A Hybrid Intelligent System for Stamping Process Planning in Progressive Die Design

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Abstract — **This paper presents an intelligent, hybrid system for stamping process planning in progressive die design. The system combines the flexibility of blackboard architecture with case-based reasoning. The hybrid system has the advantage that it can use past knowledge and experience for case-based reasoning when it exists, and other reasoning approaches when it doesn't exist. A prototype system has been implemented in CLIPS and interfaced with Solid Edge CAD system. An example is included to demonstrate the approach.**

Index Terms — **Blackboard architecture; Graph-based; Hybrid intelligent systems; Knowledge-based; Progressive die design; Stamping process planning**

I. INTRODUCTION

Progressive dies for producing sheet metal parts in mass production have been widely applied in various industries such as aerospace, electronics, machine tools, automobiles, and refrigeration. These dies can perform piercing, notching, cut-off, blanking, lancing, bending, shaving, drawing, embossing, coining, trimming, and other miscellaneous forming operations at a single setup. Hence a progressive die is generally very complex. Stamping process planning and die structure design are difficult and demanding tasks.

Stamping process planning starts with an unfolding of a model of stamped metal part to produce a flat pattern, followed by nesting the pattern to produce a blank layout. Next, stamping operations are planned and operations are assigned to die stations. The resulting plan is typically represented as a strip layout, which guides the subsequent die structure design. The productivity, accuracy, cost, and quality of a progressive die mainly depends on the strip layout, and hence a stamping process. However, stamping process planning still remains more of an art rather than a science. Historically, this activity is mainly carried out manually, based on designers' trial-and-error experience, skill and knowledge.

Recent advances in the field of artificial intelligence (AI) have given rise to the possibility of constructing AI-based systems that incorporate built-in intelligence and apply diverse knowledge to solving progressive die design problems, including strip layout design automation. The diverse knowledge sources (KS's) related to stamping process planning include unfolding knowledge to produce a flat pattern, nesting knowledge to produce a blank layout, various types of planning knowledge for different stamping operations like piloting, piercing, notching, cut-off, blanking, bending, etc., and staging knowledge to sequence the stamping operations. A discussion of some knowledge-based progressive die design work related to our study can be found in the next section. However, the existing work is based on the conventional architecture of knowledge-based expert systems, which are incapable of managing heterogeneous KS's effectively. In addition, these work doesn't provide a representation scheme for experts to model their valuable, but difficult-to-articulate, knowledge in terms with which they are familiar.

To address the above issue, it is necessary to provide a cooperative problem solving strategy that can foster communication between diverse KS's, and accommodate different knowledge representation schemes within an integrated framework. For this purpose, a hybrid intelligent system consisting of a blackboard control module and a few independently executing KS's is proposed. This hybrid system provides a cooperative decision making environment and facilitates a hybrid knowledge representation scheme, including procedures, production rules, object-oriented, graph-based and case-based representations. The proposed approach speeds up the progressive die design process by automating the strip layout design.

Owing to the modeling flexibility of blackboard architecture, our earlier work on case-based reasoning (CBR) for stamping process planning and die design [1] is also integrated to facilitate the search and reuse of past design experience to solve new problems. The limitation of a single CBR approach has been overcome in the proposed hybrid intelligent system, which can employ other reasoning approach such as rule-based reasoning for problem solving where relevant data have not yet accumulated in the case base.

A prototype system has been implemented in CLIPS [2], and interfaced with a parametric- and feature-based CAD system, Solid Edge. An example is provided to demonstrate our approach.

II. RELATED WORK

Research in the computer-aided stamping process planning has been widely reported since 1970s. The advantages of automated process planning are productivity improvements, cost reductions and design automation.

From mid 1970s to mid 1980s, the first generation of CAD/CAM systems for progressive die design were developed [3-6], though few of them are based on AI techniques. These early systems are characterized by basic computer graphics facilities, standardization of die components, and standardization of design procedures. They reduced design and drafting lead time. However, as these systems represent design know-how in the form of conventional procedural programming languages, only generation of the die part list and drafting of the assembly and part drawings are executed using computers. The designer still needs to decide most of the important decisions interactively, including strip and die layouts.

Since late 1980s, significant efforts have been made by worldwide researchers to integrate a wide variety of AI and traditional CAD approaches to develop dedicated progressive die design automation systems including strip layout design automation.

Knowledge engineering is a popular AI technique having been used in intelligent stamping process planning and die design system. For example, researchers at University of Massachusetts, USA have described a knowledge-based system for design of progressive stamping dies for a simple hinge part [7]. The system generates the flat pattern geometry and develops a strip layout automatically. Researchers at National University of Singapore have been developing an intelligent progressive die (IPD) design system since late 1980s. They used feature modeling and rule-based approach to realize automatic punch shape selection, strip layout development and 3-D die configuration [8, 9]. Based on a feature-relationship tree that describes the stamped metal part and its topological information, model-based reasoning and spatial reasoning techniques have been employed to reason out certain stamping processes and guide the overall planning process to develop the strip layout automatically. Researchers at the Indian Institute of Technology have developed a computer-aided die design system, CADDS, for sheet-metal blanks [10], based on heuristic rule-based reasoning and parametric programming techniques. The greatest advantage achieved by the system is the rapid generation of the most efficient strip layouts. Researchers at the University of Liverpool have worked on design automation for progressive piercing and blanking dies [11, 12]. Their work is based on applying a coding technique to characterize the stamped part geometric features, which is subsequently used to generate the type and layout of the die punches, and then develop the strip layout automatically. Researchers at Huazhong University of Science and Technology, China,
have developed an intelligent progressive die design system, HPRODIE [13]. With feature mapping, rule-based reasoning and case-based reasoning techniques, most of design processes including strip layout design can be carried out automatically. Researchers at Pusan National University, Korea, have developed a compact computer-aided process planning (CAPP) system for progressive die design [14]. Based on production rules, the work is capable of carrying out an intelligent stamping process planning work with automatic development of blank layout, strip layout and die layout.

Though knowledge engineering has achieved a lot of success in stamping process planning, most of the "intelligent" progressive die design automation prototypes reviewed above are rather restricted to specific application domains, or still need considerable interactive input from experienced designers to develop strip layout. This is because they still inherit the disadvantages of the conventional architecture of knowledge-based expert systems, which are incapable of managing heterogeneous KS's effectively.

Researchers at the National Taiwan Institute of Technology have adopted various AI techniques including fuzzy reasoning, pattern recognition, rule-based reasoning, back-propagation neural network, genetic algorithms and petri net for the stamping process planning and design of progressive shearing cut and bending dies [15-17]. However their work lacks an explicit and consistent model to integrate these AI techniques into a comprehensive design environment.

In our previous work, another AI approach, case-based reasoning (CBR) was adopted for stamping process planning and die design [1]. CBR can avoid difficult knowledge representation issue when applying a rule-based approach to model complicated die design problem. The developed retrieval strategy can narrow down the design search space efficiently and retrieve the most similar design case in a reasonable period of time. However, in stamping process planning, it is difficult to obtain enough cases to cover the whole problem space in the initial stage when the system is set up. CBR may fail to generate a strip layout solution where the number of cases is insufficient.

Each of the above mentioned AI-based approaches has advantages and disadvantages. One approach to deal with complex real world problems is to integrate the use of several AI technologies in order to combine their different strengths and overcome a single technology's weakness to generate hybrid solutions [18]. In this paper, a blackboard architecture is adopted to develop a hybrid intelligent system for stamping process planning due to its capability in cooperative decision making and accommodation of hybrid knowledge representation schemes. In the last two decades, blackboard architecture has been successfully used in a wide variety of areas, such as speech recognition, signal processing, engineering design and process planning. Thompson & Lu [19] used a blackboard

architecture to represent design rationales in the form of design plans and design constraints and to establish the relationships between descriptions and design processes. The system provides a cooperative decision making environment that is suitable for concurrent product and process design. Srihari et al. [20] developed a real-time CAPP system for printed circuit board (PCB) assembly by integrating multiple KS's, including planning expert and dynamic information processing modules in the blackboard architecture. The integrated system generates process plans that can be implemented in real time. Chen et al. [21] developed a concurrent, two-stage design evaluation system for product design, using a blackboard architecture. A qualitative evaluation is applied during the stage of searching for combinations of solution principles, then a quantitative evaluation is applied to provide information on performance, assemblability, maufacturability, and costs to facilitate design selection.

In the past few years, blackboard architecture has proven to be suitable for tooling design such as fixture design [22] and injection moulding design [23], though this kind of application is still in its infancy stage. However, we have not found in the literature any attempt to apply the blackboard architecture to stamping process planning for sheet metal parts. It has been mentioned in our earlier work [24] that a blackboard architecture is well suited for constructive problem solving like process planning of stamping operations, where the problem space is large and knowledge from many different sources must be integrated to achieve a solution. The latter topic is discussed in the present paper.

III. BLACKBOARD ARCHITECTURE FOR STAMPING PROCESS PLANNING

Cooperative decision making for knowledge-based stamping process planning involves a variety of KS's such as unfolding knowledge to produce flat pattern, nesting knowledge to produce blank layout, various types of planning knowledge for different stamping operations like piloting, piercing, notching, cut-off, blanking, bending, etc., and staging knowledge to sequence the stamping operations. These KS's may be expressed in different representation schemes such as procedures, rules and objects. This justifies the use of a blackboard architecture in hybrid intelligent process planning environment. The KS's interact through the blackboard to develop a solution incrementally.

The proposed blackboard architecture consists of three major components: the blackboard data structure, KS's and a control module (Fig. 1). The different components of the blackboard architecture are described in the following sub-sections.
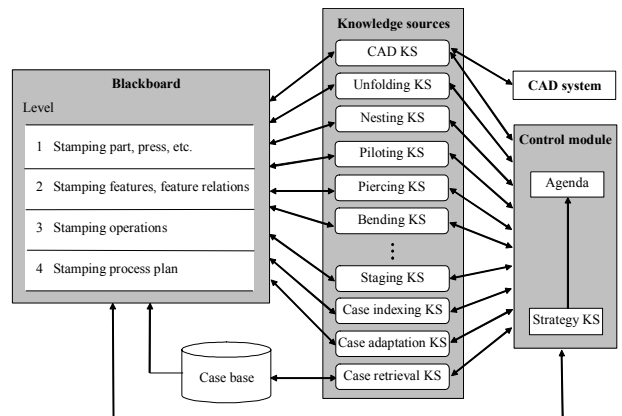

Fig. 1. Blackboard architecture for stamping process planning.

A. Object-Oriented Blackboard Data Structure

The blackboard is a globally accessible database, which contains the data and partial solutions and is shared by a number of independent KS's. The KS's contribute their partial solutions to the blackboard, which lead to a final solution incrementally. The blackboard is structured as a hierarchy of abstraction levels, which represent different aspects or stages of the solution process. Partial solutions are associated with each level and may be linked to information on other levels using algorithmic procedures or heuristic rules. Each level contains planning objects that are used to represent the solution space in an object-oriented manner. The attributes indicate the common data of the object, while the methods are usually encapsulated as procedural programs. The object-oriented approach makes the data structure of the representation tight, concise and easy to manipulate, thus making it possible to avoid any repetition of common data.

Referring to Fig. 1, the planning solution is partitioned into four different object levels – (1) input data including stamped part and press; (2) stamping features and feature relations; (3) stamping operations; and (4) operation relations and stamping process plan – each representing initial input or different partial solutions posted on the blackboard by the specialist KS's. They are described as bellows.

1) Input Data to the Blackboard

Input data to the blackboard mainly includes the part and press objects. The generic declaration of a part object includes the basic attributes such as part type, part dimensions, weight, surface treatments, blank thickness, blank material, annual production, blank dimensions, etc., and pointers to its constituent stamping features and feature relations that will be elaborated later on. The press object contains the attributes such as press type, press tonnage, bolster dimensions, bed open dimensions, shut height, number of strokes, etc. The press data are useful for determining the stamping operations that will be elaborated later on.

2) Object-Oriented Feature Modeling to Stamped Metal Parts

Since traditional geometric modeling techniques do not capture design intent (e.g., design for manufacturing), they are in general unable to support sophisticated and intelligent reasoning capabilities, e.g., knowledge-based process planning. Recently, the concept of machining features has been introduced to create a direct link between design and manufacturing [25]. Feature modeling is a relatively new way of storing design and manufacturing information in CAD/CAM/CAPP systems. Similarly, stamping features of a stamped metal part can enable stamping process planning tasks to be performed directly from the geometric model. Stamping features are information carriers that are used to model a stamped part with a set of design and manufacturing information including geometric and non-geometric attributes. Each of these stamping features can be manufactured with a specific stamping operation or a combination of stamping operations.

Using the hierarchical classification structure of general design features by Chen et al. [26], a stamped metal part can be modeled with four categories of stamping features:

Primary features: flat, drawing, etc.

Positive secondary features: tab, curl, emboss, hem, bead, flange, etc.

Negative secondary features: hole, extrusion hole, profile, deform, slot, step, etc.

Connective secondary features: bend, blend, etc.

Object-oriented feature representation has been employed to encapsulate design and manufacturing information in a stamping feature object. For example, a *Hole* feature object contains the basic attributes such as feature type, feature ID, primary feature ID, position, orientation, depth, diameter, precision, roughness, etc., and methods to calculate perimeter (some attributes are inherited from its upper class of feature object, i.e., Negative feature).

Besides representation of individual stamping features, a comprehensive representation of feature relations guarantees that all the stamping features associated with stamping process planning are considered. In addition, the data on feature relations are useful for determining the sequence of stamping operations and sometimes the stamping operations themselves. Four critical types of relations among stamping features – *is-in*, *is-on*, *adjacent-to* and *precision-associated* are identified in this paper. The first three relation types – *is-in*, *is-on* and *adjacent-to* – are adopted from Chen et al.'s [26] definition of relations among general design features. Within the specific domain of stamped metal parts, the *is-in* relation can be used to indicate the spatial interaction that arises when a negative stamping feature is in another stamping feature (e.g., primary feature). Similarly, the *is-on* relation can be used to indicate the spatial interaction that arises when a positive stamping feature is on another stamping feature (e.g.,

primary feature), and the *adjacent-to* relation can be used to indicate the spatial interaction that occurs when a connective stamping feature is adjacent to another stamping feature (e.g., primary feature). A *precision-associated* relation type is introduced in our earlier work [1] to represent design constraints that arise when a stamping feature does not directly connect to, but is associated with, another stamping feature by a toleranced dimension.

3) Stamping Operation Objects Mapped from Stamping Feature Objects

On the blackboard, the stamping operation objects are at a lower level than the stamping feature and feature relation objects. They are used to define the manufacturing process from metal strip to the formed metal part. Essentially, the stamping process planning task is to transform a set of stamping features and feature relations into a set of stamping operations, and describe the relations among these stamping operations. The generic declaration of a stamping operation object includes stamping operation type, geometric shape, geometric constraint, precision, roughness, relationship with stamping feature, and control parameter. Typical stamping operation objects include piercing, notching, cut-off, blanking, lancing, shaving, drawing, embossing, coining, and trimming. A stamping feature may be manufactured with a specific stamping operation (one-to-one mapping) or a combination of stamping operations (one-to-many mapping). Several stamping features may also be manufactured with a single stamping operation (many-to-one mapping).

4) Graph-Based Stamping Process Plan

After the mapping from stamping features to a set of stamping operations, the remaining process planning task is to assign stampings operation to die stations in an optimal sequence. Stamping operations are sequenced in a progressive manner, by creating stamping operation relations used as a partial stamping process plan.

A graph-based approach is used to arrange the stamping operation objects in a stamping process plan. The graph consists of a set of nodes that store information about the stamping operations, and a set of arcs that store information about the operation relations. Stamping operations are related to one another through two kinds of relationship, *cluster* or *precedence* relations. Cluster stamping operations are executed simultaneously and can be staged at the same die station. Stamping operations in precedence must be performed in sequence and so they are staged in adjacent die stations. *Cluster* relation, and *precedence* relation are represented by dashed ellipses and directed solid line respectively, as shown in Fig. 2. Note that stamping operations *C* and *D* work simultaneously, and are staged at the same die station, while stamping operation *A* precedes operation *C*, and is staged in a die station immediately prior to the one for the operation *C*.
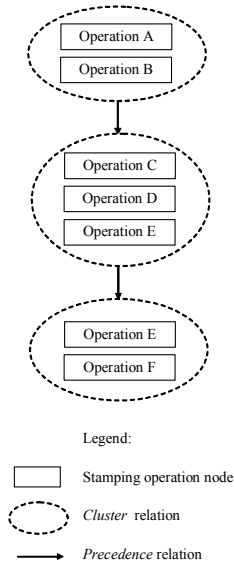
Fig. 2. Graph-based partial stamping process plan.

The strip layout can be generated by a computer automatically using the graph-based stamping process plan, which is suited for computer implementation and leads to efficient formulation and solution procedures.

B. Specialist Knowledge Sources (KS's)

The planning objects on the blackboard outlined above are not isolated data structures, but are interrelated to each other by a set of specialist KS's that resemble experts by embodying the problem solving knowledge. These KS's are independent chunks of knowledge and do not communicate directly with each other. Instead, they participate in the problem solving process by contributing their partial solutions on the blackboard, or updating the contents of the blackboard.

The KS's related to stamping process planning include, but are not limited to, unfolding, nesting, piloting, piercing, bending and staging. Due to the modularity of blackboard architecture, it is convenient for end-users to expand the KS space in the system by integrating different methods of knowledge representation such as procedures, rules and objects. A rule example in bending KS is shown below:

If a bend has a bending angle between $90^0 \sim 135^0$, then it needs a two-step bending operation.

Owing to the modeling flexibility of blackboard architecture, our earlier work on case-based reasoning (CBR) for stamping process planning and die design [1] is also integrated to improve the productivity of stamping process planning by reusing past design experience stored in case base (Fig. 1). KS's for case indexing, case retrieval and case adaptation are built for this purpose.

Fig. 3 elaborates the CBR process with the interaction from these KS's. Initially, the case base consists of only a few cases that are acquired using traditional knowledge-based systems or input by designers. To facilitate case retrieval, each new stamped part is first described using the object-oriented feature model illustrated earlier, then input to the case indexer that can identify stamping features and feature relations accurately through case indexing KS. The indexed case is then passed to the case retriever, which extracts a case (from the case base) that resembles the input case most closely through case retrieval KS. If the retrieved closest case doesn't exactly match the query part's design, it is passed to a case adapter that tailors the retrieved case to meet the requirements of the new part through case adaptation KS. Once the current problem is solved through the retrieval or adaptation of a historical case, the final strip layout solution is output to the user, and stored in a new historical case in the case base. This has the effect of continuously improving the CBR sub-system by expanding the case base whenever a new stamping process planning problem is solved. For conciseness, the detailed CBR methodology can be referred to [1] and will be not repeated in this paper.
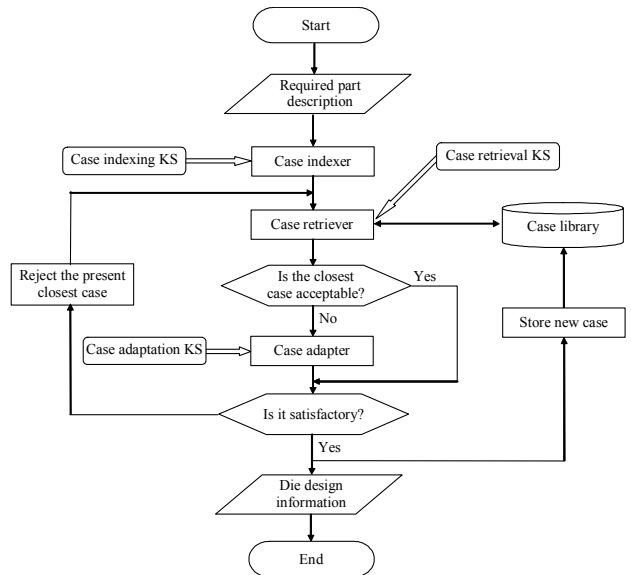

Fig. 3. Activity flow of the proposed CBR process for stamping process planning.

Though the blackboard architecture provides strength in knowledge-based framework construction and cooperative problem solving process, it doesn't support representation or extraction of the geometrical and topological information from stamped metal parts, the intermediate flat pattern and blank layout, and the resulting strip layout. Therefore it is necessary to integrate the blackboard architecture with an existing CAD system. Solid Edge was chosen because of its parametric nature, its ability to enable the user to design with features, and its built-in functions that facilitate feature recognition. The CAD interface can be considered as a consultation of a CAD expert (knowledge source) module, i.e., CAD KS. The application programming interface (API) is an object linked and embedded (OLE) programming interface to Solid Edge. It contains hundreds of functions that can be

called from C++, which provides programmers with direct access to the Solid Edge user function. Therefore it's possible to model stamped metal parts parametrically, extract the stamping features from design easily, create assemblies and drawings automatically, and so on.

C. Agenda-Based Control Module

The specialist KS's respond opportunistically to the changes on the blackboard. An agenda-based control module is used to monitor the changes on the blackboard and decides the actions to be taken next. The agenda keeps track of all the events on the blackboard, serves as a repository of specialist Knowledge Source Activation Records (KSAR's) that can be selected for execution, and calculates the priority of execution.

The control module uses heuristic control rules as the strategy KS to set the above agenda, e.g., by defining the dynamic priorities of triggered KSAR's at the particular point in different stamping process planning stages, and invoking execution of a KSAR with the highest priority. Examples of strategy KS are given below.

Rule *Strategy501*: If the piercing operations to stamp two pilot holes have not been added to the blackboard, the priority of piloting KS is set to 100. Note that the priority of a specialist heuristic rule can be represented using the *salience* feature in CLIPS programming language.

Rule *Strategy502*: If the piercing operations to stamp two pilot holes have been added to the blackboard, the priority of piloting KS is set to 0.

During cooperative problem solving process, the solution is built up a step at a time. The sequence of KS execution is dynamic and opportunistic rather than fixed and deterministic, depending on the changes on the blackboard enacted by the specialist KS's. The specialist KS execution may result in the modification to the blackboard, bringing the system back to the beginning loop. The blackboard control cycle repeats until an acceptable solution has been found or the system can't proceed further due to lack of knowledge or data.

IV. AN ILLUSTRATIVE EXAMPLE

A typical stamped metal part modeled in Solid Edge CAD system (Fig. 4) is taken as an example to demonstrate the blackboard-based stamping process planning approach in the prototype. The system starts with the retrieval of required geometrical information from the part CAD model, and user input of other technical information (e.g., part weight, surface treatments, blank material, annual production, press type, press tonnage, bolster dimensions, bed open dimensions, shut height, etc.) to produce the first level of abstraction on the blackboard, i.e., stamped part level.
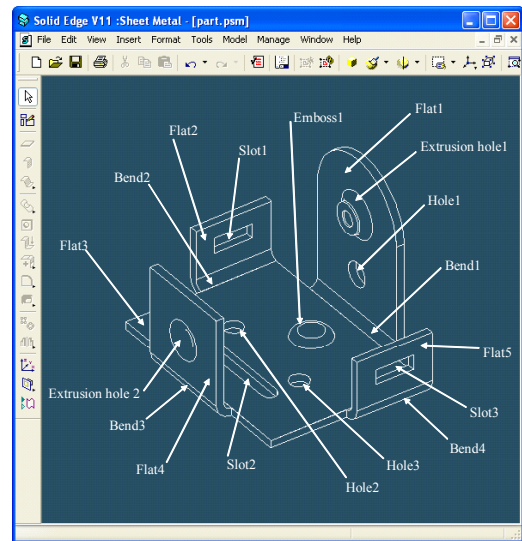

Fig. 4. 3-D feature model of a sample stamped metal part.

Then the CAD KS (CAD API functions) analyzes the geometrical and technological information of the part and press objects, and extracts stamping feature and feature relation objects to form the second level of abstraction on the blackboard, i.e., stamping feature level.

Assume there is no solution after execution of CBR KS because there are only a few case objects stored in the case base. Then the system opportunistically consults with other planning KS's for different stamping operations to transform the stamping features into a set of stamping operations that forms the third level of abstraction on the blackboard, i.e., stamping operation level.

After further consulting with the staging KS, the stamping operations can be sequenced through a graph-based stamping process plan that forms the fourth level of abstraction on the blackboard, i.e., stamping process plan level (Fig. 5). In this user interface, the right hand window shows the graph-based stamping process plan, in which different stamping operations are staged in a same station or sequentially in different station. The figure shows 10 *Piercing* operations, 2 *Bending* operations, 1 *Embossing* operation, 2 *Extruding* operation, 5 *Notching* operations, and 2 *Cut-off* operations. The left hand window shows detailed information about a selected stamping operation.

Fig. 6 shows the corresponding 2-D strip layout solution generated by the computer, and stored in the case base for future CBR [1]. Of course, the user can always override the computer-generated strip layout by modifying the default solution with interactive tools residing in the CAD system.
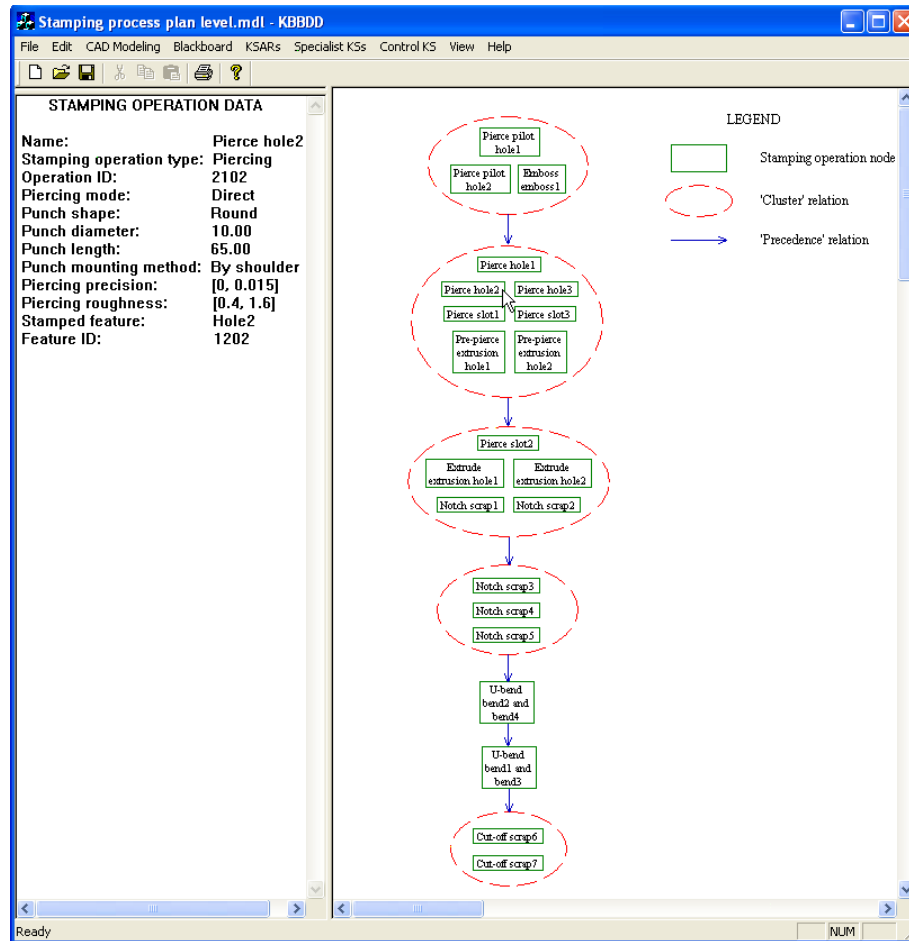
Fig. 5. Stamping process plan level of the blackboard for the sample stamped metal part.

V. CONCLUSION

Stamping process planning for the strip layout is a difficult and creative task in progressive die design. This paper presents a methodology for stamping process planning using a hybrid intelligent systems approach, to simulate the collaborative thinking among a group of die designers. The proposed approach provides a cooperative decision making environment in a unified blackboard architecture and facilitates hybrid knowledge representation schemes including procedures, production rules, object-oriented, graph-based and case-based representations. It reduces the obstacles that exist in the conventional architecture of knowledge-based expert systems, and is therefore capable of managing heterogeneous KS's for stamping process planning effectively. A stamping process planning example was presented to illustrate the benefits of the approach presented in the paper.

Our future research is aimed at developing a concurrent engineering environment for progressive die design using the hybrid intelligent systems approach, and extending the inferential capability of the system by incorporating graph theoretic algorithms to solve particular aspects of the design, e.g., colouring algorithms for clustering.

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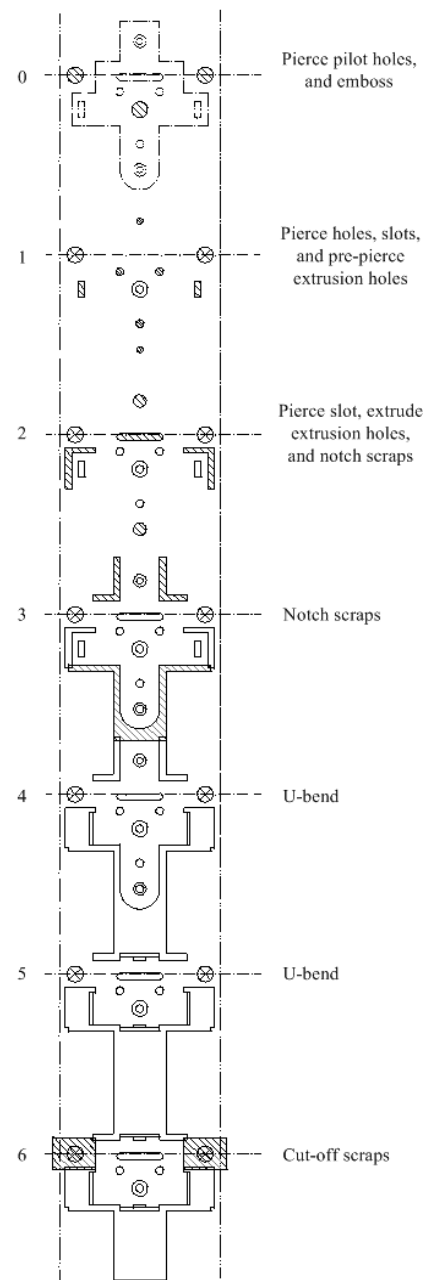
Fig. 6. 2-D strip layout solution for the sample stamped metal part [1].