Design of a Parametric Driving and Model Replacement System for Product Families

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Abstract: Product families usually contain multiple variants derived from a common structure, but frequent changes in specifications still require considerable manual modification of CAD models and assembly relationships. In practical design processes, parameter adjustment alone cannot satisfy the requirements of some variants because certain components need to be replaced with different models. This study develops a parametric driving and component replacement system for product-family design based on CAD secondary development. The system integrates parameter-driven modeling, equation-based dimensional linkage, component substitution, and mate reconstruction within the CAD environment. A database is established to manage product parameters, component file paths, and assembly constraints, while SolidWorks API is used to realize model modification and assembly operations. With this workflow, users can generate product variants by providing design parameters and completing the required CAD operations. A CD250 hydraulic-cylinder family was selected as an example for system verification. The results show that the developed system can update related dimensions, replace specified components, and recover assembly mates during product variation. Compared with manual modification, the proposed approach reduces repeated modeling operations and improves the efficiency of variant design for mechanical products with similar structures.

Keywords: Product Family; Parametric Driving; Model Replacement; Automatic Mating; Hydraulic Cylinder; CAD Secondary Development.

1. Introduction

In mechanical manufacturing, many products are developed in the form of product families rather than independent models. Different variants within the same family generally share similar structural characteristics while varying in several key specifications, such as dimensions, connection methods, or local components. Hydraulic cylinders, reducers, and stacker cranes are representative examples of this type of product. Although these products have high component similarity and strong parameter relationships, the design process of different variants still involves repeated CAD modification and assembly adjustment [1].

For a new specification derived from an existing product, designers usually need to modify dimensions, replace some components, and verify assembly relationships manually. Such operations are time-consuming, especially when changes involve multiple dependent parts. Previous studies have indicated that reuse of existing design resources can reduce repeated modeling work and improve engineering efficiency [2]. Parametric design provides an effective approach by establishing relationships between design parameters and model dimensions, allowing CAD models to be updated when input parameters change [3]. Recent studies have further emphasized that robust parametric CAD modeling principles are important for maintaining model stability during repeated design changes and product variation [4]. Based on this concept, researchers have carried out studies on hydraulic-cylinder parametric modeling, CAD secondary development, standard-part libraries, and series-component design methods [5-11].

However, current research mainly focuses on individual part modeling or the construction of reusable component libraries. In actual product-family variation, the modification of a single dimension is often insufficient. Some variants require replacement of specific components, such as cylinder heads, guide sleeves, or connection structures. After component replacement, the original assembly relationships may become invalid because referenced faces, axes, or geometric features are changed. Existing CAD systems generally require designers to manually repair these assembly constraints, which reduces the efficiency of rapid variant design [12]. To support rapid product development, digital variant design methods have been proposed to organize product variation processes and improve the reuse of existing design knowledge [13]. In addition, automated approaches for generating new variant design options from existing product families have shown the potential of systematic variant generation, but the reconstruction of detailed CAD assembly relationships still remains a practical challenge [14].

Assembly modeling is another important aspect of product-family variation. For complex mechanical products, the design intent is not only reflected in part dimensions, but also in the hierarchical structure and assembly constraints between components. Multi-level assembly models and top-down design methods have been studied to support the organization and propagation of product information in mechanical product design [15]. Meanwhile, semantically enriched CAD models and model-based definition methods provide useful ideas for describing geometric entities and manufacturing information in a more explicit way, which is beneficial for downstream digital manufacturing and model reuse [16]. These studies indicate that incorporating semantic information and standardized references into CAD models can improve the robustness of model modification and replacement.

In this work, a parametric driving and model replacement approach is developed for product-family variation. The proposed system targets mechanical products with similar architectures and interchangeable components. A CD250 hydraulic-cylinder family is selected as the verification object, and SolidWorks secondary development is adopted as the implementation method. The system integrates parameter-driven modeling, equation-based dimensional linkage, component replacement, and automatic mate reconstruction based on standardized entity naming. These functions allow parameter modification, model updating, and assembly recovery to be performed within one integrated design process.

2. Key Technologies and Methods for Rapid Product-Family Variation

The system includes four functional modules: parameter-driven modeling, equation-based dimensional linkage, component replacement, and automatic mate reconstruction. The first two functions are mainly responsible for controlling dimensional changes within the product family, while the latter two focus on component-level variation and assembly consistency. By combining these operations, the system provides a complete workflow for generating different product variants from a common CAD model.

2.1 Parametric Driving for Product Families

Parametric driving is the basic approach used to generate different variants in a product family. In this method, important geometric dimensions are defined as controllable parameters and stored through parameter tables or database records. According to the selected product specification or user-defined inputs, the corresponding model dimensions can be modified automatically and the CAD model can be rebuilt.

The coding scheme of the CD hydraulic-cylinder family is shown in Figure 1. Each part of the product code represents a specific design requirement, including pressure level, bore diameter D, rod diameter d, and stroke S.

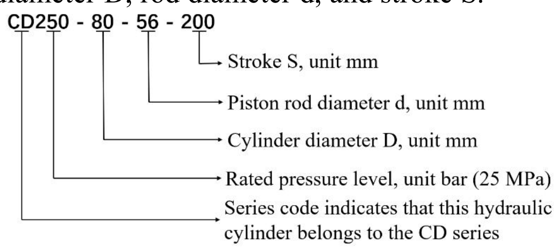

Figure 1. Coding Scheme for the CD Hydraulic-Cylinder Family

For product-family design, parameters can be classified into three groups, as illustrated in Figure 2. The first group contains basic parameters, including cylinder bore D, rod diameter d, and stroke S, which directly determine the product specification. The second group includes derived parameters, such as cylinder-tube outer diameter, piston width, and guide-sleeve length, which are calculated from the basic parameters. The third group consists of structural parameters, including mounting type, connection structure, and sealing configuration. These parameters determine whether certain components need to be replaced during variant generation.

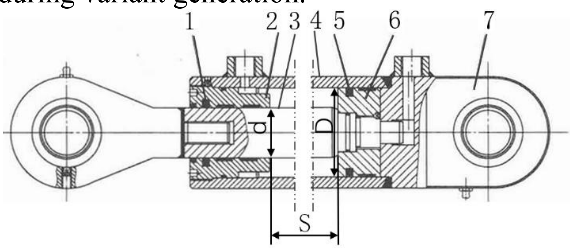

Figure 2. Structure of a Double-Acting Single-Rod Hydraulic Cylinder

He numbered components are: 1, rod sealing system; 2, cylinder head; 3, piston rod; 4, cylinder tube; 5, piston sealing system; 6, piston; and 7, cylinder base with a single clevis.

In a CAD environment, parameter-driven modeling is generally realized by accessing dimension objects through secondary-development interfaces. Taking SolidWorks as an example, the API structure allows programs to access document objects, feature objects, and dimension objects step by step, as shown in Figure 3. The program can identify required dimensions by their names, assign new values, and rebuild the model. In the hydraulic-cylinder case, bore diameter, rod diameter, and stroke are selected as driving parameters to update the cylinder tube, piston rod, bushing, and guide sleeve.

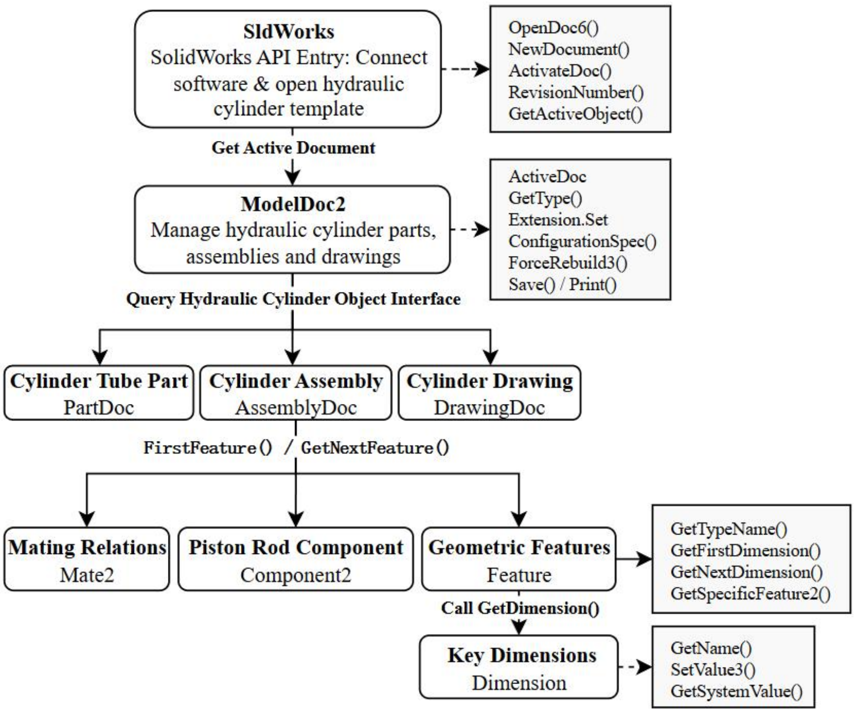

Figure 3. SolidWorks API Object Hierarchy Used in Hydraulic-Cylinder Design

2.2 Equation-Based Dimensional Linkage

Components in a product family usually contain internal dimensional relationships. Directly modifying each dimension separately may cause inconsistent changes between related components. For example, piston diameter is associated with cylinder bore and clearance requirements, guide-sleeve diameter depends on rod diameter, and cylinder-tube length is related to stroke and end structures. Therefore, dimensional dependencies need to be defined explicitly.

The basic approach is to define the primary driving parameters as global variables and express associated component dimensions as functions of those variables. Let the basic parameters of the hydraulic cylinder be bore diameter D, rod diameter d, and stroke S. The associated dimensions can then be expressed as:

$$x_i = f_i(D, d, S) \quad (1)$$

where xi represents the i-th dependent dimension and fi represents the relationship between this dimension and the basic parameters. According to the structural characteristics of the hydraulic cylinder, typical dimensional relationships can be established, as shown in Figure 4.

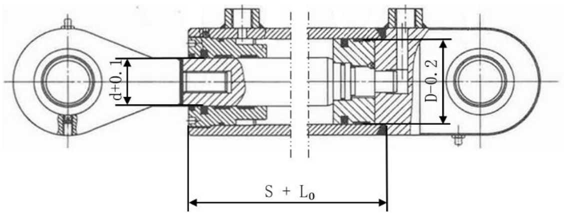

Figure 4. Typical Dimensional Linkage in a Hydraulic Cylinder

In this relationship, piston diameter is determined by bore diameter D and the designed clearance, guide-sleeve diameter is determined by rod diameter d and fitting allowance, and cylinder-tube length is calculated from stroke S and end compensation length L0. When the basic parameters are modified, the equation manager updates the dependent dimensions automatically, maintaining consistency among different components.

Compared with independent dimension modification, equation-based linkage provides a more reliable method for maintaining design relationships. Although the current implementation focuses on hydraulic cylinders, the same principle can be applied to other mechanical products with clear parameter dependencies.

2.3 Model Replacement

For many product families, variation between specifications cannot be achieved only by changing dimensions. Some components must be replaced with corresponding models designed for different specifications. In hydraulic cylinders, changes in bore diameter, rod diameter, or mounting structure may require replacement of components such as cylinder tubes, bushings, cylinder heads, and connectors.

Traditional replacement processes usually require designers to manually delete old components, search for new files, insert models, and repair assembly relationships. This process increases workload and may introduce errors. Therefore, the model replacement function is introduced to automatically substitute components according to the target product specification.

The replacement process includes five steps: (1) obtaining the components requiring replacement from the target model information stored in the database; (2) retrieving corresponding component paths from the mapping table; (3) recording assembly mates related to the replaced components; (4) executing component replacement through the CAD interface; and (5) rebuilding assembly relationships after replacement.

In SolidWorks, the ReplaceComponents2 method is used to perform component substitution. Figure 5 shows the replacement process of a cylinder head. Although the original assembly structure can usually be maintained after replacement, differences in geometric references may cause some mates to become invalid. Therefore, an additional mate reconstruction strategy is required to restore assembly constraints.

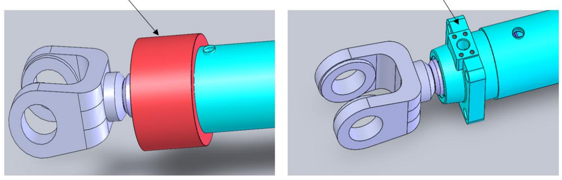

Figure 5. Example of Component Replacement in a Hydraulic Cylinder

2.4 Automatic Mate Reconstruction

Automatic mate reconstruction is the key operation following model replacement. Its purpose is to identify and restore the original assembly relationships after a component has been substituted, thereby maintaining assembly integrity and correctness. The main difficulty is that the geometry of the new component may differ from that of the old one, so the faces, edges, and axes used by the original mates must be matched to equivalent entities in the replacement part.

To address this problem, the system adopts a naming-based reconstruction strategy. During template modeling, important mating faces and axes are assigned standardized names. For example, the outer cylindrical face of a piston may be named “Piston_OD”, while the inner cylindrical face of a cylinder tube may be named “Cylinder_ID”, as shown in Figure 6.

These names are retained in the feature tree and can be accessed through the API. Component replacement automatically triggers the following sequence. First, the system records each mate associated with the selected component, including mate type (e.g. concentric, coincident, or distance), the name of the referenced entity, the owning component, and any mate parameters such as distance. Second, the old component is replaced according to the path mapping table. Third, the system searches the new component for a face or edge with the recorded entity name; for standard cylindrical or planar faces, geometric type is also used as an auxiliary criterion. Finally, the mate is recreated through the mate-creation API. Distance mates additionally require the distance value and alignment direction.

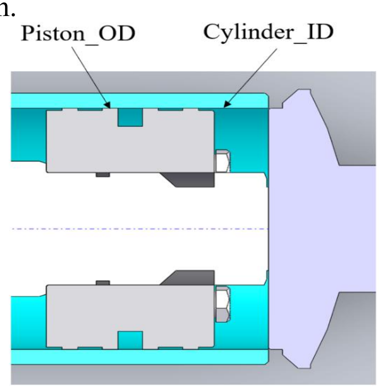

Figure 6. Naming of Key Mating Entities in the Hydraulic-Cylinder Model

The success of this strategy depends strongly on a consistent naming convention during template development. An enterprise can define an internal naming standard and apply it across all template models to maintain a high reconstruction success rate. Complex mates that cannot be resolved by name are logged and submitted for manual correction.

3. System Design and Implementation

3.1 Overall Functions

A CAD-based system was constructed to support the variation design of product families. Based on a product parameter table, a component model library, and assembly templates, the system performs automatic modeling and replacement through the CAD secondary-development interface.

Product-model selection: The user can select an existing hydraulic-cylinder model through the interface. After selection, the system obtains corresponding design parameters, component file locations, and assembly-related information from the database.

Key-parameter input: the user may manually enter bore, rod diameter, stroke, and other driving parameters. The system calculates derived dimensions and updates the model.

Dimension driving: The system modifies corresponding model dimensions according to parameter information, enabling different specifications within the same product family to be generated from a common design template.

Equation-based linkage: global variables and equations maintain inter-part dimensional relationships and ensure synchronized change.

Model replacement: For components that cannot be modified only through dimension changes, such as cylinder tubes, bushings, end covers, and connectors, the system retrieves suitable models from the component library and performs replacement operations.

Mate reconstruction: Before component replacement, existing assembly relationships are recorded. After replacement, corresponding geometric references are identified and assembly mates are recreated automatically.

Logging and feedback: parameter access, dimensional updating, component replacement, mate reconstruction, and exceptions are recorded for inspection and maintenance.

3.2 System Architecture

The software architecture contains four layers: user interface, business logic, API interaction, and data management, as illustrated in Figure 7. This structure separates user operations, design rules, CAD communication, and data management, which facilitates system maintenance and functional expansion.

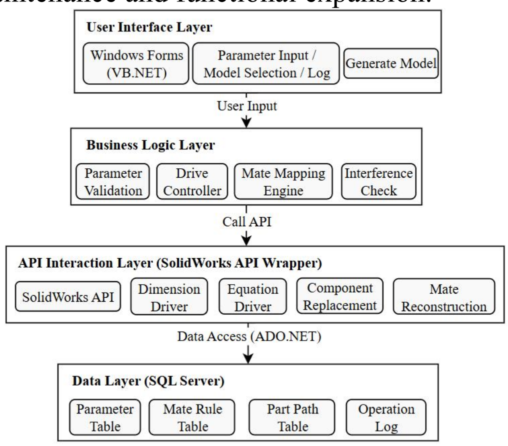

Figure 7. Overall System Architecture

3.2.1 Development environment and tools

The system was developed using Visual Studio 2022 with the. NET 8.0 framework. VB.NET was selected as the programming language because its syntax is compatible with VBA and provides convenient interaction with SolidWorks API. SolidWorks 2020 was used as the CAD platform, while SQL Server 2019 was adopted for product data storage. The system operates under Windows 10 or later environments.

3.2.2 Layer descriptions

(1) User-interface layer. The user-interface

layer was developed using Windows Forms. It provides functions including hydraulic-cylinder model selection, parameter input, mounting-type selection, and execution-status display. Through this interface, users can define design requirements and obtain feedback from the system.
(2) Business-logic layer. The business-logic layer is responsible for processing design rules and controlling the variation process. It performs parameter checking, dimension-driving control, mate mapping, and interference-related operations. According to user input, this layer coordinates the API interaction layer to complete model updating, component replacement, and assembly reconstruction.
(3) API interaction layer. The API interaction layer provides communication between the application and SolidWorks. Common CAD operations, including document opening, dimension access, equation modification, component replacement, and mate creation, are encapsulated as reusable functions. This design reduces the complexity of direct API calls in the upper-level programs.
(4) Data layer. SQL Server stores product parameters, component-path mappings, and mating rules. The principal tables are CylinderParams, which stores the model ID, bore D, rod diameter d, stroke S, mounting type, outer-diameter coefficients, and related paths; MateRules, which stores the two component names, mating-entity names, mate type, and associated parameters; PartPathMap, which maps product models to component-file paths; and OperationLog, which records each design operation for traceability.
3.2.3 System data flow
When a user selects a product model or enters design parameters, the business-logic layer first obtains corresponding information from the database. The API interaction layer then performs dimensional modification, equation updating, component replacement, and mate reconstruction sequentially. Execution results are stored in OperationLog. After completing the variation process, SolidWorks saves the generated model, and the updated file information can be reused in later design tasks.

3.3 Implementation of the Core Modules
The core modules were implemented using a CD250 hydraulic-cylinder family. They operate around a mapping chain of “parameter-dimension-component-mate.” Product parameters are first retrieved from the database and used to update model dimensions. Equations then maintain cross-component dimensional relationships. Local components are replaced according to path mappings, after which assembly mates are restored according to predefined naming rules. SolidWorks API and SQL Server cooperate throughout the process.
(1) Dimension-driving module. The system uses the product model as an index to retrieve bore D, rod diameter d, and stroke S from CylinderParams. It traverses dimension objects through SolidWorks API, locates key dimensions by name, and assigns the corresponding values. Derived dimensions, such as cylinder-tube outer diameter = D × 1.25, are calculated in code. ForceRebuild3 () is then called to regenerate the model. This module updates the principal dimensions of the cylinder tube, piston rod, and bushing, as illustrated in Figure 8.

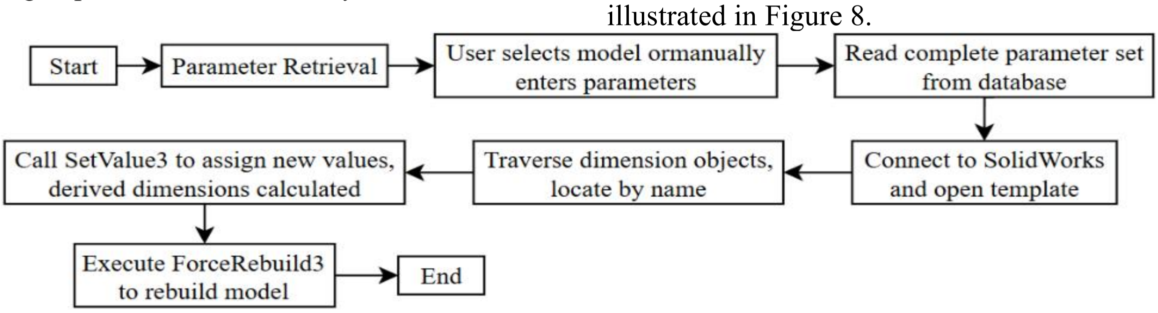

Figure 8. Workflow of the Dimension-Driving Module

(2) Equation-driving module. Global variables D, d, and S are defined in the assembly template and related to component dimensions through equations, such as PistonOD = D − 0.2. The program obtains the equation manager through GetEquationMgr (), traverses the equation list, replaces the right-hand values of expressions containing D, d, and S with the current inputs, and calls ForceRebuild3 (). As a result, the cylinder bore, piston diameter, and guide-sleeve diameter are updated simultaneously, as illustrated in Figure 9.

(3) Model-replacement module. PartPathMap defines the mapping among product model, component name, and model-file path. After the target model has been specified, the system queries the replacement list, locates each old component in the assembly, and calls ReplaceComponents2 () to substitute the corresponding file. Replacement status is recorded in the log, avoiding repeated manual deletion, file searching, and reassembly, as illustrated in Figure 10.

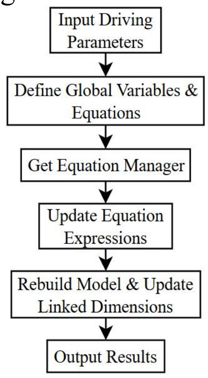

Figure 9. Workflow of the Equation-Driving Module

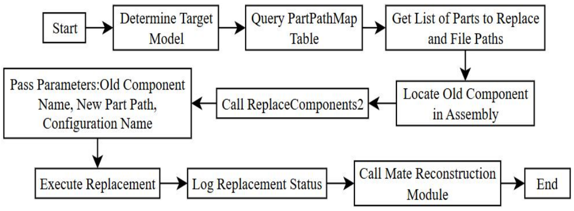

Figure 10. Workflow of the Model-Replacement Module

(4) Automatic mate-reconstruction module. Before replacement, the system traverses the mate features of each selected component and records mate type, reference-entity name, owning component, and mate parameters. After replacement, corresponding faces or edges are located in the new component by entity name, with geometric type used as an additional check. AddMate () then reconstructs concentric, coincident, and distance mates. If no valid entity can be found, the exception is written to OperationLog and the user is prompted to correct it manually, as illustrated in Figure 11.

4. Case Study

A CD250 double-acting single-rod hydraulic cylinder was selected to examine the practical performance of the developed system. This type of hydraulic cylinder represents a typical product family because different models share similar structural components while varying in several key specifications. Components such as the cylinder tube, piston rod, piston, cylinder head, guide sleeve, bushing, and connectors are reused among different variants, whereas bore diameter, rod diameter, stroke, and mounting configuration determine the final product specification.

In this study, the model CD250-80-56-200 was selected for verification. The main design parameters are a bore diameter D of 80 mm, a rod diameter d of 56 mm, a stroke S of 200 mm, and a clevis mounting structure. This model contains both dimensional modification and component replacement requirements, making it suitable for evaluating the proposed variation process.

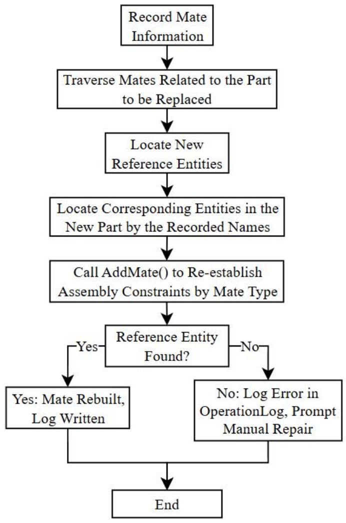

Figure 11. Workflow of the Automatic Mate-Reconstruction Module

4.1 Parameter Input and Model Driving

After starting the system, as shown in Figure 12, and connecting to SolidWorks 2020, the user selects "CD250-80-56-200" from the main interface or manually enters D = 80, d = 56, and S = 200 and selects clevis mounting.

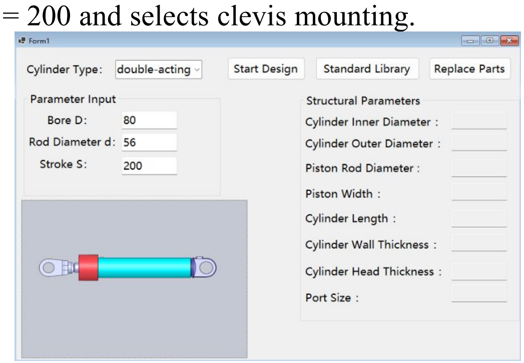

Figure 12. Parameter-Input Interface

When the Start Design command is executed, the system reads the complete parameter set from SQL Server, including the cylinder-tube outer-diameter coefficient and piston-width coefficient, and then performs dimension driving, equation updating, model replacement, and mate reconstruction in sequence.

4.2 Model-Generation Process

(1) Dimension driving and equation linkage. The system first traverses the dimension objects of the cylinder tube, bushing, and other components and locates the key dimensions by name. Derived values are calculated as follows: cylinder-tube outer diameter = D × 1.25 = 100 mm; cylinder-tube length = S + 80 = 280 mm; and bushing inner diameter = d + 0.5 = 56.5 mm. These values are assigned through SetValue3 (). Global variables D, d, and S are also predefined, with equations such as “BoreDiameter” = “D” and “PistonOD” = “D” − 0.2. GetEquationMgr () is used to replace the right-hand values with 80, 56, and 200, respectively. ForceRebuild3 () then regenerates the model so that direct and linked dimensions are updated together.

(2) Model replacement. For the target model CD250-80-56-200, the system reads the destination file paths of the bushing, cylinder head, and other parts from PartPathMap. The corresponding components in the template assembly are replaced, while their mate information is recorded for subsequent reconstruction.

As shown in Figure 13, the original cylinder head is replaced by the one associated with CD250-80-56-200. The assembly remains correctly positioned after replacement because the mate-reconstruction module restores the required constraints.

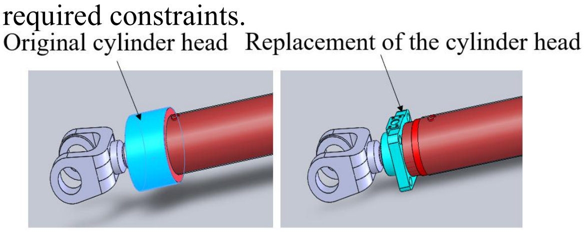

Figure 13. Cylinder-Head Model Before and After Replacement

(3) Mate reconstruction. The system follows the sequence “record-replace-search-rebuild.” Mate rules are retrieved from MateRules. For example, “Cylinder_OD” identifies the outer cylindrical face of the cylinder tube and “Bushing_ID” identifies the inner face of the bushing. GetFaceByName () locates the corresponding entities in the new components, and AddMate () rebuilds concentric and coincident relationships.

As shown in Figure 14, the cylinder-tube outer diameter and length become 100 mm and 280 mm, respectively. At the same time, the component position within the assembly remains unchanged, indicating that dimensional updating and component replacement can be performed together within the proposed workflow.

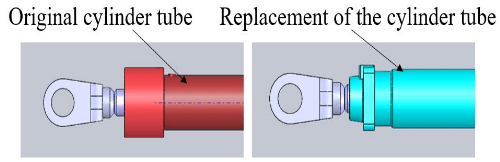

Figure 14. Cylinder Tube Before and After Replacement

4.3 Results and Discussion

The verification case shows that the developed system can perform the main operations required for hydraulic-cylinder variant design. After the user provides basic product information, the system retrieves corresponding data from the database and performs dimension updating, equation linkage, component replacement, and mate reconstruction.

The updated cylinder tube, bushing, and related components satisfy the specified design parameters, demonstrating that the parameter-driving and equation-linkage functions maintain dimensional consistency among different components. As shown in Figure 15, the assembly structure remains unchanged after component replacement, and no apparent positional deviation is observed.

The case study also indicates that the proposed approach can reduce repetitive operations in CAD variation design, especially for component searching, replacement, and assembly constraint recovery. However, the reconstruction performance relies on consistent naming of mating entities in template models. When component geometries differ significantly or naming rules are incomplete, additional manual adjustment may still be required.

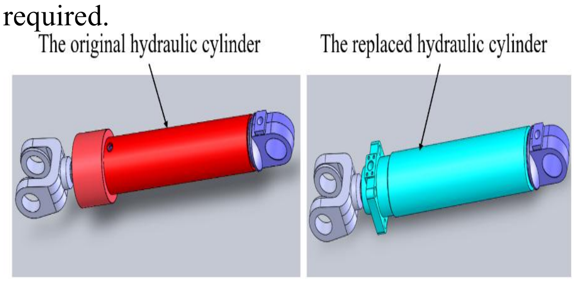

Figure 15. Hydraulic-Cylinder Assembly Before and After Variation

5. Conclusions

This study proposed a parametric driving and model replacement method for rapid variant design of product families, with the aim of reducing repetitive parameter editing, complex component substitution, and mate failure after replacement. A CD250 hydraulic-cylinder family was used to implement and evaluate the method. The main conclusions are as follows.

(1) The design requirements of product families were clarified. Such products share similar structures, include multiple specifications, exhibit strong parameter dependence, and often contain locally replaceable components. Dimension driving at the individual-part level alone is therefore insufficient for rapid assembly-level variation.

(2) Parametric driving was integrated with equation-based linkage. Key parameters drive model dimensions, while global variables and equations preserve relationships among dimensions in different components, thereby maintaining consistency during variation.

(3) An assembly-level model-replacement method was developed. Component-path mappings allow the system to replace selected parts automatically according to the target product model.

(4) A naming-based mate-reconstruction method was designed. Mate information is recorded before replacement, corresponding mating faces or axes are located in the new component by name, and concentric, coincident, and distance mates are recreated.

(5) A complete system was implemented through CAD secondary development. Using SolidWorks as the validation environment, the system provides product-model selection, parameter input, dimension driving, equation linkage, model replacement, mate reconstruction, and execution logging. The hydraulic-cylinder case confirms that the system can improve product-variant design efficiency and reduce manual modification and assembly-repair work.

Although hydraulic cylinders were used for demonstration, the underlying workflow can be extended to reducers, stacker cranes, fixtures, standardized mechanical components, and other products with family-based architectures. Future research will address the recognition of complex curved mating entities, automatic generation of replacement rules, integration with PDM systems, and adaptation to multiple CAD platforms.

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