Title:
A Root Cause Analysis Method of Design Problems Using Extenics and LT Dimension

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Introduction:
Causal chain analysis is a key tool for theory of the solution of inventive problems (TRIZ) to identify systematic problems [6]. The problems often occur as a result of a combination of causes at multiple levels. From the perspective of cause levels, causes are divided into direct, intermediate and root causes to form a causal chain. The 'and' and 'or' structure is used to show the relationship between hierarchical causes [8]. Root causes can be analyzed from a problem-solving perspective along with the beneficial effects of each cause [5]. But its expression of causes makes the root causes analysis limited by thinking. Although extenics has been incorporated into the causal chain analysis to improve the expression of the causes [1], it still lacks a systematic approach to root cause mining. Therefore, in order to make the causal chain analysis process expandable and logical, this research proposes a causal chain analysis process model that integrates extenics and length time (LT) dimension.

Main Idea:
The causal chain analysis process model proposed in this research is shown in Fig. 1. 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. Finally, based on the type of root causes, the parameter changes or conflict resolution is applied in the TRIZ tool.

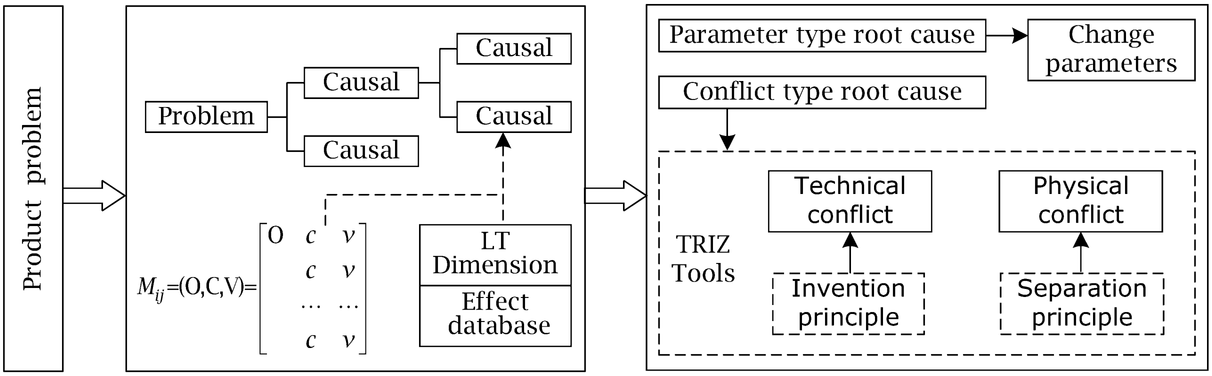

Fig. 1: Causal chain analysis process model.

Extenics Expresses 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 [7]. Multiple contextual functional elements are explored along different pathways through the extensible relationships between object elements to achieve a divergent thought process. The hidden object element characteristics are derived through the arithmetic law of object elements. The causal chain analysis analyzes the problem to further explore the hidden root causes, which is consistent with extenics searching for hidden object element characteristics. Therefore, it is feasible to assist the causal chain analysis through extenics. The extenics model is shown in Eqn. 1.

$$M_{ij}=(\mathrm{O}_{ij},\mathrm{C}_{ij},\mathrm{V}_{ij})=\begin{bmatrix}\mathrm{O}_{ij}, & c_{ij1} & v_{ij1}\\ & c_{ij2} & v_{ij2}\\ & \cdots & \cdots\\ & c_{ijn} & v_{ijn}\end{bmatrix} \tag{1}$$

where, M is the initial problem. M_{ij} is the j th cause in the i th level 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}, $c_{ij2},\cdots,c_{ijn}$, and c_{ijk} corresponding value v_{ijk}.

LT Dimension Expresses 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) [3]. 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 [4]. Inspired by this, Bartini used mathematical tools to deduce and experimentally prove that the two-dimensional dimension of both mass and power is L^3T^{-2} [2]. Dimension operations follow rules of index operations in mathematics. The LT dimension is shown in Tab. 1. 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. The characteristics of the object element are represented by the dimensions in Eqn.1, which can be expanded by the effect database to uncover the root causes of the causal chain.

Dimension	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}	Refractiveindex	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	Impulse	Angular momentum / Impulsive moment
T^{-2}		L^1T^{-2}	Mass density/ Angle acceleration	Linear acceleration	Voltage	Mass/ Electricity	L^4T^{-2}	Rotational inertia

Dimension	L^{-2}	L^{-1}	L^{0}	L^{1}	L^{2}	L^{3}	L^{4}	L^{5}
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 inertialmoment	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}	$L^{-2}T^{3}$	$L^{-1}T^{3}$	$L^{0}T^{3}$	$L^{1}T^{3}$				

Tab. 1: LT dimension of the content.

Causal Chain Analysis Process:

For the same level causes expressed in terms of dimension c_{ijk}, the expansion of causes is shown in Eqn. 2 based on the object element multiplication.

$$M_{11} \otimes M_{12} = \begin{bmatrix} O_{11} \otimes O_{12} & c_{111} & v_{111} \otimes v_{121} \\ & c_{122} & v_{112} \otimes v_{122} \\ & c_{113} \otimes c_{123} & v_{113} \otimes v_{123} \\ & \cdots & \cdots \\ & c_{11l} \otimes c_{12h} & v_{11l} \otimes v_{12h} \end{bmatrix} \tag{2}$$

For the next level of causes, the implicit causes are mined using the dimension transformation method. The representation of the causal chain analysis based on extencis and physical dimension is shown in Fig. 2.

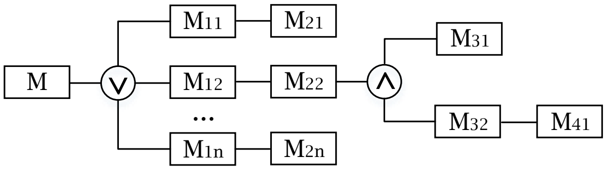

Fig. 2: Causal chain analysis.

M is the problem exhibited by the product. M_{ij} is the root cause for further analysis. Causes at the same level 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 Fig. 2, where $\vee$ denotes the 'or' relationship. Each cause of this level is solved. The causes of the previous level can only be solved effectively. $\wedge$ denotes the 'and' relationship.

Solving Root Cause:

After the initial problem is analyzed for root causes, two types of the root causes are decided as follows.

Type 1: For parametric root causes, the corresponding parameter is directly modified, such as the low hardness and high temperature.

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, temporal separation principle, whole and part separation principle, conditional separation principle. 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.

Case Study:

A beam oil pumping machine is a device for extracting oil. In order to increase the oil recovery efficiency, multiple beam oil pumping machines are usually used, which creates a large workload and reduces the oil recovery efficiency. Therefore, the improvement is considered for this problem.

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 Fig. 3. The unit flow rate is represented by an extenics model. It contains the reason of the small flow rate mainly because 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.

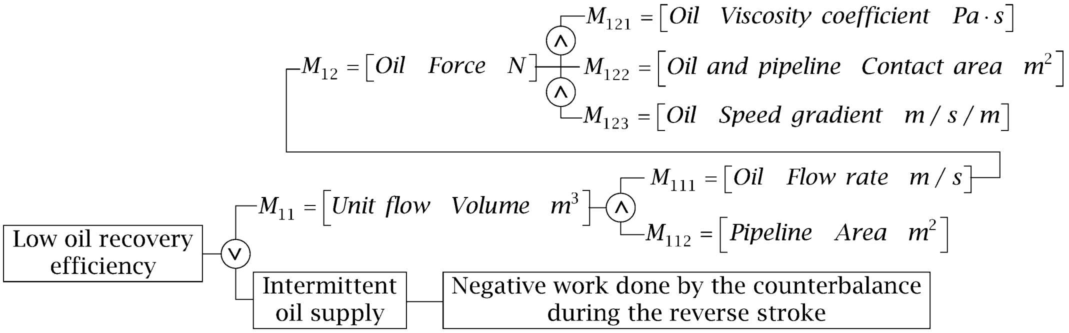

Fig. 3: Causal chain analysis of beam oil pumping machine.

The root cause of the low flow problem is influenced by three parameters. Since the three parameters are 'and' relationships, only one parameter, the temperature of the oil in the oil pipe, needs to be improved for the problem. An auxiliary heat device is added to the oil rod at intervals, as shown in Fig. 4.

Fig. 4: Oil rod improvement solution.

In order to improve the problem of the balancing piece doing negative work during the reverse stroke, the balancing piece needs to be non-existent. But, in order to balance the structure, the balance piece needs to be present again. It is a physical conflict for different conditions with different requirements, and it cannot be expressed in an extenics model. 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 block rising process is converted into useful work by the oil rod rising. The problem of intermittent oil supply is solved by alternate oil extraction of the two oil rods as shown in Fig. 5.

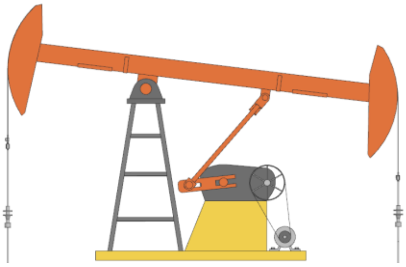

Fig. 5: Negative work improvement solution.

The above two solutions form the final innovative design solution which solves the problem of large oil viscosity and useless work and improves the oil recovery efficiency.

Conclusion:

This paper proposes a root cause analysis method based on extenics and LT dimension. For the key root cause, the solution is searched by using the parameter improvement or conflict tool in TRIZ. The method is verified through the improvement of a beam oil pumping machine. Comparing with the existing root cause analysis process, the extenics makes the expression of root cause analysis process standard for using the LT dimension in root cause mining. This is a useful method to analyze and solve problems of products. 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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