increase the operating range of the centralizer arms and widen the length of the energy flow of the centralizer arms so that the corresponding function could be realized

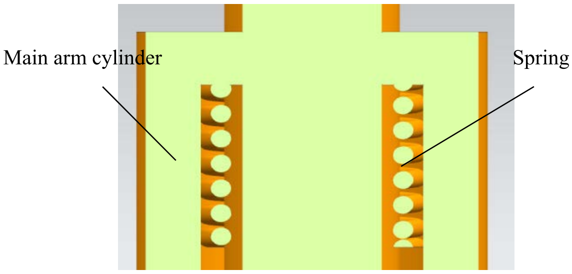


FIGURE 13. **Design of the spring in the extension limit position.**

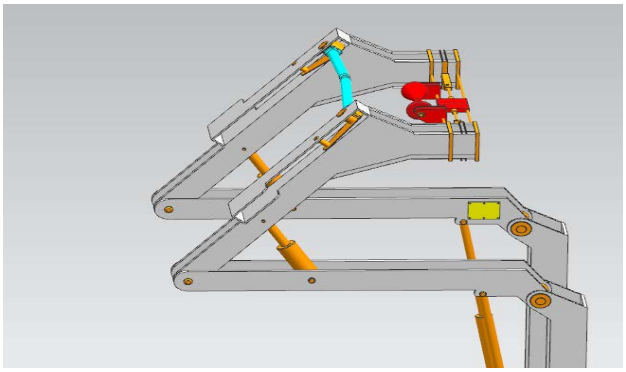


FIGURE 14. **Schematic of the improved centralizer arm structure.**

TABLE 10. Contour matrix of energy flow and flow type.

F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	
1	0	0	0	0	0	0	0	b_1
1	0	0	0	0	0	0	0	b_2
1	0	0	0	0	0	0	0	b_3
1	0	0	0	0	0	0	0	b_4
1	0	0	0	0	0	0	0	b_5
1	0	0	0	0	0	0	0	b_6
1	0	0	0	0	0	0	0	b_7
1	0	0	0	0	0	0	0	b_8
0	0	0	0	1	0	0	0	b_9
1	0	0	0	0	0	0	0	b_{10}
1	0	0	0	0	0	0	0	b_{11}
1	0	0	0	0	0	0	0	b_{12}
1	0	0	0	0	0	0	0	b_{13}
0	1	0	0	0	0	0	0	b_{14}
1	0	0	0	0	0	0	0	b_{15}
0	0	1	0	0	0	0	0	b_{16}
0	0	1	0	0	0	0	0	b_{17}
0	0	1	0	0	0	0	0	b_{18}
0	0	0	0	0	0	0	1	b_{19}
1	0	0	0	0	0	0	0	b_{20}
0	0	0	0	0	0	0	1	b_{21}
0	0	0	0	0	0	0	1	b_{22}
1	0	0	0	0	0	0	0	b_{23}
1	0	0	0	0	0	0	0	b_{24}
0	0	0	0	0	0	0	1	b_{25}
0	0	0	0	0	0	0	1	b_{26}
1	0	0	0	0	0	0	0	b_{27}
1	0	0	0	0	0	0	0	b_{28}

when the centralizer arms do not reach the limit position. The new forearms structure has been shown in Figure 14.

3) TECHNOLOGY-DRIVEN EVOLUTION SOLUTION

By analyzing the transfer and transformation forms of the energy flows b_{19}-b_{21}-b_{22}-b_{25}-b_{26} of the TFM system, it was found that there is excessive rigidity in the transmission between the structures that make up the machinery, which leads to the sudden change in the transmission of the energy flow in the system due to the rigid transmission between the components. This results in energy flow problems, eventually leading to the problems such as getting stuck, jittering, and rough operation. Therefore, the solution route 3–2 of the flow evolution solution driven by the technological evolution

TABLE 11. A list of the different flow problems and manifestations.

Problematic flows	Flow types	Flow problems	Manifestations
b_9	Stagnant flow	Retention	The range of centralizer arm clamping pipe is limited, can only be clamped in the WC position, and the pipe cannot be clamped during the flat to vertical position.
b_{14}	Insufficient flow	Insufficient effect	The rollers are in poor contact with the rails.
b_{16}	Excessive flow	Over-effect	The shuttle is prone to jitter when walking in a working state.
b_{17}	Excessive flow	Over-effect	
b_{18}	Excessive flow	Over-effect	
b_{19}	Conflicting flow	Conflict effect	The jitter is obvious when the centralizer arm extends out more quickly without load.
b_{21}	Conflicting flow	Conflict effect	
b_{22}	Conflicting flow	Conflict effect	
b_{25}	Conflicting flow	Conflict effect	
b_{26}	Conflicting flow	Conflict effect	
c_4	Conflicting flow	Conflict effect	Fingers are easily blocked by the righting arm when holding the pipe, which affecting the operator's judgment of the operation.

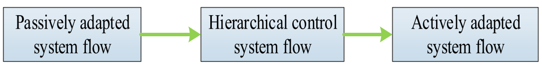


FIGURE 15. Evolution to an adaptive system flow.

mentioned in Table 5, namely, adaptive system evolution to flow, as shown in Figure 15, can be selected to solve the flow problem.

FIGURE 16. A buffer design added to the retracted limit position of the centralizer arm.

According to the flow evolution route, flexible system components and sensing system components are added to the TFM system with the design improvement, which enables the flow transmission of the system to be gentle, thus eliminating the flow conflict caused by the drastic change in the flow and damage to the components. In this study, adding a polyurethane buffer at the limit position of the retraction of the centralizer arm, as shown in Fig. 16, enabled the energy flow transfer to have a flexible flow mode during the transfer process and could efficiently reduce the jitter phenomenon of the centralizer arm when the retracting speed was fast.

V. CONCLUSION

Compared to the existing studies, the main contributions of the current research can be summarized as follows:

(1) A judgment method for flow problems in complex engineering systems was proposed. On the basis of constructing a model that can simply and clearly express the transfer and transformation process of the system flow, the attributes of the material flow, energy flow, and information flow were categorized, and the polychromatic sets theory was introduced to perform the contour matrix and conjunctive XNOR operation in order to determine and calculate the relationship between the flow attributes, the flow types, and the flows of the complex technical system, and also determine the flow problems existing in the system.

(2) A process model for determining and solving strategies for complex engineering system flow problems was constructed. Depending on the manifestation of flow problems in the system, from the microscopic and macroscopic dimensions, three strategies for solving flow problems based on the extensics theory, flow evolution law, and technology-driven evolution were proposed. Combined with the flow problem judgment method, the flow problem determination and solution strategy process model for a complex engineering system were established. The feasibility of the research theory was verified using the TFM system of a large integrated marine resource survey ship, and an innovative scheme

was obtained, which was recognized by the cooperative enterprises.

VI. DISCUSSION

However, this study has certain limitations. On the one hand, the operation state of the complex engineering system has not been discussed in-depth, which leads to the neglect of changes in the material flow, energy flow, and information flow caused by the working environment when analyzing the flow of the system. On the other hand, due to constraints on the length of the paper, the timeliness of the judgment and solution of the flow problem has been insufficiently explored in this study. In the process of flow analysis, flow problem judgment, and flow problem solving of complex engineering systems, the more thorough the analysis is, the more beneficial it is to solve the problem, but it also indicates that the calculation is more complex. Therefore, the designers' thinking needs to rely on the powerful computing power of the computer software in order to have a better application effect on practical cases. Furthermore, the solution of the flow problem is an iterative process. Along with the solution of the flow problem, new hidden flow problems that are difficult to identify can be generated. Constructing a time-to-time dynamic model comprising the flow analysis, flow problem judgment, and flow problem solving, and further systematically excavating the hidden flow problems and proposing solutions is the direction of future research.

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JIANHUI ZHANG received the master's and Ph.D. degrees in mechanical manufacturing and automation from the Hebei University of Technology, China, in 2015 and 2019, respectively. He is currently a Professor with the Faculty of Mechanical Engineering and the Director of the National Engineering Research Center for Technological Innovation Method and Tool, High-Value Patent Innovation Research Institute, Hebei University of Technology, China. He has published more than 60 articles and coauthored three books. His research interests include TRIZ, innovative design of the complex technology systems, computer aided design manufacturing, and bionic design. He is the Expert Committee of the *International Journal of Mechanical Engineering Science* (IJMES).

JIANYONG LI received the master's degree in mechanical manufacturing and automation from the Hebei University of Technology, China, in 2022. He has some articles in his research areas. His research interests include TRIZ, innovative design of the complex technology systems, and flow analysis.

XUEJIE PU received the master's degree in mechanical manufacturing and automation from the Hebei University of Technology, China, in 2022. He has some articles in his research areas. His research interests include TRIZ, innovative design of the mechatronic product, and complex conflict solving.

XUERUI WANG received the master's degree in mechanical manufacturing and automation from the Hebei University of Technology, China, in 2020. He is currently an Assistant Engineer with Treolica (Tianjin) Company Ltd., and has work experience in the machinery manufacturing industry for two years. His research interests include complex product design methodology and product service systems.