Knowledge-based Engineering for Process Planning and Die Design for Automotive Panels

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ABSTRACT

This work automates process planning and die design in automotive panel production using a novel knowledge-based engineering (KBE) methodology. Automotive panels are more complicated than common stamped parts because automotive panels are composed of groups of freeform surfaces. Stamping process planning identifies and sequences the necessary operations, finally producing the appropriate press dies. Case-based reasoning (CBR) is integrated into ordinary process planning and die design processes to generate a hybrid KBE system. Utilizing the CBR methodology to plan stamping process and design stamping dies for automotive panels reuses existing designs to develop new designs. In the proposed flexible system, process-planning and die-design functions can adapt existing designs or generate new designs based on stamping knowledge. Tacit knowledge of stamping parts is preserved and automotive panel manufacturing is accelerated by design automation when using the proposed KBE system.

Keywords: knowledge-based engineering, automotive panel stamping, die design.
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1 INTRODUCTION

Sheet-metal parts are conventionally used to replace expensive cast and forged products in mass production in the automotive industries. Sheet-metal stamping to produce parts with freeform geometries (e.g. hood panels and fender panels) has many advantages such as little material waste and high productivity, and produces high-quality parts. At the start of a manufacturing process, the appropriate stamping operations are defined and organized into the appropriate order based on the geometrical features of an automotive panel. Press dies are then delicately designed depending on the panel shape and each stamping operation stage. However, stamping process planning and press die design require considerable skills from experienced designers [5]. Process planning and die design have become crucial to shortening development time and reducing manufacturing cost of the sheet-metal panel manufacturing cycle.

The computer-aided process planning (CAPP) system for sheet metal has been extensively studied. Feature-based schemes are derived from manufacturing feature recognition, which is important in engineering applications. Wang and Bourne [20] identified important features for the sheet-metal bending process. The application of features and potential problems associated with feature interaction were also discussed. Tang *et al.* [18] proposed an intelligent feature-based design for a stamping system to evaluate stamping ability. Smith *et al.* [17] devised a relational system that efficiently integrates feature-based process planning and expert system strategies for sheet-metal parts. However, successful extraction of stamping features during the feature recognition phase is difficult with feature-based techniques, especially when features intersect.

An increasing number of advanced technologies, including knowledge-based engineering (KBE), are adopted to support various aspects of the product life-cycle [14-15]. Notably, KBE is a novel artificial intelligence methodology for solving engineering problems. Using intelligent methods for process planning and die design enhances design quality and the ability for innovative design. Based on the KBE technique, engineering tasks are carried out using knowledge not immediately accessible. Therefore, utilizing the KBE methodology, in which experience and knowledge used in current designs improves production efficiency of panel stamping [2].

Thus, KBE has been successfully applied in the application domain of sheet-metal stamping. Dequan *et al.* [9] introduced the framework, knowledge model and reasoning mode of a knowledge-based system into stamping process planning. Ciurana *et al.* [7] developed an activity model for choosing manufacturing and characteristics of sheet-metal operations related to the drawing process. Choi *et al.* [6] developed a computer-aided design and manufacturing system for irregularly-shaped sheet-metal products. They formulated knowledge rules from plasticity theories, experimental results and empirical knowledge of field experts. Tor *et al.* [19] applied a case-based reasoning (CBR) approach with a new indexing and retrieval strategy for metal stamping die design. By using a hierarchical classification structure, a stamped metal part with four stamping feature categories is represented as a case in the case library. Zhang *et al.* [23] extended the work of Tor *et al.* by extracting a set of deep drawing features for multi-stage, non-axisymmetrical sheet-metal deep drawing. Liu *et al.* [13] presented a novel representational model for objected-oriented case information relationship. They proposed the Class-Property structure to refine case representations and utilized three hierarchical indexing strategies for case extraction. However, only a few studies have focused on process-planning systems for stamping automotive panels using KBE. Shi *et al.* [16] developed a knowledge-based process planning system, consisting of knowledge acquisition, knowledge representation and knowledge-based design, to fully support automotive panel die development and design automation. Leake *et al.* [11] employed a set of principles and techniques for integrated case-based design support systems. The Stamping Advisor, a system that supports feasibility analysis for sheet-metal automotive parts, was applied to illustrate applications of case-based design. Recently, Chen *et al.* [4] applied an object-oriented hierarchical case representation scheme for automotive panels in process planning. Zheng *et al.* [24] employed a KBE framework as the master model at the system level and as a procedural model at the activity level for a CAPP system for automotive panels.

This work presents a novel hybrid KBE framework for the automotive-panel stamping process planning and press die development to achieve the goal of design automation. The CBR methodology is applied to the proposed KBE system to improve efficiency of the entire automotive panel manufacturing process. Based on CBR, a suitable automotive panel can be retrieved from the case library, along with its process plan, operational sequence and press dies. An interactive process planning function is utilized to adapt previous solutions to a current case. Furthermore, the process plan and press dies can be generated using a parametric design procedure when no similar case exists. The surface model of each automotive panel is analyzed to extract geometric and topological data for forming an attributed graph for indexing. Additionally, the graph-based representation can be converted into features to form a high-level structural representation used in parametric die design. In this work, a KBE system for stamping panel process planning and die design is implemented and integrated with a product data management (PDM) system [21] and CATIA V5 [8]. According to CBR, the hybrid system has the advantages for assisting enterprises in preserving tacit knowledge of stamped parts and accelerating automotive panel manufacturing via design automation.

2 FRAMEWORK OF KNOWLEDGE-BASED ENGINEERING

Notably, KBE is based on the assumption that engineering problems can be solved using intelligent methods. Thus, KBE provides a flexible architecture and reuses experience and knowledge. The principal objectives of KBE are to solve a particular design problem by applying KBE and retaining domain knowledge required to solve design problems within the same domain [1]. Knowledge is accumulated and stored in a digital form in the library for subsequent engineering applications. The KBE systems complement traditional CAD/CAM systems by adding the engineering knowledge driving the product design process [10]. During the course of a design, KBE application, which is becoming an essential part of a strategy for improving design effectiveness, guides design engineers through different stages of a design process. An innovative KBE system combined with hybrid architecture for automotive panel stamping die design is utilized in this work to achieve design automation. Figure 1 shows a schematic diagram of the proposed KBE framework for metal stamping process planning and die design.

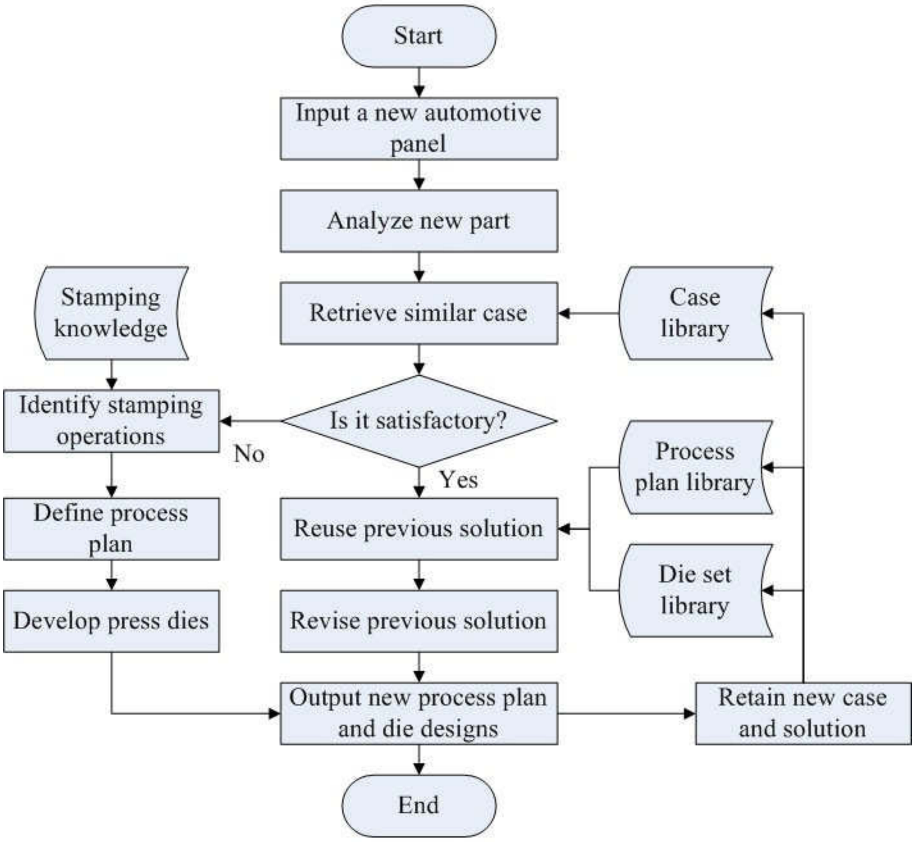


Fig. 1: Schematic diagram of the proposed KBE framework.

The surface models of new automotive panels to be stamped are first input into the KBE system. To facilitate process planning, a new sheet-metal part is analyzed to indentify fundamental features in the form of an attributed graph. The new case, which is represented in a graph-based scheme for indexing, is then passed to a case retriever to extract an existing case that most closely resembles the input case. Successful cases, process plans and die designs are stored in their respective libraries. The similarity between an input case and each case in the library is assessed using a graph-based comparison method. If an existed design is sufficiently similar to the new design, the process plan and die sets relevant to the selected case are acquired. The solution is then revised to meet new design requirements. When all existing solutions in the library are unsatisfactory, stamping operations are based on geometric characteristics of the surface model. After identifying these operations, the required mechanisms are identified for relevant operations and the stamping sequence is established. The press dies are then designed using the die-design module, which is an external CAD system combined with the KBE system. Finally, the new case with its process plan and die sets are retained in the libraries, respectively, as a successful case. Whenever a new case is solved, the case library is expanded and the KBE system is improved.

3 PROPOSED APPROACH

3.1 Representation and Indexing

Surface models with freeform surfaces are commonly used in sheet-metal applications. A novel graph-based descriptor, a flat-bend graph, is utilized to represent these surface models. The B-rep scheme of a surface model can be translated into an attributed graph for case indexing and comparisons. Three fundamental entities, bend-type faces, flat-type faces and holes, are identified in the panel model (Fig. 2). The flat-type faces are considered graph nodes representing the primary model shape. The bend-type faces are regarded as graph arcs used to identify relationships among flat-type faces. The holes are the other node type, which also describe the model shape. The graph structure is built using topological information of these fundamental entities and, additionally, graph attributes are collected from other geometric data.

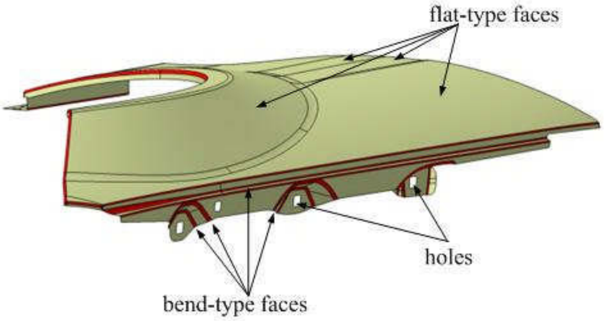


Fig. 2: The fundamental entities (flat-type faces, bend-type faces and holes).

To create a flat-bend graph, all faces from the input surface model are first analyzed to determine whether they are bend-type faces or flat-type faces. When bend-type faces are detected, they are extracted from the model and the remaining faces are flat-type faces. Connected flat-type faces then are gathered as a group. These groups are the nodes in the flat-bend graph describing the general shape of the surface model. In each group, hole detection is performed to extract hole features from the model as the other type of nodes. After completing these steps, a graph can be constructed based on the relationships between nodes. Finally, some geometric characteristics are set as node attributes and arc attributes.

Each node in the attributed graph has two different attributes—type and direction. Node type indicates that a node is a GROUP or HOLE. Direction determines the relationship between pressing directions and group/hole directions. When manufacturing of stamped parts, the pressing direction plays a main role. The same shape with a different outer orientation may have entirely different stamping operations. When the angle between a pressing direction and group/hole direction is <10 degrees, the direction is set as SAME. When the angle exceeds 10 degrees and is <90 degrees, the direction is set as POSITIVE; otherwise, the direction is set as NEGATIVE. Each arc in the attributed graph has three attributes—type, convexity, and angle. Generally, arc type of a link connecting two groups is set as NORMAL. A special case of the normal connection is the circular connection. If bend-type faces between two groups form a closed loop, arc type is set as CIRCULAR. When a link connecting a group and a hole, the arc type is set as BELONG. The convexity attribute verifies that the angle between groups is CONVEX or CONCAVE. Finally, the angle between two groups is set as ACUTE or OBTUSE. These attributes guarantee that geometric data are included in the graph representation.

Figure 3 shows an example of a simplified surface model and its flat-bend graph. Figure 3a shows the process for constructing a flat-bend graph. The simplified surface model (Fig. 3c) is a portion of the model for an automotive fender panel (Fig. 3b). The bend-type faces are removed and the remaining faces are integrated into six groups (Fig. 3d). The hole detection process is applied to each group in the model to identify all holes in the model. The links between groups are constructed based on the relationships between groups and bend-type faces. Accordingly, groups and links are regarded as nodes and arcs, respectively, in the flat-bend graph. Holes are taken to be the other type of nodes connected to group nodes based on the groups to which they belong. The circular nodes represent groups; square nodes represent holes; continuous arcs represent concave and normal links; dashed arcs represent convex and normal links; and dot arcs represent belong-to links (Fig. 3e).

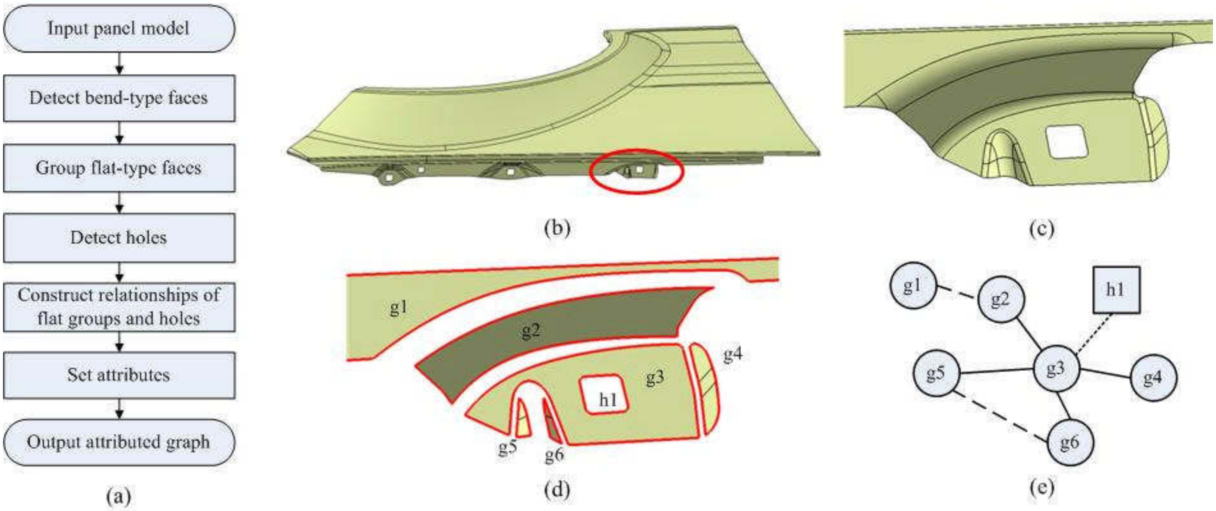


Fig. 3: An example of a simplified surface model and its flat-bend graph.

3.2 Similar Case Assessment

Notably, CBR is a methodology for solving problems by using or adapting solutions to old problems. Via the CBR methodology to a plan stamping process and design stamping dies for automotive panels, one can reuse an existed design to develop a new design. Retrieving appropriate cases is key in CBR and has a significant impact on system efficiency.

The quality and robustness of any CBR system depends on the retrieval mechanism. For simplicity, a variation on a classical subgraph isomorphic algorithm is used to determine the similarity among attributed graphs. Therefore, the problem of assessing the similarity between cases can be simplified as the problem of determining the maximum size of the common subgraph. Many algorithms have been developed for solving the maximum common subgraph (MCS) problem. One strategy is to reduce the MCS problem of two graphs to a maximum clique (MC) problem [3].

To obtain efficient applicable solutions, an effectual scheme called independent maximal cliques (IMC) detection described in [22] is employed. The IMC detection with a simulated annealing algorithm is used to solve the graph-matching problem. The association graph, which is used for IMC detection, is constructed from two attributed graphs while retaining their attributes. All independent maximal cliques that represent the maximum number of common features between cases are determined using simulated annealing. This method is used to measure the degree to which local feature correspondence between 3D solid models outperforms traditional MC methods in terms of efficiency and efficacy. Hence, the IMC detection method is applied in this work. Figure 4 shows the process of comparing the query case with a candidate case based on IMC algorithm.

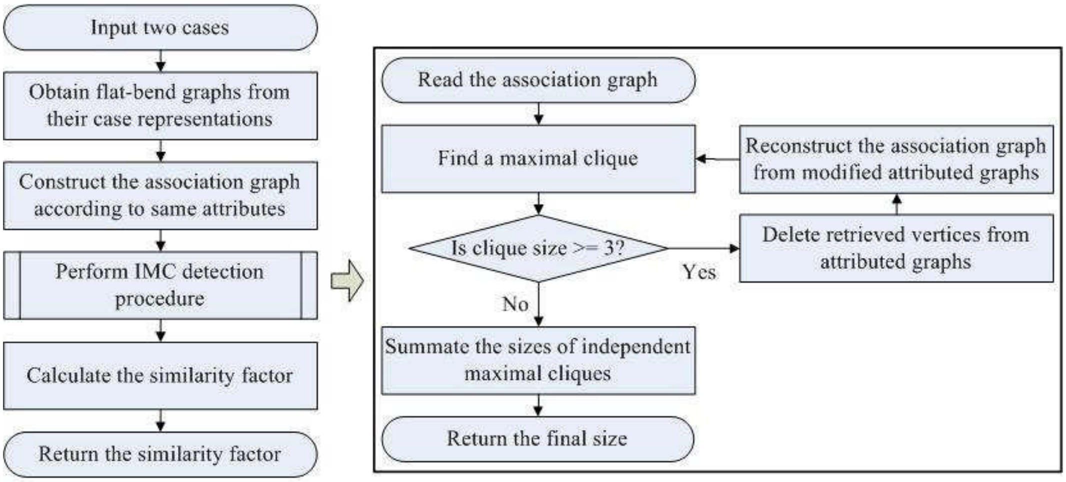


Fig. 4: The process of similar case assessment.

The IMC detection scheme is adopted to acquire repeatedly the maximal clique of the association graph in a heuristic manner. Once assessment is complete, the sizes of independent maximal cliques are summed for calculating the similarity factor between two cases. Factor S, which is employed to assess the similarity between two graphs, is calculated as $S=2N/(N1+N2)$, where N is the total number of vertices in each independent maximal clique, $N1$ is the number of nodes in the graph of the query case, and $N2$ is the number of nodes in the graph of the candidate case for comparison.

If two cases have many common features, their similarity factor is high. Conversely, the similarity factor is low when few features are shared. The retrieval operation compares the query case with all cases in the case library and calculates similarity factors from each pair of comparisons. Based on comparison results, the case with highest factor is the most similar case. As the query case and selected case share many features, the process plans and die designs of the selected case can be reused in the new design. Figure 5 shows an example of the similarity measurement result determined through IMC detection, where Ni is the number of nodes in the flat-bend graph, and Sij is the similarity factor between *Part-i* and *Part-j*. Models whose numbers of nodes are in the same order are chosen in this example to produce feasible results based on the similarity among local features. *Part-1* and *Part-2* differ only slightly and have many common features and, thus, have a high similarity factor (Fig. 5). Conversely, the similarity factor for *Part-1* and *Part-3* is low because few features are shared, as is the case for *Part-2* and *Part-3*. This example demonstrates that IMC detection can determine whether two models are similar and can be applied to retrieve similar models.

3.3 Process Planning and Die Design

Stamping operations are the most fundamental elements when producing a process plan in automotive panel manufacturing. A combination of several common stamping operations should be considered to form one automotive panel composed of groups of freeform surfaces. Different portions of a sheet-metal part can be formed by certain stamping operations based on stamping technology. In this work, stamping operations are categorized into drawing (DR), trimming (TR), flanging (FL), restriking (RST) and piercing (PI) operations. These stamping operations are identified in both graphical representations and model information, as are operational parameters. Hence, relevant mechanisms, depending on the direction and range of processing, can be developed based on determined data.

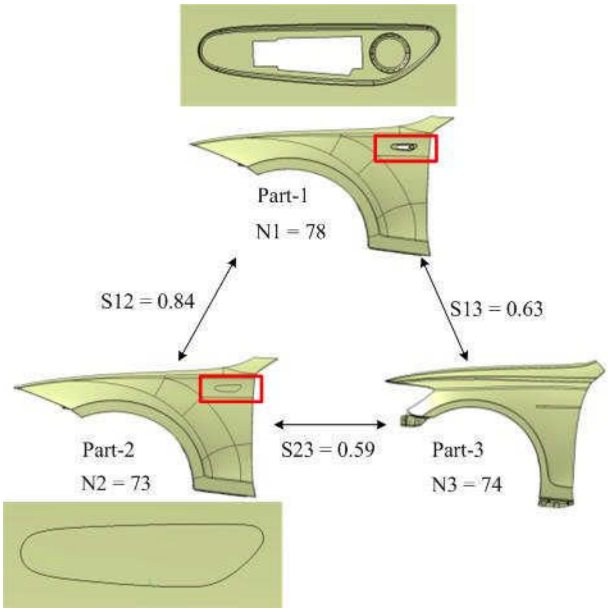


Fig. 5: Illustration of similarities between each pair of three models.

Figure 6 shows the process of stamping operation detection and sequence planning. The geometric and topological data must be acquired from the automotive panel for recognizing operational features. Based on the graph-based representation, the panel model is translated into a main set and several side sets that are connected to the main set. The main set is the major portion of the model and should be considered during DR and TR. The main goal of the DR operation is to generate an accurate die-face structure based on the shape of the main set. After die-face development, the TR curve is determined as the boundary condition for cutting off unwanted materials. Processing by DR and TR, which are two main operations when forming a sheet-metal part, shapes the general outer appearance of a panel part. The FL, RST and PI operations are considered local manufacturing procedures in the automotive model. To accomplish the remaining stamping operations, side sets are used to determine the necessary data relevant to these operations. Using FL and RST operations, detailed geometry of a panel can be formed to meet restricted requirements. Holes in the panel are punched during the PI operation that defines the hole size, location and direction. While utilizing stamping operations, the mechanism of each operation is also determined in accordance with related parameters. Finally the operations are arranged in an appropriate sequence to create a process plan with parametric data for die development.

Forming a complex sheet-metal part, such as an automotive panel, needs to utilize several stamping operations. Generally, these operations cannot be performed at the same time. Thus, sequencing methodology is essential to generating a rational process plan. A decision-making scheme using a series of rules is employed to generate the most correct process sequence for stamping operations. Figure 7 shows the reasoning rule for defining FL and RST sequences. Based on parametric data in the side-set geometry, the FL angle is calculated to determine that the optimal operational procedure is only FL, only RST or FL → RST.

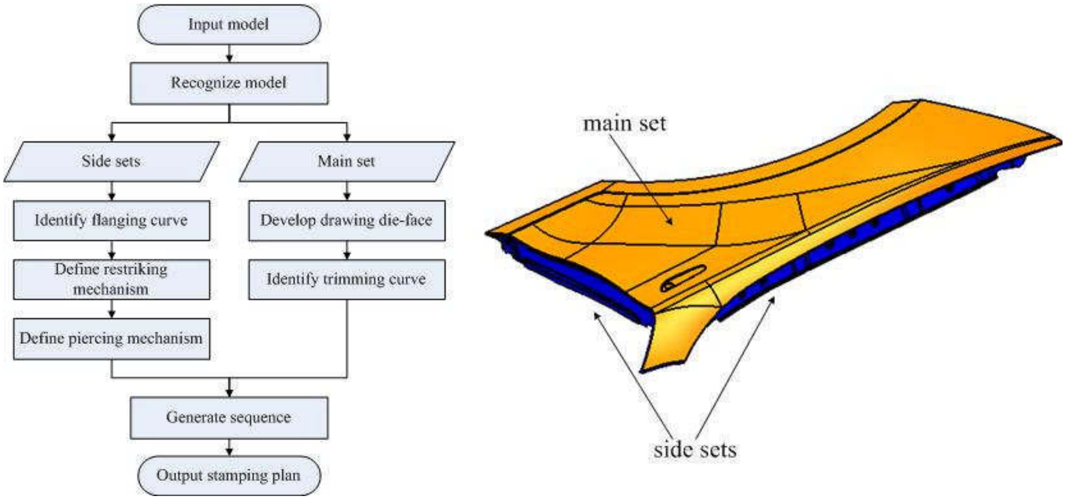


Fig. 6: The process of stamping operation detection and sequence planning.

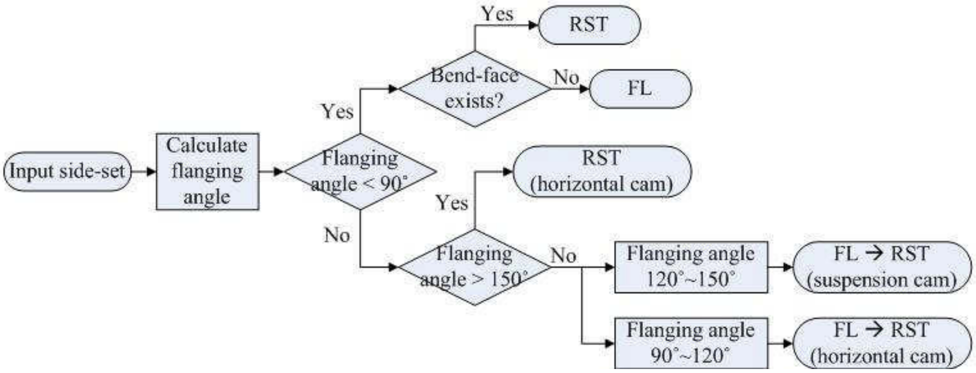
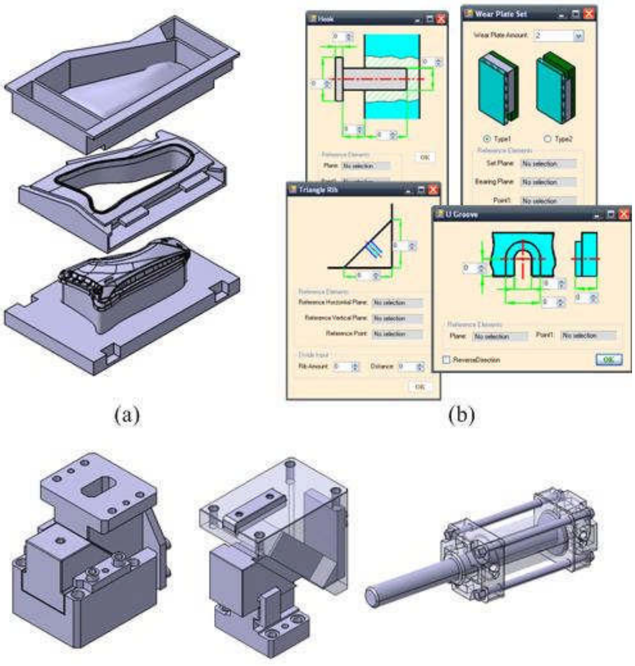


Fig. 7: Illustration of the decision rule for flanging and restriking operations.

The CAD system has been widely applied for designing stamping dies [12]. To effectively construct a press die for each production sequence, a die template, user-defined features, and standard parts are utilized based on the CATIA CAD platform, which is commonly used in the automotive industry (Fig. 8). These CATIA functions effectively improve design efficiency in press die development by applying the template concept to design functions. The die template contains several general and approximate die structures for working that are based on panel shape and the stamping sequence. Based on the parametric data output from the process planning stage, the die structure is generated automatically. User-defined features are then used to supplement die creation by adding secondary features to the die structure. Finally, several standard parts are selected to generate the necessary mechanisms defined in the process plan. By employing the template concept and parametric design, the die set is developed efficiently instead of designing using a step-by-step process.



Wear Plate Amount: 2
● Type1 ○ Type2
Reference Elements
Plane: No selection
Set Plane: No selection
Bearing Plane: No selection
Point1: No selection
Reference Horizontal Plane: No selection
Reference Vertical Plane: No selection
Reference Point: No selection
Divide Input
Rib Amount: 0 Distance: 0
Plane: No selection Point1: No selection
☐ ReverseDirection

(a) (b)

(c)

Fig. 8: Illustration of development functions of the die-design module: (a) die template, (b) user-defined features and (c) standard parts.

4 SYSTEM IMPLEMENTATION

The proposed KBE system consists of a representation module, reasoning module, recognition module, process-planning module and die-design module (Fig. 9). The representation module provides a graph-based descriptor for the panel model to be used in case retrieval or stamping operation recognition. The SpringSolid system developed by the Solid Model Laboratory, National Taiwan University, is employed to obtain the B-rep structure from the surface model in the Standard for the Exchange of Product model data (STEP) format. Acquiring topological (faces, edges, and vertices) and geometric (surfaces, curves, and points) information from the B-rep structure facilitates construction of an attributed graph. The CBR methodology plays a significant role in the reasoning module for retrieving similar models with documents relevant to the target design. To facilitate case retrieval, the IMC detection method is applied to retrieve cases from the PDM system that stores data for cases, process plans, and die sets. Process plan modification, including sequence correction, is performed interactively through the process-planning module. Furthermore, the process-planning module generates a process plan integrated with stamping operation identification in the recognition module whenever no suitable case is retrieved. When the process plan is determined, press dies are constructed using the die-design module embedded in the CAD system, CATIA V5.

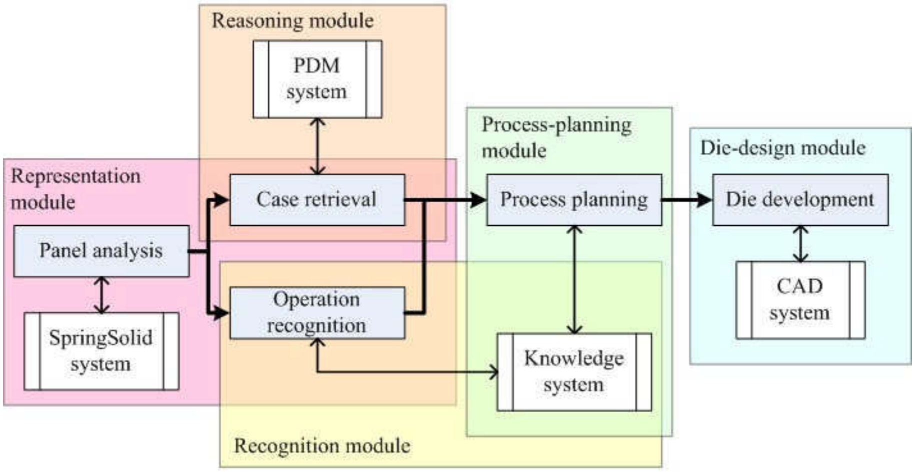


Fig. 9: System architecture of proposed hybrid KBE framework.

Figure 10 shows an example of die set development based CBR. Initially, the new case is uploaded into the PDM system and a flat-bend graph is built. The new case that is ready for comparison with other cases is then selected. The retrieval process compares the query model with all models in the case library (Fig. 10a). The retrieval process compares the query model with all models in the case library. In the proposed similarity assessment process, the similarity measure depends on local feature correspondence. This experimental result suggests that numerous local features are common between the best solution and the new case (Fig. 10b). Figure 10b also shows the operation differences between new and retrieved cases. After retrieving the most similar case from the case library, the previous solutions, process plan and press dies are also obtained from the process plan library and die-set library respectively. The retrieved process plans are regarded as references for the new case and several modifications of the detailed process plan are carried out (Fig. 10c). The die sets of the new case are also developed by modifying the retrieved die sets to meet new design requirements (Fig. 10d).

Another example (Fig. 11) demonstrates process plan generation and die set development of a new panel when no case is retrieved that is sufficiently similar to the current design. By analyzing the surface model along with the flat-bend graph, stamping operations are identified. At the same time, the necessary mechanisms are also defined in the recognition module. The operational sequence is planned based on stamping technology and stamping mechanism dimensions. The operations, such as DR and TR, that shape the main body of the panel are applied first in the sequence. The remaining operations that produce detailed features can be combined into another one or two processes.

5 CONCLUSIONS

Stamping process planning and press die development processes for automotive panels are automated using the novel KBE framework. The flat-bend graph is utilized in the representation module to extract topological and geometric data from the surface model for case indexing and stamping feature recognition. The CBR methodology, used in the reasoning module, effectively and efficiently improves the development of process plan and die design by reusing existing design knowledge retained in the PDM library whenever a new case is solved completely. In accordance with the analysis of panel characteristics, stamping operations are recognized and the process sequence is organized. The ultimate goal of die design is accomplished by processing parametric data to construct press dies on the CATIA V5 platform. Based on the hybrid architecture, process plan and stamping dies can be developed by revising a previous design or generating a new design. The KBE system assists enterprises in preserving tacit knowledge of stamping parts and accelerates automotive panel manufacturing by design automation.

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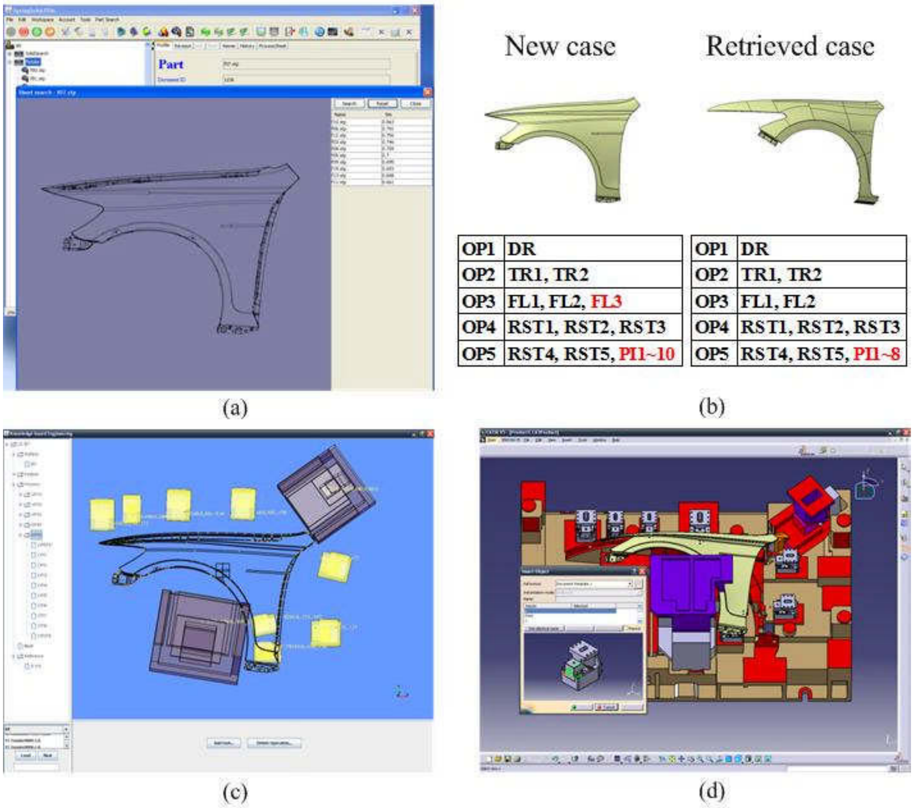

New case

OP1	DR
OP2	TR1, TR2
OP3	FL1, FL2, FL3
OP4	RST1, RST2, RST3
OP5	RST4, RST5, PI1~10

Retrieved case

OP1	DR
OP2	TR1, TR2
OP3	FL1, FL2
OP4	RST1, RST2, RST3
OP5	RST4, RST5, PI1~8

Fig. 10: Process planning and die design based on the CBR methodology.

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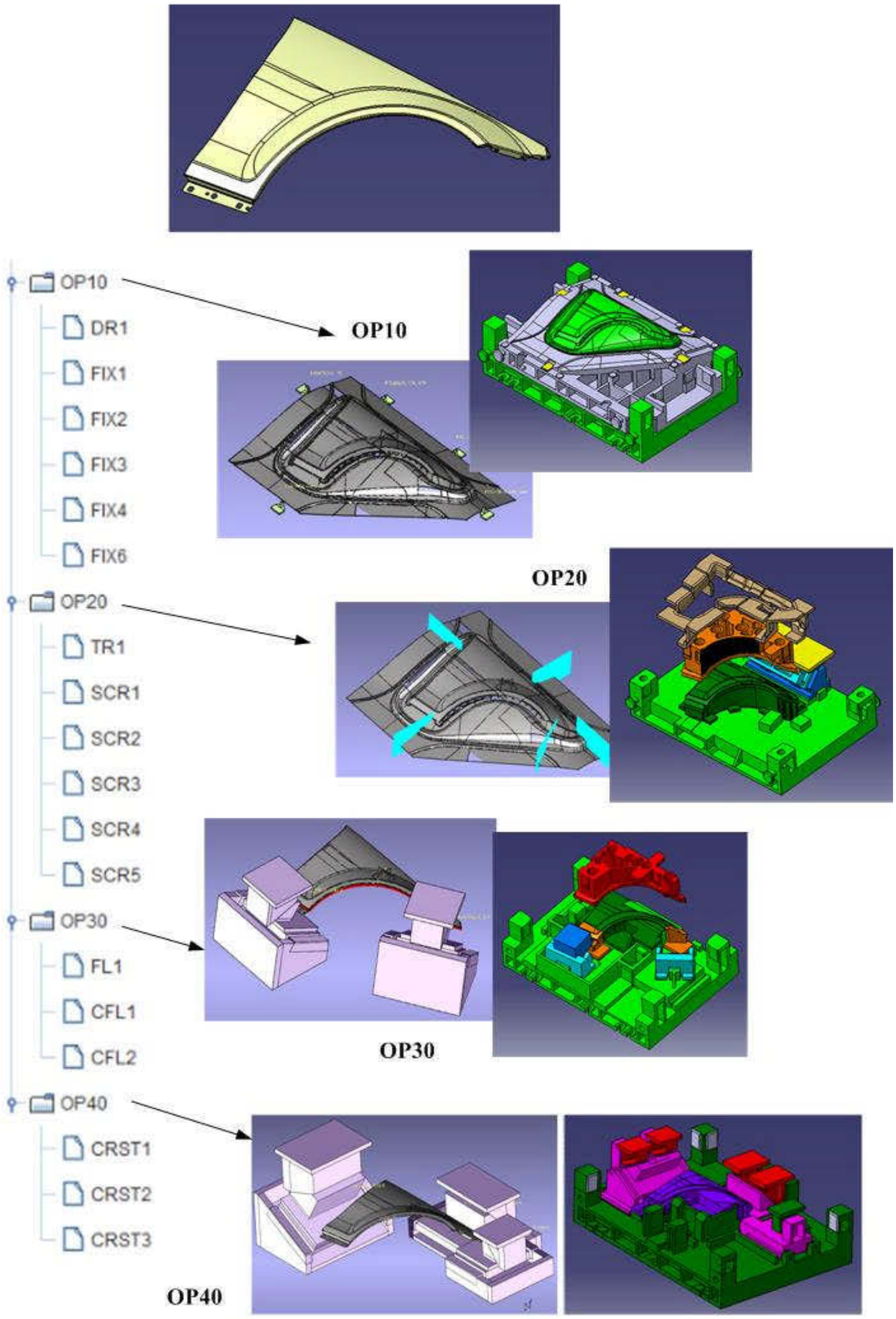

Fig. 11: Illustration of new process plan generation and die set development.