A Causal Chain Analysis Method of Design Problems Using Extenics and LT Dimension

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Abstract. It is a prerequisite to accurately understand design problems before searching for solutions to the problems. The causal chain analysis in the Theory of the Solution of Inventive Problems (TRIZ) provides an effective way to find the root cause of problems. However, the existing causal chain analysis process lacks expansiveness and logic, which limits the root cause mining. A problem causal chain analysis method is proposed in this paper based on the fusion of extenics and length time (LT) dimensions. Causes at each tier of the causal chain are expressed using an extenics model. Physical parameters are described by the LT dimension. Causes at the same tier are extended by a dimension multiplication method. Causes at the next tier are mined by effects corresponding to the LT dimension. Parameter modification or TRIZ conflict tools are used to solve the problem of the key root cause. A complete process from the problem analysis to solutions is formed. The method is illustrated in the design of a beam oil pumping machine. The effectiveness of the method is verified.

Keywords: Causal Chain Analysis, Extenics, LT Dimension, TRIZ
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1 INTRODUCTION

Innovative product design is a continuous evolution process. As a product system continues to improve, the accurate identification of causes of problems is a prerequisite for generating innovative solutions [15-16]. The causal chain analysis is a key tool of the theory of the solution of inventive problems (TRIZ) to identify systematic problems [20]. It identifies the true cause of a problem to eliminate the cause. A cause is a condition or event that makes a problem appear. The problem often occurs as a result of the combination of causes at multiple tiers. From the perspective of cause tiers, causes are divided into direct, intermediate, and root causes to form a causal chain, as shown in Figure 1. For the initial problem or the appearance of the problem, the designer finds defects in a design process or deficiencies in the use of the product raised by the user with measurable and sensory. For the direct cause, the first tier of cause in the causal chain is obviousness. It is similar to the initial problem observed, but it exists in a sequential logical order and at the entry point for the entire causal chain analysis process, which is usually not actionable and requires the further analysis. For the intermediate causes, the second tier to N-1 causes of causal chain, between direct and root causes, is obtained by step-by-step analysis. For the root cause or the Nth tier cause, the key tier cause is for solving the problem. The 'and' and 'or' structure is used to represent the relationship between hierarchical causes [25].

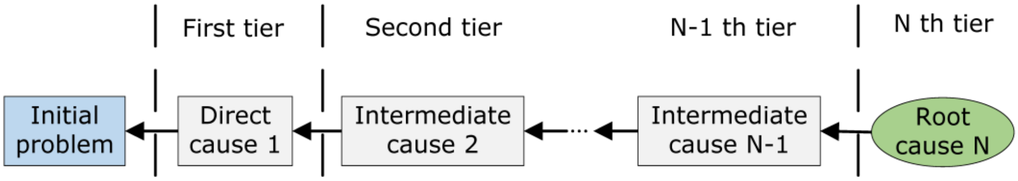

Figure 1: Different tiers of cause.

Research on the causal chain analysis has been conducted in theoretical developments and practical applications. In terms of theoretical studies, Sun [18] identified key causes based on the percentage of weight of each tier of causes for solving the initial problem. Lee [10] analyzed root causes along with beneficial effects of each cause from a problem-solving perspective. But the expression of causes makes the causal chain analysis limited by thinking. Although extenics has been incorporated into the causal chain analysis to improve the expression of causes [1], it lacks a systematic approach to root cause mining.

For practical applications, Jawwad [8] developed a Drain-Pipe-Diagram causal chain representation method to discern the type of causes based on the pipe diameter and color, which is applied to the extrusion process of metals. Swee [19] used the causal chain analysis to find the root cause of the e-waste generation. Hu [7] used the current reality tree to describe problems of the design process and explore the poor ability of sheet metal crimping operations according to the causal chain analysis process. Cui [3] used root cause mapping to analyze essential factors of the conflict.

A system or component in the system has a certain property. The purpose of causal chain analysis is to determine the root cause of the problem and the problematic parameters of component corresponding to the root cause. It is therefore a key to effectively represent the problematic parameters of a component, and mining properties in the causal chain analysis. In order to make the causal chain analysis process expandable and logical, this research proposes a causal chain analysis process model that integrates the extenics [14] and length time (LT) [2] dimension. Problems of the component or problem attribute representation are solved by expressing the root cause in an extenics model, in which each object element can express multiple features and their values [13] The LT dimension and the corresponding effects database are used for the extension or mining of object features in the extenics model to assist in the establishment of a causal chain. This solves the difficult causal chain analysis in the form of expression of the causal chain and root cause mining.

Following parts of the paper are organized as follows. Section 2 introduces steps of the proposed method including the extenics causal chain, LT dimension characteristics of object elements, causal chain analysis process, solving root causes, and solution evaluation. Section 3 presents the design process of a beam oil pumping machine to verify the effectiveness of the proposed method. Section 4 summarizes the paper and suggests the future work.

2 PROPOSED METHOD

The causal chain analysis concept of the proposed method in this research is shown in Figure 2. The existing problems of a product are first identified. The causal chain analysis is then assisted based on extenics, LT dimension and its corresponding effects database. The oval-shaped wireframe in Figure 2 indicates that the cause can be represented and mined by the extenics model and LT dimension. For other parts of the causes, the linguistic description is used. Based on the type of root causes, the parameter changes or conflict resolution [24] is applied in the TRIZ tool.

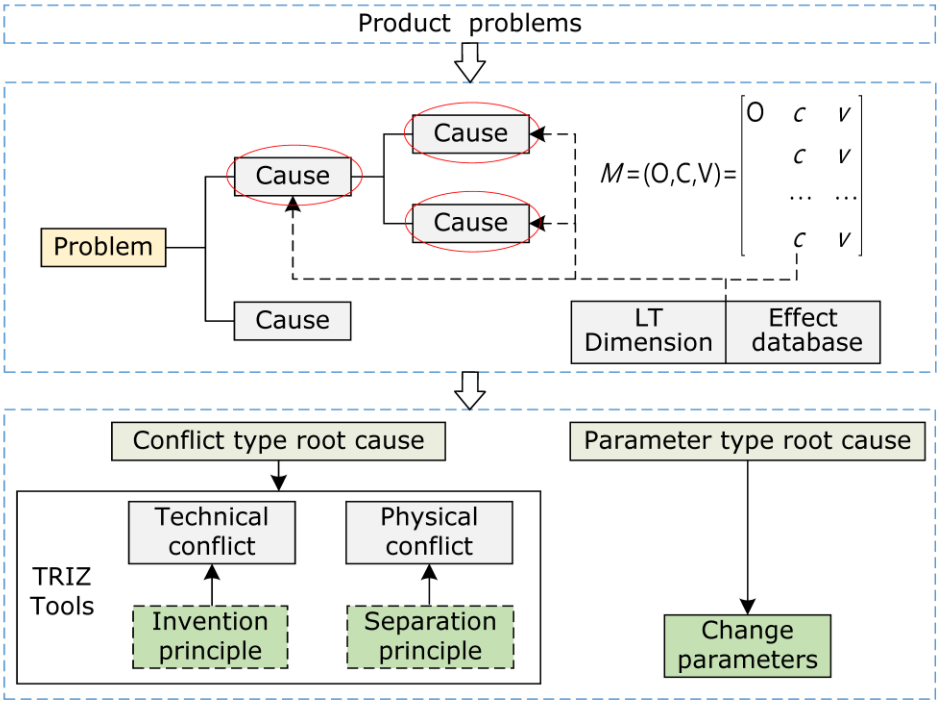

Figure 2: Causal chain analysis concept of the proposed method.

2.1 Extenics Causal Chain

Extenics is a formal method of describing things and objects in the objective world. It is used to analyze the possibility of expansion of things and objects, and the law of expansion innovation, which has the characteristics of simplicity, unity and ease of use [11, 23]. The core of topology is the primitive theory, extenics set theory and extenics logic theory. Its main idea is to express things, relations, and information through the extenics model, study the possibility of expansion, and establish a set of reasoning methods to solve problems. The extensible transformation is the core of the extenics, while the extensible analysis is the prerequisite for the implementation of the extensible transformation, and its depth and breadth determine the effectiveness of the extensible transformation. Multiple contextual functional elements can be explored along different pathways through the extensible relationships to achieve a divergent thought process [12, 21]. The algorithm of extenics contains the plus and minus of object elements, to multiply and divide of object elements, plus and minus of things, multiply and divide of things, plus and minus of relations, and multiply and divide of relations [17]. The causal chain analysis of the problem explores the hidden root causes, which is consistent with extenics searching for hidden object element characteristics. Therefore, this research uses the extenics model to express the cause by multiplying and dividing object element rules to mine the root cause. The extenics model is shown in Equation (1).

$$M_{ij}=(O_{ij} \quad C_{ij} \quad V_{ij})=\begin{bmatrix} O_{ij} & c_{ij1} & v_{ij1} \\ & c_{ij2} & v_{ij2} \\ & \dots & \dots \\ & c_{ijn} & v_{ijn} \end{bmatrix} \tag{1}$$

where, M_{ij} is the j th cause in the i th tier. O_{ij} is an object element, C_{ij} is its characteristics, and V_{ij} is its value, they form a triad. C_{ij} includes n characteristics $c_{ij1}, c_{ij2}, \dots, c_{ijn}$, and c_{ijk} corresponding value v_{ijk}.

An extenics model is used to represent the causes, describe the causes' parameters and mine other parameters. The application of Equation (1) in the process of causal chain analysis is illustrated by the example of gear, as shown in Equation (2). The gear is used as one of the causes in the causal chain analysis, the characteristics and value related to the gear are expressed using the extenics model. Other characteristics are obtained through the analysis as derived causes at the same tier or the next tier.

$$M_{ij}=\begin{bmatrix} \textit{Gear} & \textit{Hardness} & \textit{Small} \\ & \textit{Pitch circle diameter} & \textit{30} \\ & \textit{Gear width} & \textit{10} \\ & \textit{Pressure angle} & \textit{20} \end{bmatrix} \tag{2}$$

2.2 LT Dimension for Characteristics of Object Element

In physics, a dimension is the basic property of a physical quantity. Physical quantities are divided into two categories: fundamental quantities and derived quantities. The number of fundamental quantities changes in different applications. The international system of units has seven fundamental quantities. In the Gaussian system of units there are three fundamental quantities: length (L), mass (M) and time (T) [5]. To simplify expressions and calculations, the British physicist Maxwell first proposed the idea of using only two fundamental quantities, but no practical progress was made [9]. Inspired by this, Bartini used mathematical tools to deduce and experimentally prove that the 2 dimensions of both mass and power is L^3T^{-2} [4]. Dimension operations follow rules of index operations in mathematics. For example, the dimension of velocity in the Gaussian unit system is $L^{-2}M^1T^1$, which becomes L^1T^{-1} after converting it into 2 dimensions. Similarly, parameters of physical quantities in different fundamental quantity systems can be converted into the form of LT dimension. The LT dimension is shown in Table 1 [22]. The effect corresponding to the LT dimension and physical quantity can be searched in the effect database of LT dimension for the causal chain analysis, as shown in Table 2. The characteristics of the object element are represented by dimensions in Equation (1), which can be expanded by the effect database to uncover root causes of the causal chain.

Dime-nsion	L^{-2}	L^{-1}	L^0	L^1	L^2	L^3	L^4	L^5
T^{-6}					L^2T^{-6}	L^3T^{-6}	L^4T^{-6}	L^5T^{-6}
T^{-5}				L^1T^{-5}	L^2T^{-5}	Refractiv eindex	L^4T^{-5}	Power
T^{-4}			L^0T^{-4}	Gravity/ Pressure gradient	Pressure	Rigidity/ Surface tension	Force	Work/ Energy/ Momentum/ Temperature
T^{-3}			L^0T^{-3}	Current density	Magnetic field intensity/ Viscosity	Current	Imp-ulse	Angular momentum/ Impulsive moment

Dimension	L^{-2}	L^{-1}	L^{0}	L^{1}	L^{2}	L^{3}	L^{4}	L^{5}
T^{-2}		$L^{1}T^{-2}$	Mass density/ Angle acceleration	Line acceleration	Voltage	Mass/ Electricity	$L^{4}T^{-2}$	Rotational inertia
T^{-1}	$L^{-2}T^{-1}$	Volume charge density	frequency/ Angular velocity	Line speed	Area change rate	Volume change rate	$L^{4}T^{-1}$	$L^{5}T^{-1}$
T^{0}	$L^{-2}T^{0}$	Curvature conductivity	Angle/ Radian	Length/ Capacity	Area	Volume	Area inertial moment	Volume inertial moment
T^{1}	$L^{-2}T^{1}$	Resistance	Cycle/ Resistivity	$L^{1}T^{1}$	$L^{2}T^{1}$	$L^{3}T^{1}$		
T^{2}	Permeability	Self-induced /Mutual inductance	$L^{0}T^{2}$	$L^{1}T^{2}$	$L^{2}T^{2}$			
T^{3}	$L^{-2}T^{3}$	$L^{-1}T^{3}$	$L^{0}T^{3}$	$L^{1}T^{3}$				

Table 1: LT dimension part of the content.

Name	Formula	Related quantities	LT dimension
Hooke's law	$F=kx$	F (Force), k (Elastic modulus), x (Displacement)	$L^{4}T^{-4}$
Newton's law of viscosity	$F=\eta S(dv/dx)$	F (Viscous force), η (Proportional coefficient)， S (Contact area)， (dv/dx) (Velocity gradient)	$L^{4}T^{-4}$
Pendulum	$T=2\pi(L/g)^{\frac{1}{2}}$	T (Period), L (Length of pendulum), g (Acceleration of gravity)	$L^{0}T^{1}$
Bernoulli's principle	$P=C-\frac{1}{2}pv^{2}-\rho gh$	P (Pressure), C (Constant), p (Fluid density), v (Flow velocity), g (Acceleration of gravity)、h (Height)	$L^{2}T^{-4}$
Coulomb's law	$F=KQ_{1}Q_{2}/r^{2}$	F (Force), K (Coulomb constant), Q_{1} Q_{2} (Quantity of electric charge), r (Distance)	$L^{4}T^{-4}$
Unit flow	$Q=Av$	Q (Unit flow), A (Cross-sectional area), v (Flow rate)	$L^{3}T^{0}$
Newton's second law of motion-force and acceleration	$F=ma$	F (Force), m (Mass), a (Acceleration)	$L^{4}T^{-4}$
Kinetic energy theorem	$E_{k}=\frac{1}{2}mV^{2}$	E_{k} (Kinetic energy), m (Mass), V (Velocity)	$L^{5}T^{-4}$
Joule's Law	$Q=I^{2}Rt$	Q (Quantity of heat), I (Current), R (Resistance), t (Time)	$L^{5}T^{-4}$
Boyle's law	$P_{1}V_{1}=P_{2}V_{2}$	P_{1} P_{2} (Pressure), V_{1} V_{2} (Volume)	$L^{2}T^{-4}$

Name	Formula	Related quantities	LT dimension
Parallel axis theorem	$I_z=I_c+md^2$	I_z (Moment of inertia of z axis), I_c (Moment of inertia of the centroid axis), m (Mass), d (Distance)	L^5T^{-2}
Moment of inertia	$I_c=ab^3/12$	I_c (Rectangular moment of inertia), a (Length), b (Width)	L^4T^0

Table 2: Effects database of LT dimensional part of the content.

2.3 Causal Chain Analysis

For the same tier causes expressed by physical quantity c_{ijk}, the expansion of causes is shown in Equation (3) based on the object element multiplication.

$$M_{11}\otimes M_{12}=\begin{bmatrix} O_{11}\otimes O_{12} & c_{111} & v_{111}\otimes v_{121} \\ & c_{122} & v_{112}\otimes v_{122} \\ & c_{113}\otimes c_{123} & v_{113}\otimes v_{123} \\ & \cdots & \cdots \\ & c_{11l}\otimes c_{12h} & v_{11l}\otimes v_{12h} \end{bmatrix} \tag{3}$$

For example, the same tier of cause M_{11} (hydrogen) and M_{12} (oxygen) are represented in Equations (4-5). Dimension corresponding to volume, density and temperature are L^3T^0, L^0T^{-2}, L^5T^{-4}, respectively. The above dimension is subjected to power operations to derive a new and meaningful dimension of L^3T^{-2}, the mass, as shown in Equation (6). The mass can be the cause of each of M_{11} or M_{12}, the cause of hydrogen and oxygen derivatives of water, or the cause of the gas mixture.

$$M_{11}=\begin{bmatrix} Hydrogen & Density & d_1\ g/mm^3 \\ & Temperature & T_1\ ^{\circ}C \end{bmatrix} \tag{4}$$

$$M_{12}=\begin{bmatrix} Oxygen & Volume & v_2\ mm^3 \\ & Temperature & T_2\ ^{\circ}C \end{bmatrix} \tag{5}$$

$$M_{11}\otimes M_{12}=\begin{bmatrix} Hydrogen\otimes Oxygen & Volume & (v_1\otimes v_2)\ mm^3 \\ & Density & (d_1\otimes d_2)\ g/mm^3 \\ & Temperature & (T_1\otimes T_2)\ ^{\circ}C \\ & Mass & (v_1d_1\otimes v_2d_2)\ g \end{bmatrix} \tag{6}$$

For the next level of causes, the implicit causes are mined using the dimension transformation method. For example, the adsorption force of an oil fume machine is insufficient resulting in the fumes not being completely adsorbed, which is manifested as a negative pressure problem. The physical quantity related to negative pressure in the LT table is pressure, and the corresponding dimension is L^2T^{-4}. The effect available for L^2T^{-4} is Bernoulli's principle. The physical quantity associated with this principle is P, C, p, v, g, h. These four physical quantities can be used as candidate causes for the next implication analysis.

The representation of the causal chain analysis based on the extenics model and LT dimension is shown in Figure 3.

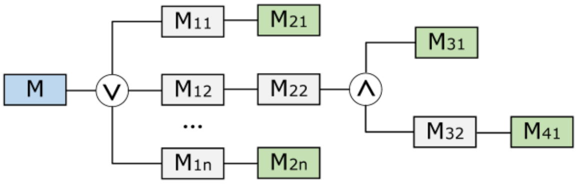

Figure 3: Causal chain analysis.

where M is the initial problem exhibited by the product, M_{ij} is the cause for further analysis, which is expressed using the extenics model. Causes at the same tier can be derived from the expansion of the object element multiplication. The causes of the next level can be expanded according to the physical quantities based on the effect database of LT dimension. For causes that cannot be expressed using the extenics model, a linguistic description is used in Figure 3, where $\vee$ denotes the 'or' relationship. Each cause of this level is solved. Causes of the previous level can only be solved effectively. $\wedge$ denotes the 'and' relationship.

2.4 Solving Root Cause

After the initial problem is analyzed by the causal chain, there may be multiple key root causes to be solved depending on the 'and' or 'or' relationship between the root causes. Types of the root cause can be divided into two categories: parameter type and conflict type. The resolution is shown in Figure 4.

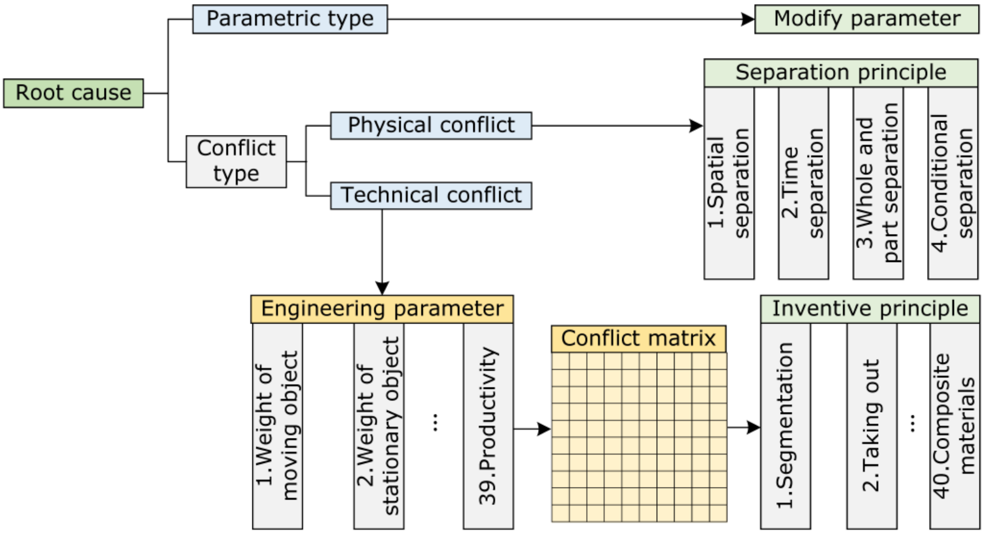

Figure 4: Root cause solution.

Type 1: For parametric root causes, the corresponding parameter is directly modified, such as the low hardness and high temperature, it can be solved by directly replacing the material or changing the temperature value.

Type 2: For conflict type root causes. The conflict tool in TRIZ is used. Physical conflicts are solved using four separation principles, spatial separation principle, time separation principle, whole and part separation principle, and conditional separation principle. When a solution cannot be formed based on only the four separation principles mentioned above, the solution to the problem can be further found based on the invention principle corresponding to each separation principle. The correspondence between separation principles and inventive principles is shown in Table 3. For technical conflicts, they are described by 39 engineering parameters. The corresponding inventive principle is found by searching the conflict matrix. The solution of the abstract problem based on the inventive principle is converted into the solution of the concrete problem.

Separation principle	Inventive principle
Spatial separation	1, 2, 3, 4, 7, 13, 17, 24, 26, 30
Time separation	9, 10, 11, 15, 16, 18, 19, 20, 21, 29, 34, 37
Whole and part separation	12, 28, 31, 32, 35, 36, 38, 39, 40
Conditional separation	1, 7, 25, 27, 5, 22, 23, 33, 6, 8, 14, 25, 35, 13

Table 3: Effects database of LT dimensional part of the content.

2.5 Solution Evaluation

Multiple innovative design solutions may be formed after the root cause is solved using TRIZ tools. A solution with the highest overall index should be selected for development. Equation (7), idealization level [6] is introduced to calculate the ideal degree of each design solution. The evaluation interval is set to 1-5 with m evaluators.

$$I_j=\frac{\overline{U}_j}{\overline{C}_j+\overline{H}_j}=\sum_{i=1}^{m}\frac{U_{ij}/m}{C_{ij}/m+H_{ij}/m}=\sum_{i=1}^{m}\frac{U_{ij}}{C_{ij}+H_{ij}} \tag{7}$$

where I_j denotes the ideality of the j *th* solution. $\overline{U}_j$ denotes the average value of useful feature evaluation index brought by the j th solution. $\overline{C}_j$ is the average value of cost evaluation index of the j th solution. $\overline{H}_j$ denotes the average value of harmful factors evaluation index brought by the j th solution. U_{ij} denotes the evaluation of the useful feature of the j th solution by the i th evaluator. C_{ij} denotes the evaluation of the cost of the j th solution by the i th evaluator. H_{ij} denotes the evaluation of the harmful factors of the j th solution by the i th evaluator.

3 CASE STUDY

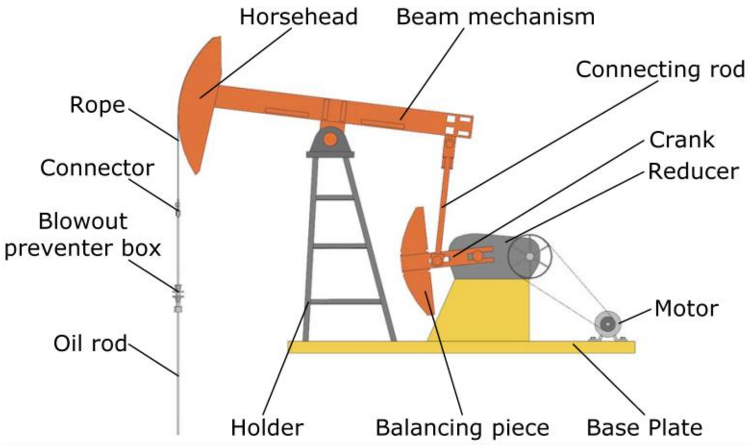

Figure 5: A beam oil pumping machine.

A beam oil pumping machine is a device to extract oil, as shown in Figure 5. The working process is to supply power from the motor. The reducer changes the high-speed rotation of the motor into the low-speed rotation of the oil pumping machine crank. The crank-connecting rod-beam mechanism changes the rotational motion into the upward and downward reciprocating motion of the horsehead. The rope and connector drive the pumping rod up and down for oil recovery work. In order to increase the oil recovery efficiency, multiple beam oil pumping machines are usually used. But it creates a high workload of the transportation and site erection. Therefore, the improvement is considered for this problem.

3.1 Causal Chain Analysis

A causal chain analysis is performed. The initial cause is the low flow of the oil rod or intermittent oil supply problem, which limits the overall efficiency of the beam oil pumping machine. The flow corresponds to volume L^3T^0 in the LT table. L^3T^0 in the effects database of LT dimension corresponds to unit flow $Q=Av$. Based on its corresponding physical quantity, an extenics analysis of the root cause is shown in Figure 6. The unit flow is represented by an extenics model. Its implied causes include the flow rate and area, which are 'and' relationships that require only one cause to be solved. The main reason for the small flow rate is the viscous force of oil, which limits the speed of the up and down movement of the oil rod. The viscous force corresponds to force L^4T^{-4} in the LT table. The effect of dimension L^4T^{-4} is Newton's law of viscosity $F=\eta S(dv/dx)$. It is implied by three parameters: viscosity coefficient, contact area, and speed gradient. The root cause of the intermittent oil supply is analyzed to be the negative work done by the balance piece during the reverse stroke, it cannot be expressed by the extenics model, which can only be described by language.

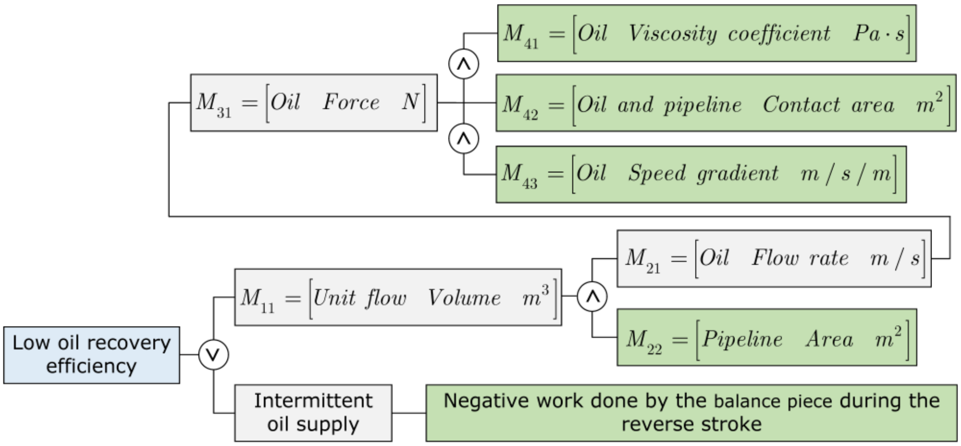

Figure 6: Causal chain analysis of beam oil pumping machine.

3.2 Solving Root Cause

There are two direct reasons for the low oil recovery efficiency. The two direct causes in this case cannot be multiplied by the object element and cannot generate other causes of the same tier. Since the two direct causes are in an 'or' relationship, their root causes are solved, the initial problem can be solved.

The root cause of the low flow is influenced by three parameters, viscosity coefficient, contact area, and speed gradient. Since the three parameters are 'and' relationships, solving one parameter will solve the cause of the low flow. The viscosity coefficient of the oil can be changed by changing the temperature, it is easier to operate than the other two parameters. Therefore, the cause of the low flow is solved by improving the temperature of the oil in the oil pipe. At the oil extraction site, the energy source is electricity, so an auxiliary heat device is added to the oil rod at intervals, as shown in Figure 7.

Figure 7: Oil rod improvement solution.

As for the cause of negative work done by the balance piece during the reverse stroke, if the balance piece is removed, the cause of negative work done by the balance piece during the reverse stroke can be solved, but this lacks a balancing device, i.e., in order to solve the problem of negative work done by the balance piece during the reverse stroke, the balance piece is not needed, but in order to balance the system, the balance piece is required. It is a physical conflict for different conditions with different requirements. The 6th invention principle, universality, makes a part or object perform multiple functions to eliminate the need for other parts, under the conditional separation principle. Therefore, one oil rod is used to replace the balancing piece, so that the oil rod with oil extraction function performs the function of balancing at the same time. The negative work of the balancing piece rising process is converted into the useful work by the oil rod rising. The problem of intermittent oil supply is solved by the alternate oil extraction of two oil rods. Two innovative design solutions are formed by modifying the existing beam mechanism and holder to have the function of supporting two oil rods, as shown in Figure 8.

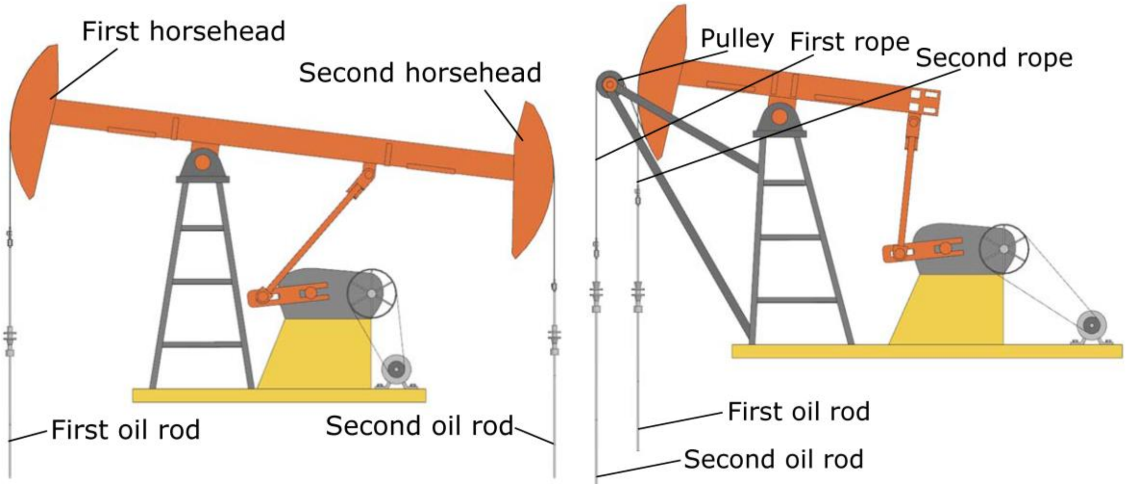

Figure 8: Negative work improvement solution: (a) Solution 1, (b) Solution 2.

Figure 7 shows the solution for the root cause of oil viscosity coefficient. Figure 8 shows the two solutions for the root cause of negative work done by the balance piece during the reverse stroke. Both root causes need to be solved to solve the initial problem, therefore, the two root cause solutions are aggregated to form the total two design solutions, as shown in Figure 9.

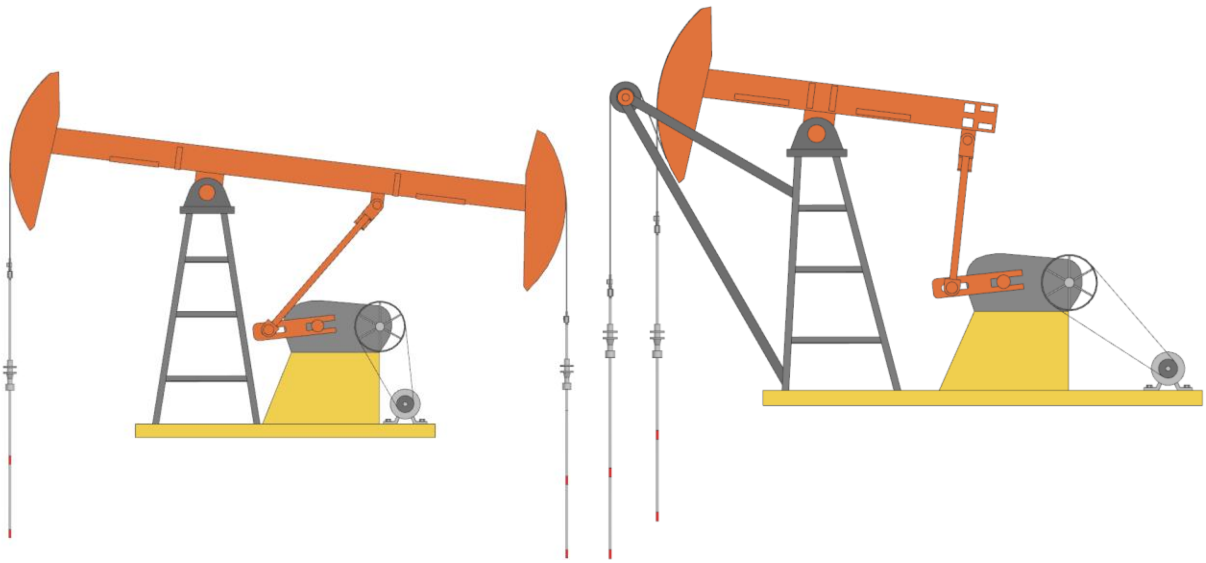

Figure 9: Summary solutions: (a) Summary solution 1, (b) Summary solution 2.

3.3 Solution Evaluation

Three group members are used for the solution evaluation including professors, engineers and graduate students. The solution is evaluated comprehensively in terms of extraction efficiency (EE), cost (C), and negative work consumption (NWC). The original solution is also added to the evaluation for the comparison. The evaluation interval is set to 1-5, the evaluation results are shown in Table 4. S_0, S_1 and S_2 represent the original solution, summary solution 1 and summary solution 2, respectively.

Member	M1			M2			M3		
	EE	C	NWC	EE	C	NWC	EE	C	NWC
S_0	2	3	5	3	3	4	2	3	5
S_1	4	4	2	5	5	3	4	4	3
S_2	4	4	2	4	4	2	3	4	3

Table 4: Design solution evaluation.

The ideality of each solution is calculated according to Equation (7). I_0=0.304, I_1=0.619, and I_2=0.579. It can be seen that the ideal degree of both design solutions is higher than the original design solution. The ideality of summary solution 1 is higher than summary solution 2. Therefore, summary solution 1 is used as the final innovative design solution. The effectiveness of the proposed method is verified.

4 CONCLUSION

This paper proposes a causal chain analysis method based on the extenics and LT dimension. For the key root cause, solutions are searched by using the parameter improvement or conflict tool in TRIZ. The method is verified in the improvement of a beam oil pumping machine.

The problem-solving process without using our proposed method also requires determining causes of the problem to occur before solving it. Not using the method proposed in this study requires traditional methods such as the brainstorming approach, which is not conducive to the problem analysis and solution. This research provides a systematic approach for uncovering the root causes of the problem and solve it.

Classic causal chains can only describe one parameter of each cause, and there is no logic in the next step of cause mining. The use of extenics can describe multiple parameters of each cause. The effect database of LT dimensions can be expanded for cause parameters, which makes the root cause mining process effectiveness.

However, the proposed method requires manual mapping of the causal chain and retrieval of the LT effect database. The development of a computer-aided software tool is our future work.

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