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# Innovative Design and Structural Optimization of an Automatic Clamping Mechanism Integrating Extenics and TRIZ

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**Abstract:** The design of automatic clamping mechanisms often involves trade-offs between clamping stability, structural compactness, manufacturability, and operational reliability. These trade-offs are difficult to handle in early design stages, where decisions are largely experience-based and design alternatives are not yet fully defined. An integrated design approach combining Extenics and TRIZ is applied to support the innovative development and structural optimization of an automatic clamping mechanism. Functional requirements and structural constraints are first expressed in the form of Extenics element models. Key design conflicts are then identified through functional analysis and addressed using TRIZ contradiction principles and inventive principles, which guide the generation of alternative structural configurations. The candidate designs are evaluated with respect to mechanical performance, manufacturability, and structural feasibility in order to select a configuration that better satisfies practical engineering requirements. The approach is illustrated through the redesign of an automatic clamping mechanism. The results show that the selected configuration improves clamping stability and structural reliability while maintaining reasonable manufacturability. The study suggests that the combined use of Extenics and TRIZ can support systematic innovation in mechanical structure design and provide practical guidance for similar precision engineering applications.

**Keywords:** Automatic clamping mechanism; Mechanical structure design; Extenics; TRIZ; Structural optimization

## 1 Introduction

Innovation is the core of mechanical product design. Using innovative methods to solve difficult problems in mechanical product design and obtain innovative product solutions is an important way to achieve mechanical product design. Especially in design scenarios involving precision mechanical structures, motion mechanisms, and complex manufacturing constraints, innovative methods are of great significance for improving structural performance, manufacturability, and system reliability. There are many types of innovation methods, and more systematic innovation methods include TRIZ theory and Extenics innovation methods [1], while the integration of these two methods is an important research direction.

Chang and Chen [2] used element models to express design objects and sought innovation keys for design objects using extension and transformation methods. They used TRIZ methods to solve conflicts in design and constructed an integrated innovation method combining TRIZ and Extenics. Wu et al. [3] integrated TRIZ's substance-field method, contradiction matrix method, and Extenics method, and established an integrated innovation method used in bicycle design. Yang et al. [4] applied TRIZ theory to solve customer relationship problems in eco-innovative product design. Wang et al. [5] established a method combining BERT and TRIZ to solve problems in the design of unmanned ships. Li et al. [6] proposed an agile conflict identification-driven innovation process model for complex electromechanical products. Wu et al. [7] combined TRIZ theory with AD, fuzzy, and correlation analysis for new product concept design. Yap et al. [8] used various tools of TRIZ theory to design a bubble rupture atomization system to improve cutting lubrication and extend tool life. Zhao et al. [9] proposed an innovation solving method integrating Extenics and TRIZ, which was verified in solving the noise reduction problem of screw compressors. Song et al. [10] proposed a structural design decision model combining behavior analysis, failure mode effects analysis, and TRIZ theory and applied it in the design of a hemiplegic upper limb rehabilitation exoskeleton to solve design conflicts. Ismail et al. [11] used TRIZ's functional analysis method to design a highway C2L cone lifter, clarifying the functions and relations of system components using the functional analysis model and using engineering contradiction analysis to identify core contradictions, then redesigning the cone lifter. Tests showed that the new design improved the equipment's reliability and operational safety. Muhammad et al. [12] used functional analysis tools and engineering contradiction tools to simplify the lift mechanism design of a drone docking station, improving its functionality and reliability. Rau et al. [13] applied TRIZ theory to innovate products in green design, identifying the product's overview and basic green features using function and attribute analysis, and solving contradictions in meeting green requirements using the contradiction matrix. Vanko et al. [14] used functional and cost analysis and the ARIZ algorithm for solving structural problems in ultrasonic welding machines. Seo et al. [15] addressed issues such as powder collection and removal functions of powder collectors. By observing the working environment and surveying field operator feedback, they identified key issues, used functional analysis and causal chain analysis, then applied the ARIZ algorithm to derive creative solutions. Jiang et al. [16, 17] integrated TRIZ and Extenics for analysis and proposed a new design method, applying it to innovative design in disk parts polishers and tables. The results showed that the integrated innovative design theory could gain creative ideas from different perspectives and significantly improve the efficiency of innovative design. Zhang et al. [18] integrated Extenics elemental theory and TRIZ functional analysis to improve the functional analysis method, which can effectively mine information from systems. Chen et al. [19] proposed a process design method integrating the functional structure model and Extenics theory, providing new theoretical design ideas for optimizing existing products. Gui et al. [20] proposed the RFPS (Requirement-Function-Principle-Structure) model integrating Extenics and TRIZ for product innovation design and product upgrading. Ge et al. [21] applied TRIZ's evolutionary law for Extenics expression, merging Extenics models, rules, transformations, and principles to establish an Extenics intelligent design method and applied it in the dust spray system design. Guo et al. [22] refined the product innovation design method integrating Extenics and TRIZ, applying the theory to mobile phone chargers to obtain various creative design solutions. Wu [23] proposed a children's toy design method combining D-S theory and Extenics to better meet users' intrinsic needs. Huang et al. [24] proposed a third innovation method for product innovation based on the evolutionary tree, using the application characteristics of the evolutionary tree to overcome the shortcomings of extension analysis, and tested the theory's effectiveness using socket examples. Chen et al. [25] proposed an innovation method combining the elemental model and substance-field analysis to solve the problem of difficult transportation of viscous oil, which reduced costs in practical engineering applications. Lin et al. [26] also integrated TRIZ and Extenics innovation methods.

The above studies show that TRIZ and Extenics have good applicability in various mechanical systems, mechanism design, and engineering equipment optimization, especially in precision mechanical design problems involving function reconstruction, structural improvement, and manufacturing constraint coordination.

Regarding the difficulties of function realization and extension in mechanical design, Zhang et al. [18] and Chen et al. [19] have made beneficial explorations. However, they only used element descriptions and their extensions/transformation in the processes of component analysis and component interaction analysis, and did not establish functional models based on element expressions, or established structural models, which makes it difficult to accurately locate functional defects, limiting the extension of objects. This paper uses element descriptions for the entire functional analysis process and functional models, establishing a mechanical design method based on functional Extenics (the functional and functional models of components with Extenics expressions). This extends the divergent pathways of functional models, laying the foundation for quickly obtaining more design solutions. This method is particularly suitable for mechanical system design scenarios that require system reconstruction at the functional level while considering structural implementation and manufacturing feasibility.

The functional Extenics method proposed in this paper establishes a complete functional Extenics method system, which is a significant improvement over Zhang et al.[18]. Zhang Wenlin et al. only established a functional relationship diagram using event and relational elements, without building a complete functional model with element expressions, thus limiting the extension of objects. Chen et al. [19] built a functional structure diagram instead of component analysis and functional models. They only extended event elements, which made it difficult to obtain functional defects and multiple element extension objects. A single functional model mainly aims to acquire functional defects, but it is hard to find solutions to problems. Likewise, a single Extenics innovation method can only extend elements in structures and cannot identify functional defects, making the extension objects insufficient. Therefore, a functional model based on element expressions can effectively expand the extension objects and generate more creative paths for Extenics transformations, laying the foundation for generating more creative solutions. This framework helps form a more systematic functional reconstruction and structural generation mechanism in precision mechanical design and complex structural system development, thereby supporting more efficient mechanical structure innovation and engineering optimization.

## 2 Element Description of Function Model

A function model is a graphical description of functional analysis, representing the functions and interactions between different components. According to the function model, it can only identify functional defects, and the solutions generated to correct these defects are few. If the element model is used to describe the characteristics and values of the functions, components, and structural relationships, it is beneficial for further expansion analysis. The function analysis mainly involves component analysis, component interaction analysis, and function modeling. Each stage is described using the element model.

### 2.1 Element Description of Component Analysis

A matter element is the basic unit that describes an object, using features and corresponding values to describe the internal attributes of the object. The component analysis in the function analysis process is the analysis of an object, and this component analysis process can be described using the matter element model. According to the original model, the main parts are divided into three levels: the current system, system components, and super-system components. The specific division is as shown in Table 1.

**Table 1.** Component analysis and matter element division

| **System** | **System Components ($M_{ei}$)** | **Super-System ($M_{ai}$)** |
|---|---|---|
| $M_c$ | $M_{e1}, M_{e2}, M_{e3}, M_{e4}, M_{e5} \ldots$ | $M_{a1}, M_{a2} \ldots$ |

In component analysis, the main task is to filter out system components related to the problem and necessary super-system components, and describe them using matter elements. The description of matter elements for system components is as follows (where the subscript $i$ is the element number, and the subscript $j$ is the feature number):

$$M_{ei} = \begin{bmatrix} \text{Component} & i, & c_1, & v_1 \\ & & c_2, & v_2 \\ & & c_j, & v_j \\ & & \cdots & \cdots \\ & & c_n, & v_n \end{bmatrix} \tag{1}$$

Common features used in component matter element descriptions include material, accuracy, size, geometric tolerance, shape, mass, grade, processing method, etc. The same processing applies to super-system components.

### 2.2 Element Description of Structural Relationship Between Components

The structural relationships between components are described using relation elements, which describe the relationship attributes using features and their corresponding values. The component interaction analysis in function analysis is the analysis of the interaction relationships between components. This is described in two steps: first, using relation elements to describe whether there is a connection between the components, i.e., whether there is a contact relationship; then using matter elements to describe the specific nature of the action.

The first step of component interaction analysis is shown in Table 2. For components with interactions, the relation elements are given where they intersect.

Common relation words used in relation element models include contact relationship, friction relationship, fit relationship, positioning relationship, control relationship, connection relationship, fixed relationship, etc. For example, in the table above, a structural relationship between $M_{ei}$ and $M_{ej}$ is described as:

$$\begin{aligned} & R_i\left(M_{ei}, M_{ej}\right) \\ & = \begin{bmatrix} \text{Relationship } i, & \text{Preceding item,} & M_{ei} \\ & \text{Succeeding item,} & M_{ej} \\ & \text{Associated medium,} & \text{Lubricating oil} \\ & \text{Mode of connection,} & \text{Clearance fit} \\ & \text{Degree,} & \text{Strong} \end{bmatrix} \end{aligned} \tag{2}$$

### 2.3 Matter Element Description of the Interaction Between Components

The specific interactions between components are described using functional matter elements, which describe the functional attributes using features and their corresponding values. To describe the function, it is necessary to clarify the carrier, name, level, and other factors of the function, and complete the analysis of functional levels and performance. An example is shown in Table 3.

**Table 2.** Interaction between matter elements and components

| | $\boldsymbol{M_{e1}}$ | $\boldsymbol{M_{e2}}$ | $\boldsymbol{M_{e3}}$ | $\boldsymbol{M_{e4}}$ | $\boldsymbol{M_{a1}}$ | $\ldots$ |
|---|---|---|---|---|---|---|
| $\boldsymbol{M_{e1}}$ | - | $R_1$ | | | | |
| $\boldsymbol{M_{e2}}$ | $R_1$ | - | $R_2$ | | | |
| $\boldsymbol{M_{e3}}$ | | $R_2$ | - | $R_3$ | | |
| $\boldsymbol{M_{e4}}$ | | | $R_3$ | - | $R_4$ | |
| $\boldsymbol{M_{a1}}$ | | | | $R_4$ | - | $\ldots$ |
| $\ldots$ | | | | | $\ldots$ | - |

**Table 3.** Function analysis

| Carrier Matter Element | Receptor Matter Element | Structural Matter Element | Functional Matter Element | Functional Attributes | Functional Level |
|---|---|---|---|---|---|
| $M_{e1}$ | $M_{e2}$ | $R_1$ | $A_1$ | Basic Function | Excessive |
| $M_{e2}$ | $M_{e3}$ | $R_2$ | $A_2$ | Harmful Function | |
| $M_{e3}$ | $M_{e4}$ | $R_3$ | $A_3$ | Auxiliary Function | Normal |
| $M_{a1}$ | $M_{e4}$ | $R_4$ | $A_4$ | Additional Function | Insufficient |

In the matter element model shown above, the objects being acted upon and the acting objects are matter element components. The functional attributes can be normal, excessive, insufficient, or harmful, or they can be basic, auxiliary, or additional functions. Therefore, functional defects can be judged through the attribute features of the matter element model. For example, a functional relationship between $M_{ei}$ and $M_{ej}$ is expressed as:

$$A_i\left(M_{ei}, M_{ej}\right) = \begin{bmatrix} \text{Function } a_i, & \text{Controlled object,} & M_{ei} \\ & \text{Actuated object,} & M_{ej} \\ & \text{Mode of action,} & \text{Medium propulsion} \\ & \text{Stroke range,} & 0-40\text{ mm} \\ & \text{Degree,} & \text{Moderate} \end{bmatrix} \tag{3}$$

In practice, due to the structural relationship between components, there must be mutual interaction, and there are overlapping parts between them. Therefore, in subsequent extension analysis, only one of the relation elements or matter elements above can be selected for extension analysis.

### 2.4 Function Modeling

Based on the above analysis, a system-level analysis is further performed to establish the element-based function model. The function model here combines the advantages of graphical and element formalization. Each component is described using matter elements, and the interaction relationships are described by a fusion of relation elements and matter elements, as shown in Figure 1.

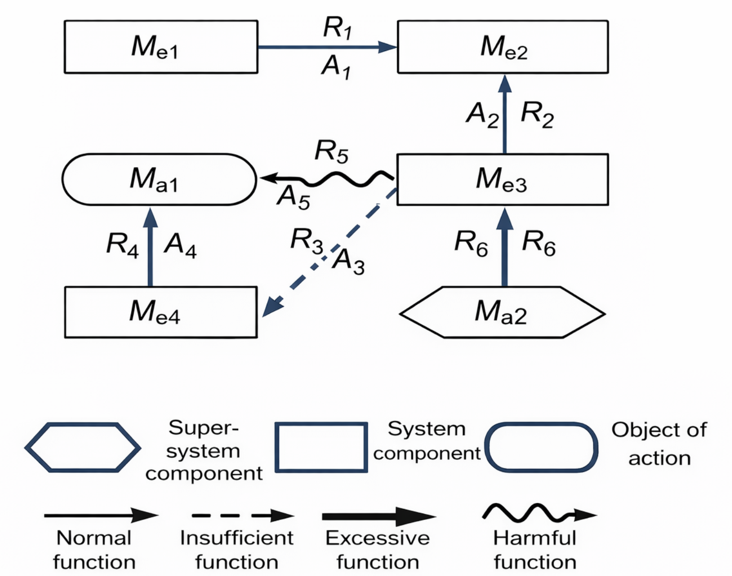


**Figure 1.** Function model diagram based on extension description

TRIZ theory's function modeling can only distinguish between insufficient, excessive, and harmful functions. Solutions are then focused on these functional defects, making it difficult to generate many solutions. However, after using element modeling, solutions can be sought through extension analysis of the elements, and because there are many extension methods, a large number of solutions can be generated. This is the advantage of combining the two methods.

## 3 Construction of Mechanical Innovation Design Method Based on Functional Extenics

By integrating the advantages of functional analysis and Extenics innovation methods, a mechanical innovation design method based on functional Extenics is constructed. The process is divided into four main stages: problem identification, problem analysis, problem solving, and creative evaluation. Each stage can be further divided into several steps. The specific process of mechanical innovation design based on functional Extenics is shown in Figure 2.

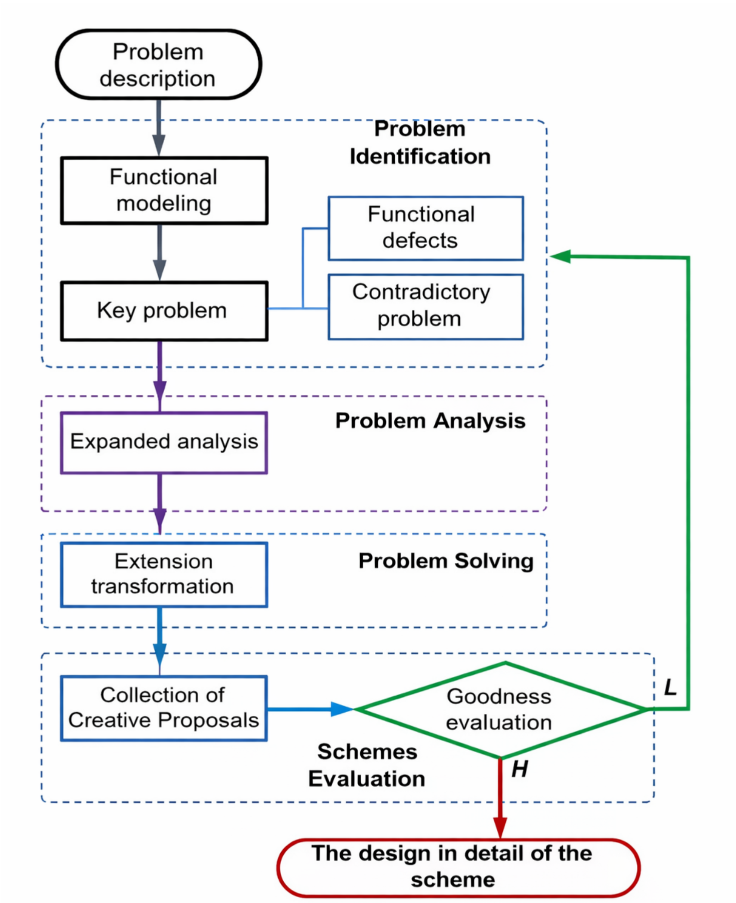


**Figure 2.** Extension innovative design process of functional analysis

In enterprises, mechanical product innovation design problems generally fall into three categories: optimizing existing products, improving deficiencies in existing products, or designing entirely new products. Here, product optimization is used as an example to describe the specific steps of mechanical product innovation design as follows.

### 3.1 Problem Identification

#### 3.1.1 Problem description

The goal of product innovation design is to meet the needs of users or the market. Therefore, it is necessary to investigate the needs of users or the market and the functions and characteristics of the original product. The application, working conditions, and performance of the original product should be clearly described. By comparing the functions and characteristics of similar products, the direction of optimization is determined.

#### 3.1.2 Function model construction

This includes system decomposition, component matter element description, structural relationship element description, functional matter element description, and function modeling, etc.

(a) System Decomposition: In the original product model, several issues need to be addressed: What is the overall function of the product, and does it fail to meet the user's needs? The total function should be decomposed, clearly expressing the relationships between the structural elements of the system and the role of this structure in the system. Then, analyze the existing product function structure to determine the relationships between functions. This analysis lays the logical foundation for subsequent component analysis, component interaction analysis, and element description.

(b) Component Matter Element Description: According to the results of system decomposition, the problematic parts are divided into the current system, subsystems, and super-systems. Then, an element model is created for the components involved, achieving a matter element-based Extenics description of the components.

(c) Structural Relationship Element Description: A matrix analysis is performed for the interactions between the components, determining their interaction relationships. For those with structural connections, a structural relationship element model is established, realizing the Extenics description of the structural relationship elements.

(d) Functional Matter Element Description: A function analysis table is created based on the functional elements of the interactions between components, including key factors such as carriers, receptors, structural relationships, and functional levels, achieving the Extenics description of functional matter elements.

(e) Function Modeling: Based on the above, an element-based function model is established to describe the components, relationships, and mutual functions, including information on components, interactions, and structural relationships within the product, realizing the element description of the function model (as shown in Figure 1), to identify the core problems (i.e., functional deficiencies, harmful function defects, etc., or contradiction issues).

3.1.3 Core problem determination

Based on the core problems identified in the function model, the problems to be improved (such as functional deficiencies, harmful function defects, etc., or contradiction issues) are determined.

Input for this step: Preliminary description of the design problem, such as user or market needs and the functions and characteristics of the original product. Output: Core issues such as functional deficiencies, harmful function defects, or contradiction issues.

## 3.2 Problem Analysis

3.2.1 Determine key elements

According to the type of problem to be improved, identify several key elements and their related relationship or matter elements, and analyze the characteristics and values of these elements.

3.2.2 Extension analysis

Perform extension analysis on the key component matter elements, functional matter elements, and structural relationship elements using methods such as divergence trees, split-combine chains, implication systems, and related networks. This will provide multiple product innovation paths. An example of extension analysis using the divergence tree method is shown in Eq. (4). As seen in the equation, the elements $M$ can extend many innovation paths according to the divergence tree rules (divergence symbol as "$\mapsto$").

$$M \mapsto \begin{cases} M_1 \mapsto \begin{cases} M_{11} \\ M_{12} \mapsto M_{121} \end{cases} \\ M_2 \mapsto M_{21} \mapsto M_{211} \\ M_3 \mapsto M_{31} \\ M_4 \\ M_5 \end{cases} \tag{4}$$

Input for this step: Core issues; Output: Creative paths.

## 3.3 Problem Solving

3.3.1 Extenics transformation

The extended creative paths (potential solutions) are subjected to basic transformations such as substitution, addition or deletion, or transformation operations, creating specific innovative design schemes. The following gives examples of Extenics transformations such as object substitution ($T_1$), object addition ($T_{Z1}$), and value reduction ($T_{Z3}$), as shown in Eqs. (5), (6), and (7).

$$T_1 M = T_1(O, c, v) = (O', c, v) = M' \tag{5}$$

$$T_{z1} M = T_2(O, c, v) = (O \oplus O_0, c, v) = M'' \tag{6}$$

$$T_{z3} M = T_3(O, c, v) = (O, c, v \oplus v') = M''' \tag{7}$$

3.3.2 Creative set validation

After the system's problems are solved using Extenics transformations and operations, multiple creative solutions are generated. At this stage, each creative idea is modeled simply, and 2D sketches are drawn to visually check the differences between the new model and the original model.

By analyzing the sketches of each creative set, confirm whether the system's problems have been solved. If the problem is solved, it is listed as one of the preferred solutions; if not, return to the "Problem Identification" step.

Input for this step: Creative paths; Output: Creative solutions.

### 3.4 Creative Evaluation

Creative evaluation is the final stage of innovative optimization design, aiming to select the most suitable creative solution from numerous ideas to serve as the final design. During the evaluation process, first, determine evaluation indicators, then set the weighting coefficients, calculate the degree of correlation and standardized correlation (to avoid calculating standardized correlation, the value range of correlation can be limited to [-1, 1], as shown in Eq. (8)), and finally, according to Eq. (9), obtain the quality of each creative solution. The creative idea with the highest quality is chosen as the final implementation solution.

$$k(z)=\begin{cases}1, \quad z= \text{ Very high}\\ 0.5, \quad z= \text{ High}\\ 0, \quad z= \text{ Average}\\ -0.5, \quad z= \text{ Low}\\ -1, \quad z= \text{ Very low}\end{cases} \tag{8}$$

$$C\left(O_j\right)=\sum_{i=1}^{n}\alpha_i k_{ij} \tag{9}$$

The key to evaluation is determining the evaluation indicators. These indicators are determined based on user or market requirements. By establishing evaluation metrics based on user needs, the product's design can be aligned with user expectations, ensuring maximum reliability for the product.

## 4 Design of Automatic Clamping Device Based on Functional Extenics

The schematic diagram of the motion of an automatic clamping device for a workpiece is shown in Figure 3. The components are as follows: 1 is the frame, 2 and 3 are the hydraulic cylinder and piston rod, respectively, 5 is the connecting rod, and 4 and 6 are the connecting frame rods, where 6 is the execution rod used for clamping the workpiece. Based on the basic characteristics and working requirements of a hinge clamping mechanism, an innovative design is carried out using the functional Extenics mechanical innovation design method.

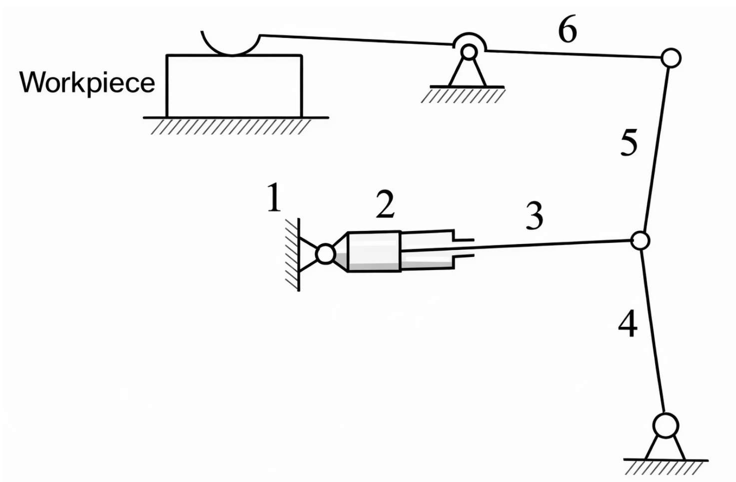


**Figure 3.** Schematic diagram of the mechanism movement of the automatic workpiece clamping device

### 4.1 Component Analysis

The components of the automatic clamping device for the workpiece shown in Figure 3 include the frame $M_{e1}$, hydraulic cylinder $M_{e2}$, piston rod $M_{e3}$, connecting rod $M_{e5}$, and two connecting frame rods $(M_{e4}, M_{e6})$, with the workpiece $M_{\mathrm{a}1}$ as the super-system component, which is also the object of action. The matter elements for these components are listed as follows.

$$M_{\mathrm{e}1} = \begin{bmatrix} \text{Frame,} & \text{Connecting hole,} & \text{Circular} \\ & \text{Assembly form,} & \text{Planes upport} \\ & \text{Material,} & \text{Castiron} \\ & \text{Surface roughness} & 6.3\mu\ \mathrm{m} \end{bmatrix}$$

$$M_{e2} = \begin{bmatrix} \text{Hydraulic cylinder,} & \text{Length,} & 54\ \mathrm{mm} \\ & \text{Diameter,} & 30\ \mathrm{mm} \\ & \text{Purpose,} & \text{Holds hydraulic oil} \\ & \text{Connecting hole,} & \text{Circular} \end{bmatrix}$$

$$M_{e3} = \begin{bmatrix} \text{Piston rod,} & \text{Length,} & 42\ \mathrm{mm} \\ & \text{Purpose,} & \text{Driving element} \\ & \text{Connecting hole,} & \text{Circular} \\ & \text{Speed,} & 20\ \mathrm{mm/s} \end{bmatrix}$$

$$M_{e4} = \begin{bmatrix} \text{Link rod I,} & \text{Length,} & 36\ \mathrm{mm} \\ & \text{Connecting hole,} & \text{Circular} \\ & \text{Mode of motion,} & \text{Swing} \\ & \text{Angle range,} & 0-50^{\circ} \end{bmatrix}$$

$$M_{e5} = \begin{bmatrix} \text{Link,} & \text{Length,} & 38\ \mathrm{mm} \\ & \text{Purpose,} & \text{Connection} \\ & \text{Mode of motion,} & \text{Planar motion} \\ & \text{Angle range,} & 0-48^{\circ} \end{bmatrix}$$

$$M_{e6} = \begin{bmatrix} \text{Link rod II,} & \text{Length,} & 73\ \mathrm{mm} \\ & \text{Purpose,} & \text{Conversion force} \\ & \text{Connecting hole I,} & \text{Circular} \\ & \text{Connecting hole II,} & \text{Circular} \end{bmatrix}$$

$$M_{a1} = \begin{bmatrix} \text{Workpiece,} & \text{Length,} & 35\ \mathrm{mm} \\ & \text{Width,} & 25\ \mathrm{mm} \\ & \text{Height,} & 18\ \mathrm{mm} \\ & \text{Surface roughness,} & \text{Ra6.3} \end{bmatrix}$$

### 4.2 Component Interaction Analysis

As seen in Figure 3, the interaction relationships between the components are shown in Table 4. If it is found that a component has no interaction with other components, the previous component analysis is incorrect and should be revisited for verification.

**Table 4.** Interaction between matter elements and components

| | $M_{e1}$ | $M_{e2}$ | $M_{e3}$ | $M_{e4}$ | $M_{e5}$ | $M_{e6}$ | $M_{a1}$ |
|---|---|---|---|---|---|---|---|
| $M_{e1}$ | - | $R_1$ | - | $R_6$ | - | $R_9$ | $R_8$ |
| $M_{e2}$ | $R_1$ | - | $R_2$ | - | - | - | - |
| $M_{e3}$ | - | $R_2$ | - | $R_3$ | $R_4$ | - | - |
| $M_{e4}$ | $R_6$ | - | $R_3$ | - | $R_{10}$ | - | - |
| $M_{e5}$ | - | - | $R_4$ | $R_{10}$ | - | $R_5$ | - |
| $M_{e6}$ | $R_9$ | - | - | - | $R_5$ | - | $R_7$ |
| $M_{a1}$ | $R_8$ | - | - | - | - | $R_7$ | - |

The interaction relationships between the components are described using relation elements as follows (since the relation elements for rotation hinges, such as $R_1, R_3, R_4, R_5, R_6, R_9, R_{10}$ are similar, only $R_1, R_3, R_4, R_5, R_{10}$ are listed, along with sliding pairs $R_2, R_8$ and higher pair $R_7$).

$$R_1 = \begin{bmatrix} \text{Hinge relationship,} & \text{Preceding item,} & M_{\mathrm{e}1} \\ & \text{Succeeding item,} & M_{\mathrm{e}2} \\ & \text{Method,} & \text{Pin} \\ & \text{Type of kinematic pair,} & \text{Lower pair} \end{bmatrix}$$

$$R_2 = \begin{bmatrix} \text{Sliding relationship,} & \text{Preceding item,} & M_{e2} \\ & \text{Succeeding item,} & M_{e3} \\ & \text{Stroke,} & 35 \\ & \text{Type of kinematic pair,} & \text{Lower pair} \end{bmatrix}$$

$$R_3 = \begin{bmatrix} \text{Hinge relationship,} & \text{Preceding item,} & M_{e3} \\ & \text{Succeeding item,} & M_{e4} \\ & \text{Method,} & \text{Pin} \\ & \text{Type of kinematic pair,} & \text{Lower pair} \end{bmatrix}$$

$$R_4 = \begin{bmatrix} \text{Hinge relationship,} & \text{Preceding item,} & M_{e3} \\ & \text{Succeeding item,} & M_{e5} \\ & \text{Method,} & \text{Pin} \\ & \text{Type of kinematic pair,} & \text{Lower pair} \end{bmatrix}$$

$$R_5 = \begin{bmatrix} \text{Hinge relationship,} & \text{Preceding item,} & M_{e5} \\ & \text{Succeeding item,} & M_{e6} \\ & \text{Method,} & \text{Pin} \\ & \text{Type of kinematic pair,} & \text{Lower pair} \end{bmatrix}$$

$$R_7 = \begin{bmatrix} \text{Clamping relationship,} & \text{Preceding item,} & M_{e6} \\ & \text{Succeeding item,} & M_{e7} \\ & \text{Method,} & \text{Line contact} \\ & \text{Relative motion type,} & \text{Sliding} \end{bmatrix}$$

$$R_8 = \begin{bmatrix} \text{Support relationship,} & \text{Preceding item,} & M_{e1} \\ & \text{Succeeding item,} & M_{a1} \\ & \text{Method,} & \text{Plane} \\ & \text{Relative motion type,} & \text{Fixed} \end{bmatrix}$$

$$R_{10} = \begin{bmatrix} \text{Hinge relationship,} & \text{Preceding item,} & M_{e4} \\ & \text{Succeeding item,} & M_{e5} \\ & \text{Method,} & \text{Pin} \\ & \text{Type of kinematic pair,} & \text{Lower pair} \end{bmatrix}$$

These relationships also correspond to interactions (functions), and the attributes of these functions are analyzed and described using functional matter elements (only the functional defect matter element models are listed).

$$A_2 = \begin{bmatrix} \text{Sliding,} & \text{Actuated object,} & M_{e2} \\ & \text{Controlled object,} & M_{e3} \\ & \text{Medium,} & \text{Hydraulic oil} \\ & \text{Functional attribute,} & \text{Insufficient} \end{bmatrix}$$

$$A_4 = \begin{bmatrix} \text{Rotation,} & \text{Actuated object,} & M_{e2} \\ & \text{Controlled object,} & M_{e5} \\ & \text{Medium,} & \text{Pin} \\ & \text{Functional attribute,} & \text{Insufficient} \end{bmatrix}$$

$$A_7 = \begin{bmatrix} \text{Clamping,} & \text{Actuated object,} & M_{e2} \\ & \text{Controlled object,} & M_{e3} \\ & \text{Method,} & \text{Direct contact} \\ & \text{Functional attribute,} & \text{Harmful} \end{bmatrix}$$

$$A_{10} = \begin{bmatrix} \text{Sliding,} & \text{Actuated object,} & M_{e4} \\ & \text{Controlled object,} & M_{e5} \\ & \text{Medium,} & \text{Pin} \\ & \text{Functional attribute,} & \text{Insufficient} \end{bmatrix}$$

### 4.3 Function Model Construction

Based on the component interaction relationships in Table 4, the function model described by elements is established, as shown in Figure 4.

From the function model in Figure 4, it can be seen that there is insufficient interaction from component $M_{e2}$ to component $M_{e3}$, insufficient interaction from component $M_{e3}$ to component $M_{e4}$, harmful interaction from component $M_{e6}$ to the workpiece $M_{a1}$, and insufficient interaction from component $M_{e4}$ to component $M_{e5}$.

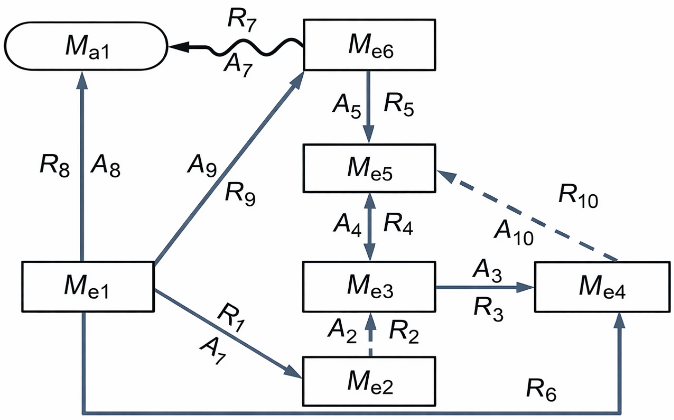


**Figure 4.** Primitive function model of automatic workpiece clamping device

### 4.4 Extension Analysis

Based on the analysis of the function model, the key components are determined to be $M_{e2}$, $M_{e3}$, $M_{e4}$, and $M_{e6}$, along with their related relation elements $R_2$, $R_4$, $R_5$, and $R_{10}$. These elements are subjected to extension analysis (mainly divergent extension, represented by $\mapsto$ ) as follows, forming paths for innovative improvements.

$$M_{e2} = \begin{bmatrix} \text{Hydraulic cylinder,} & \text{Length,} & 54\ \text{mm} \\ & \text{Diameter,} & 30\ \text{mm} \\ & \text{Pressure,} & 1.2\text{MPa} \\ & \text{Connecting hole,} & \text{Circular} \end{bmatrix} \mapsto$$

$$\left\{ \begin{array}{l} M_{e21} = \begin{bmatrix} \text{Hydraulic cylinder,} & \text{Length,} & 60\ \text{mm} \\ & \text{Diameter,} & 30\ \text{mm} \\ & \text{Pressure,} & 1.5\text{MPa} \\ & \text{Connecting hole,} & \text{Circular} \end{bmatrix} \\ M_{e22} = \begin{bmatrix} \text{Hydraulic cylinder,} & \text{Length,} & 60\ \text{mm} \\ & \text{Diameter,} & 30\ \text{mm} \\ & \text{Pressure,} & 2\text{MPa} \\ & \text{Connecting hole,} & \text{Waisted} \end{bmatrix} \\ M_{e23} = \begin{bmatrix} \text{Hydraulic cylinder,} & \text{Length,} & 65\ \text{mm} \\ & \text{Diameter,} & 30\ \text{mm} \\ & \text{Pressure,} & 2.5\text{MPa} \\ & \text{Connecting hole,} & \text{Rectangle} \end{bmatrix} \end{array} \right.$$

$$M_{e3} = \begin{bmatrix} \text{Piston rod,} & \text{Length,} & 42\ \text{mm} \\ & \text{Purpose,} & \text{Driving element} \\ & \text{Connecting hole,} & \text{Circular} \\ & \text{Speed,} & 20\ \text{mm/s} \end{bmatrix} \mapsto$$

$$\left\{ \begin{array}{l} M_{e31} = \begin{bmatrix} \text{Piston rod,} & \text{Length,} & 45\ \text{mm} \\ & \text{Purpose,} & \text{Driving element} \\ & \text{Connecting hole,} & \text{Circular} \\ & \text{Speed,} & 20\ \text{mm/s} \end{bmatrix} \\ M_{e32} = \begin{bmatrix} \text{Piston rod,} & \text{Length,} & 48\ \text{mm} \\ & \text{Purpose,} & \text{Driving element} \\ & \text{Connecting hole,} & \text{Waisted} \\ & \text{Speed,} & 20\ \text{mm/s} \end{bmatrix} \\ M_{e33} = \begin{bmatrix} \text{Piston rod,} & \text{Length,} & 50\ \text{mm} \\ & \text{Purpose,} & \text{Driving element} \\ & \text{Connecting hole,} & \text{Circular} \\ & \text{Speed,} & 25\ \text{mm/s} \end{bmatrix} \end{array} \right.$$

$$M_{e4} = \begin{bmatrix} \text{Link rod I,} & \text{Length,} & 36\ \mathrm{mm} \\ & \text{Connecting hole,} & \text{Circular} \\ & \text{Mode of motion,} & \text{Swing} \\ & \text{Angle range,} & 0-50^{\circ} \end{bmatrix} \mapsto$$

$$\begin{cases} M_{e41} = \begin{bmatrix} \text{Link rod I,} & \text{Length,} & \text{Adjustable} \\ & \text{Connecting hole,} & \text{Circular} \\ & \text{Mode of motion,} & \text{Swing} \\ & \text{Angle range,} & 0-50^{\circ} \end{bmatrix} \\ M_{e42} = \begin{bmatrix} \text{Link rod I,} & \text{Length,} & 40\ \mathrm{mm} \\ & \text{Connecting hole,} & \text{Waisted} \\ & \text{Mode of motion,} & \text{Swing} \\ & \text{Angle range,} & 0-50^{\circ} \end{bmatrix} \\ M_{e43} = \begin{bmatrix} \text{Link rod I,} & \text{Length,} & 42\ \mathrm{mm} \\ & \text{Connecting hole,} & \text{Waisted} \\ & \text{Mode of motion,} & \text{Swing} \\ & \text{Angle range,} & 0-50^{\circ} \end{bmatrix} \end{cases}$$

$$M_{e6} = \begin{bmatrix} \text{Link rod II,} & \text{Length,} & 73\ \mathrm{mm} \\ & \text{Purpose,} & \text{Conversion force} \\ & \text{Connecting hole I,} & \text{Circular} \\ & \text{Connecting hole II,} & \text{Circular} \end{bmatrix} \mapsto$$

$$\begin{cases} M_{e61} = \begin{bmatrix} \text{Link rod II,} & \text{Length,} & \text{Adjustable} \\ & \text{Purpose,} & \text{Conversion force} \\ & \text{Connecting hole I,} & \text{Waisted} \\ & \text{Connecting hole II,} & \text{Circular} \end{bmatrix} \\ M_{e62} = \begin{bmatrix} \text{Link rod II,} & \text{Length,} & \text{Adjustable} \\ & \text{Purpose,} & \text{Conversion force} \\ & \text{Connecting hole I,} & \text{Circular} \\ & \text{Connecting hole II,} & \text{Waisted} \end{bmatrix} \\ M_{e63} = \begin{bmatrix} \text{Link rod II,} & \text{Length,} & 73\ \mathrm{mm} \\ & \text{Purpose,} & \text{Conversion force} \\ & \text{Connecting hole I,} & \text{Waisted} \\ & \text{Connecting hole II,} & \text{Waisted} \end{bmatrix} \end{cases}$$

$$R_2 = \begin{bmatrix} \text{Sliding relationship,} & \text{Preceding item,} & M_{\mathrm{e}2} \\ & \text{Succeeding item,} & M_{\mathrm{e}3} \\ & \text{Stroke,} & 35 \\ & \text{Type of kinematic pair,} & \text{Lower pair} \end{bmatrix} \mapsto$$

$$\begin{cases} R_{21} = \begin{bmatrix} \text{Sliding relationship,} & \text{Preceding item,} & M_{\mathrm{e}21} \\ & \text{Succeeding item,} & M_{\mathrm{e}31} \\ & \text{Stroke,} & 38 \\ & \text{Type of kinematic pair,} & \text{Lower pair} \end{bmatrix} \\ R_{22} = \begin{bmatrix} \text{Sliding relationship,} & \text{Preceding item,} & M_{\mathrm{e}22} \\ & \text{Succeeding item,} & M_{\mathrm{e}32} \\ & \text{Stroke,} & 40 \\ & \text{Type of kinematic pair,} & \text{Lower pair} \end{bmatrix} \\ R_{23} = \begin{bmatrix} \text{Sliding relationship,} & \text{Preceding item,} & M_{\mathrm{e}23} \\ & \text{Succeeding item,} & M_{\mathrm{e}33} \\ & \text{Stroke,} & 45 \\ & \text{Type of kinematic pair,} & \text{Lower pair} \end{bmatrix} \end{cases}$$

$$R_4 = \begin{bmatrix} \text{Hinge relationship,} & \text{Preceding item,} & M_{\mathrm{e}3} \\ & \text{Succeeding item,} & M_{\mathrm{e}5} \\ & \text{Method,} & \text{Pin} \\ & \text{Type of kinematic pair,} & \text{Lower pair} \end{bmatrix} \mapsto$$

$$
\left\{
\begin{array}{l}
R_{41}=\begin{bmatrix} \text{Sliding relationship,} & \text{Preceding item,} & M_{\mathrm{e}31} \\ & \text{Succeeding item,} & M_{\mathrm{e}51} \\ & \text{Method,} & \text{Sliding pin} \\ & \text{Type of kinematic pair,} & \text{Lower pair} \end{bmatrix} \\
R_{42}=\begin{bmatrix} \text{Sliding relationship,} & \text{Preceding item,} & M_{\mathrm{e}32} \\ & \text{Succeeding item,} & M_{\mathrm{e}52} \\ & \text{Method,} & \text{Pin} \\ & \text{Type of kinematic pair,} & \text{Lower pair} \end{bmatrix} \\
R_{43}=\begin{bmatrix} \text{Sliding relationship,} & \text{Preceding item,} & M_{\mathrm{e}33} \\ & \text{Succeeding item,} & M_{\mathrm{e}53} \\ & \text{Method,} & \text{Sliding pin} \\ & \text{Type of kinematic pair,} & \text{Lower pair} \end{bmatrix}
\end{array}
\right.
$$

$$
R_5=\begin{bmatrix} \text{Hinge relationship,} & \text{Preceding item,} & M_{\mathrm{e}5} \\ & \text{Succeeding item,} & M_{\mathrm{e}6} \\ & \text{Method,} & \text{Pin} \\ & \text{Type of kinematic pair,} & \text{Lower pair} \end{bmatrix} \mapsto
$$

$$
\left\{
\begin{array}{l}
R_{51}=\begin{bmatrix} \text{Sliding relationship,} & \text{Preceding item,} & M_{\mathrm{e}51} \\ & \text{Succeeding item,} & M_{\mathrm{e}61} \\ & \text{Method,} & \text{Sliding pin} \\ & \text{Type of kinematic pair,} & \text{Lower pair} \end{bmatrix} \\
R_{52}=\begin{bmatrix} \text{Sliding relationship,} & \text{Preceding item,} & M_{\mathrm{e}52} \\ & \text{Succeeding item,} & M_{\mathrm{e}62} \\ & \text{Method,} & \text{Pin} \\ & \text{Type of kinematic pair,} & \text{Lower pair} \end{bmatrix} \\
R_{53}=\begin{bmatrix} \text{Sliding relationship,} & \text{Preceding item,} & M_{\mathrm{e}53} \\ & \text{Succeeding item,} & M_{\mathrm{e}63} \\ & \text{Method,} & \text{Sliding pin} \\ & \text{Type of kinematic pair,} & \text{Lower pair} \end{bmatrix}
\end{array}
\right.
$$

$$
R_{10}=\begin{bmatrix} \text{Hinge relationship,} & \text{Preceding item,} & M_{\mathrm{e}4} \\ & \text{Succeeding item,} & M_{\mathrm{e}5} \\ & \text{Method,} & \text{Pin} \\ & \text{Type of kinematic pair,} & \text{Lower pair} \end{bmatrix} \mapsto
$$

$$
\left\{
\begin{array}{l}
R_{101}=\begin{bmatrix} \text{Sliding relationship,} & \text{Preceding item,} & M_{\mathrm{e}41} \\ & \text{Succeeding item,} & M_{\mathrm{e}51} \\ & \text{Method,} & \text{Sliding pin} \\ & \text{Type of kinematic pair,} & \text{Lower pair} \end{bmatrix} \\
R_{102}=\begin{bmatrix} \text{Sliding relationship,} & \text{Preceding item,} & M_{\mathrm{e}42} \\ & \text{Succeeding item,} & M_{\mathrm{e}52} \\ & \text{Method,} & \text{Pin} \\ & \text{Type of kinematic pair,} & \text{Lower pair} \end{bmatrix} \\
R_{103}=\begin{bmatrix} \text{Sliding relationship,} & \text{Preceding item,} & M_{\mathrm{e}43} \\ & \text{Succeeding item,} & M_{\mathrm{e}53} \\ & \text{Method,} & \text{Sliding pin} \\ & \text{Type of kinematic pair,} & \text{Lower pair} \end{bmatrix}
\end{array}
\right.
$$

Other matter elements, relation elements, and functional elements can also be extended. In addition, methods such as related networks and implication systems can be used, thus generating several times more innovative paths than those obtained from the original function model.

### 4.5 Extenics Transformation

Based on the potential creative paths obtained from the extension analysis, further transformations such as substitution, addition, and deletion are applied to generate a series of creative solutions to address the deficiencies and harmful issues in the workpiece clamping mechanism.

For example, sequential substitution transformations are applied to $M_{\mathrm{e}2}, M_{\mathrm{e}3}, M_{\mathrm{e}5}, R_5$, and $R_{10}$, and addition transformations are applied to $R_9$ to obtain Scheme 1, that is, $D_1 = T_z M_{e2} \wedge T_z M_{e3} \wedge T_z M_{e5} \wedge T_z R_5 \wedge T_A R_9 \wedge T_z R_{10}$, where $T_z$ represents substitution transformation, and one of the previously extended matter or relation elements substitutes the original matter or relation element, $T_A$ represents addition transformation. Scheme 1 is shown in Figure 5a.

Similarly, Scheme 2, $D_2 = T_zM_{e2} \wedge T_zM_{e3} \wedge T_zM_{e4} \wedge T_zM_{e5} \wedge T_zR_5 \wedge T_AR_9$, is obtained, as shown in Figure 5b.

Scheme 3, $D_3 = T_zM_{e2} \wedge T_zM_{e3} \wedge T_{z4'}M_{e4} \wedge T_{z5'}M_{e5} \wedge T_zR_4 \wedge T_zR_{10} \wedge T_AR_9$, is obtained, as shown in Figure 5c.

Scheme 4, $D_4 = T_zM_{e2} \wedge T_zM_{e3} \wedge T_{z4'}M_{e4} \wedge T_{z5''}M_{e5} \wedge T_zR_4 \wedge T_zR_{10} \wedge T_AR_9$, is obtained, as shown in Figure 5d.

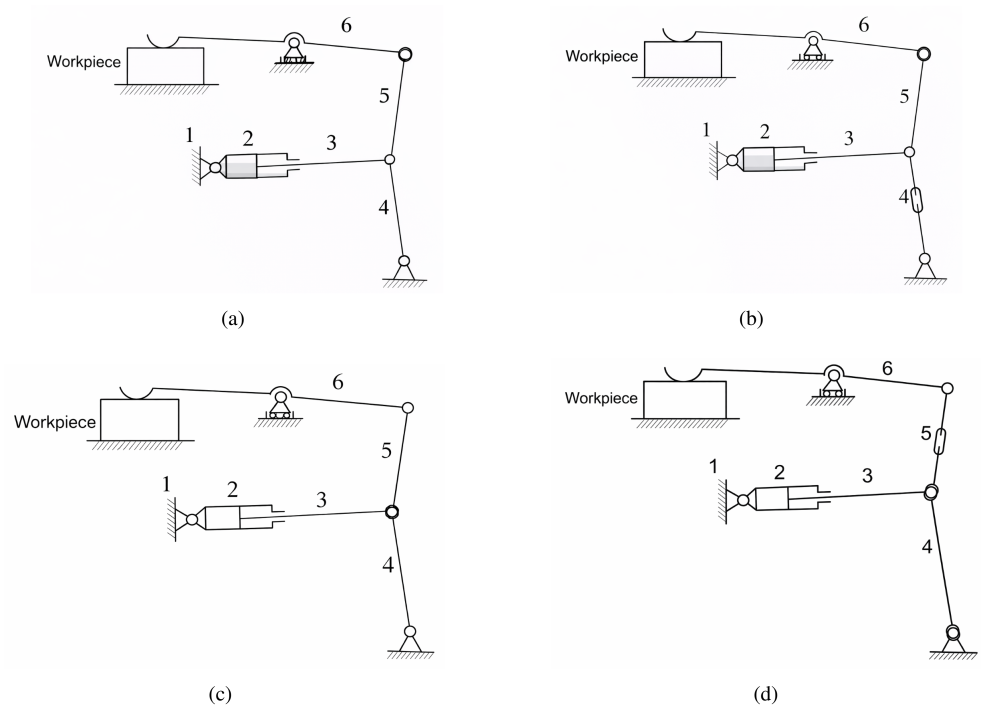


**Figure 5.** Creative ideas of automatic workpiece clamping device: (a) Creative idea 1; (b) Creative idea 2; (c) Creative idea 3; (d) Creative idea 4

The above schemes can reduce scratches on the workpiece surface (from circular hinge holes to waist-shaped holes, allowing movement between rods at the hinge, thus reducing relative sliding between the clamping jaws and the workpiece), while maintaining enough stroke to clamp the workpiece. These solutions can address the issues identified in the functional analysis. Note: Only four schemes are listed here; in fact, many more schemes can be generated through transformations, but due to space limitations, the transformations and other schemes are not detailed.

### 4.6 Scheme Evaluation

For the numerous creative solutions, an evaluation needs to be performed to select the optimal one for detailed design. Based on the conclusions from the functional analysis, harmful and insufficient effects are eliminated (i.e., reducing sliding of the clamping jaws on the workpiece surface and increasing the clamping force). Since the relative sliding of the clamping jaws on the workpiece surface can be compensated through $R_9'$ (namely the $R9$ after addition), so the sliding is zero for these solutions and is no longer considered as an evaluation indicator. Therefore, the evaluation indicators selected are relative cost (increased cost/original cost), relative clamping force (increased clamping force/original clamping force), and adjustable distance. Five experts from the mechanical industry scored the relative importance of these indicators, determining the weights for each indicator as 0.35 , 0.32 , and 0.33 , respectively. The evaluation values for each indicator are calculated based on the number of modified components and mechanical and geometric calculations (normalized), as shown in Table 5. The quality value is then calculated using Eq. (5). The evaluation reveals that Creative idea 2 has the highest quality value, and it can be selected for detailed structural design.

From this process, it can be seen that the mechanical innovation design method based on functional Extenics can integrate the advantages of functional models and extension/transformation methods, efficiently generating ideas and improving the effectiveness of innovative design.

**Table 5.** Standardized evaluation form for the scheme

| Scheme | Relative Cost ($k_{c1}$) | Relative Clamping Force ($k_{c2}$) | Adjustable Distance ($k_{c3}$) |
|---|---|---|---|
| Scheme 1 $O_1$ | 1 | 0.78 | 0.69 |
| Scheme 2 $O_2$ | 0.8 | 0.94 | 0.92 |
| Scheme 3 $O_3$ | 0.8 | 0.84 | 0.77 |
| Scheme 4 $O_4$ | 0.6 | 1 | 1 |

Note: $C(O_1) = 0.827, \quad C(O_2) = 0.884, \quad C(O_3) = 0.803, \quad C(O_4) = 0.86$

## 5 Conclusion

The application of innovation methods is key to mechanical product innovation design. Integrating various innovative methods brings together the advantages of these methods and plays an important role in mechanical innovation design. This paper integrates TRIZ theory's functional analysis with Extenics innovation methods to construct a mechanical innovation design method based on functional Extenics. Based on demand analysis and problem clarification, a product function model is constructed using element description. Through extension analysis of the core problem's related element models, as many creative paths as possible are generated. These are further transformed into creative solutions via Extenics transformations and evaluated for quality, with the highest quality solution selected for further design. This method can effectively improve the efficiency and breadth of mechanical innovation design and help form a more systematic and traceable structural generation and optimization path in complex mechanical systems, supporting reasonable configuration and performance improvement of mechanical structures.

This method is mainly applied to the improvement of existing products (i.e., optimizing or improving the shortcomings of existing products), as the function model is easier to construct based on the current product. There are no limitations in applying this method to the improvement of existing products; any existing product can have a function model built and core issues identified. This method is particularly suitable for mechanical product design and optimization scenarios involving multi-functional coupling, multi-constraint conditions, and precise structural configurations. It helps achieve performance enhancement while meeting manufacturability and structural reliability requirements.

Further, the method can be integrated with artificial intelligence to enhance the efficiency of designers in obtaining product improvement solutions. Future work will explore embedding this method into computer-aided design and manufacturing environments to achieve integration with existing design processes and engineering data systems, thus enhancing the operability and application value of this method in engineering practice.

## Author Contributions

Conceptualization, F.J. and J.D.; methodology, F.J.; software, W.C.; validation, W.C. and J.D.; formal analysis, F.J.; investigation, F.J.; resources, F.J.; data curation, W.C.; writing—original draft preparation, F.J.; writing—review and editing, F.J.; visualization, W.C.; supervision, F.J.; project administration, J.D.; funding acquisition, F.J. All authors have read and agreed to the published version of the manuscript.

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## Data Availability

The data used to support the research findings are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare no conflict of interest.

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**Nomenclature**

| | |
|---|---|
| $M$ | mater-element |
| $M_e$ | matter-element of system component |
| $M_a$ | matter-element of supersystem component |
| $A$ | event element |
| $R$ | relationship element |
| $\mapsto$ | divergent tree method |
| $T_i$ | replacement transformation |
| $T_{zi}$ | increase transformation |
| $k$ | correlation |
| $k(x)$ | correlation function |
| $C$ | superiority |
| $O$ | object |
| $C(O_i)$ | superiority of the $i$th scheme |