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Sequence planning for bending operations in progressive dies

Alan C. Lin and Dean K. Sheu*

Department of Mechanical Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan

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This paper aims to study the use of the superimposition scheme to quickly plan the bending sequence in a progressive die design for a sheet metal part which contains bending and shearing features, and to determine the best among multiple feasible solutions. The biggest problem in applying superimposition is that the possible solutions form an excessive solution space when multiple punches are used. In order to solve this problem, this paper introduces three steps: strip preparation, punch layout, and layout evaluation. The punch layout uses clustering rules to classify punches into five groups: prior use (the punches must be used first), posterior use (must be used last), simultaneous use (must be used together), sequential use (certain punches must precede others), and exclusive use (must not be used together). It then derives the compatible sets for each punch, followed by an expansion of the number of punches and punch layout, in order to obtain every feasible solution. The layout evaluation adopts a multiple-criteria decision-making (MCDM) model with a scoring function to analyse every feasible solution and determine the best sequencing plans. The scoring function used is based on the following four criteria: number of stages, moment balancing, strip stability, and feeding height. In the conclusion, this paper builds up a pilot system and demonstrates how the method can generate bending sequences and produce strips.

Keywords: progressive dies; superimposition scheme; sequence planning

1. Introduction

Progressive dies are widely used for the mass production of sheet metal parts with high accuracy and cost effectiveness. They are also particularly suitable for producing small and delicate parts, such as the connectors used in cell phone products or lead frames for the IC industry. Progressive dies combine at least two different sets of dies and punches allocated at different work stages in an appropriate sequence, which together compose the complete die. Each work stage performs one or more processes. When the strip goes through each work stage, it is sheared and formed with various features. The finished sheet metal part is cut off from the strip at the last work stage.

Progressive die design requires highly intensive experience and sequence planning, or determining the appropriate process sequence, is the most challenging task in progressive die design. When planning, designers need to thoroughly consider product features and requirements, the bed size of the punching machinery, the characteristics of the punches, the in-process change of the strip, and so on. With these factors in mind, developing an appropriate planning solution has become the most emphasised topic in the field of progressive die studies.

There are three types of operations involved in progressive dies: shearing, bending, and forming. Shearing – including punching, trimming, parting, and blanking – uses shearing force for material separation, which is the most basic and necessary process. Bending and forming use the stress generated by punches for localised plastic deformation of the metal sheet, and bending is the most common operation for plastic deformation in progressive dies. The deformation area of the bending process is only restricted to the bend line, whereas for the forming process it is the entire punching area. The methods of forming processes are highly diverse, and include drawing, embossing, flanging, and louvering. Owing to the complicated stretching and straining on sheet metal strips during the forming process, different planning methods are used according to different process types. Normally, the sequence planning of sheet metal parts independently treats the forming process first, and then combines the results with other processes. This research focuses on the planning of bending operations, and finally integrates its results with shearing planning through a merger program in order to obtain a strip layout. Bending and shearing are the essential processes in progressive dies. Either independent planning or final integration of the two processes requires extensive workloads. Integrating other forming processes could also refer to this entire planning procedure.

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*Corresponding author. Email: dean@mail.sju.edu.tw

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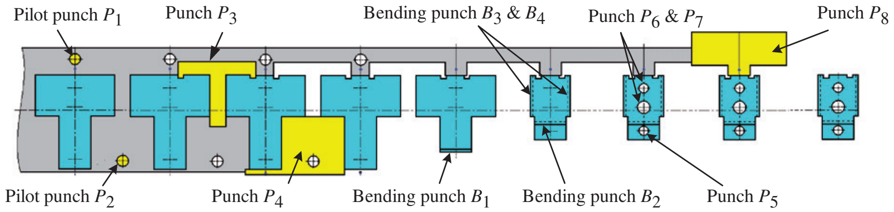


Figure 1. Sequence planning by the superimposition scheme.

Superimposition is one of the most commonly used methods for sequence planning in progressive dies. The procedure starts with designing appropriate punches corresponding to the features of sheet metal parts. Then the scaled punches are superimposed on the strip. Once every punch is in the appropriate work stage, the sequence planning is thus completed (Schubert 1967). (Figure 1) shows an exemplary case of sequence planning using superimposition; this case uses four bending punches and eight shearing punches to produce the part. This approach is quite straightforward, and it can easily detect interference among punches, as well as help designers communicate and exchange their experience. However, the main problem of superimposition is that when the number of punches increases, so does the number of possible solutions and it becomes difficult to find appropriate, feasible solutions. In this paper, the expertise of progressive die design is converted into scientific rules and formulae, which greatly reduce the solution space. The best solution is then derived regarding criteria that include number of stages, moment balancing, strip stability, and feeding height.

2. Literature review

Sequence planning is an important topic in the area of progressive dies because once the sequence is determined, the die design can be finished rapidly by using standardised punching tools and components. In the research field of progressive die design, Schaffer (1971) and Nakahara *et al.* (1978) are considered pioneers. They used CAD/CAM techniques for the automation of progressive die design. Some researchers following them have tried to integrate other techniques into the CAD/CAM environment. For example, Bergstrom *et al.* (1988) added some functions such as the calculations of stripper and punching forces, unfolding a bent part, and so on. These studies actually help with the improvement of design efficiency and design time reduction, however the sequence planning still relies heavily on the interactive commands of designers.

In the last few years, research on progressive dies has mainly been focused on how to automatically generate the strip layout. There have been two main research trends.

(1) Automatic feature recognition

The goal of feature recognition is to recognise features from a sheet metal CAD model and map these features to various process plans (Li *et al.* 2001, Tang and Gao 2007). Currently, feature recognition from CAD models faces certain difficulties, as the features of a CAD model usually lack some of the information required for manufacturing. One method to resolve these difficulties is to manually recognise the ill-defined features (Zhang *et al.* 2007). The second way is to use alternative methods to attempt to break recognition difficulties. For example, Kannan and Shunmugam (2009a) adopted a neutral format, STEP AP-203, of a sheet metal part model as input, and their system can identify a variety of features like embossing, internal flanges, collars, lances, and louvers.

(2) Automatic sequence planning

The main problem with automatic sequence planning is the large amount of possible solutions and intensive calculations. In order to solve this problem, the common solution is to use a rule-based expert system (Kumar and Singh 2008). However, more and more researchers have started to use other artificial intelligence techniques and heuristic searching schemes. For example, Duflou *et al.* (1999) formulated the bending sequence problem as a travelling salesman problem (TSP) with penalty functions, and used branch-and-bound procedures to search near-optimal solutions. Inui and Terakado (1999) used topological constraints to screen the solution space and reused previously calculated results to speed up the bending planning, while Gupta (1999) used virtual nodes to reduce calculation requirements. Thanapandi *et al.* (2001) used genetic algorithms for the bending sequence planning, and

Tor *et al.* (2005) integrated object-oriented techniques and blackboard architecture. Based on these studies, two observations can be made. One is that all these studies are mostly oriented toward checking the feasibility of using these techniques, and their systems are somewhat restrictive in specific geometric applications (Cheok and Nee 1998). The other is that these techniques may be very good at reducing the number of possible plans, but, at the same time, may lose better alternatives (Kannan and Shunmugam 2009b).

There are basically three differences between the aforementioned research and our research. (1) Solving scheme: The traditional sequence-planning technique is to arrange the sequence of features, while this research applies the concept of a superimposition scheme which converts the problem into arranging the sequence of punches. Although superimposition schemes are widely adapted by die designers, they are rarely discussed in academic research. (2) Solving procedure: Sequence planning normally uses search techniques such as tree searching, forward or backward searching, and shortening the search path by using related rules in order to find one or part of the solutions. Our research introduces punch classification, expansion of number of punches, and punch layout to obtain all feasible solutions. During the planning, it uses expertise and rules of engineering best practices to quickly eliminate infeasible planning, leaving only the few feasible plans. (3) Better solutions: This research applies a multiple-criteria decision-making (MCDM) approach to derive the best solutions from the remaining feasible plans.

3. Sequence planning for progressive dies

Sequence planning for progressive dies using the superimposition scheme involves appropriately assigning punches to different work stages according to corresponding features. When planning the sequence, the designers need to address three main questions: how many stages are used, how many punches are needed, and which punches should be placed at which stage. These three questions form such a huge search space that the task becomes very difficult. Thus, this research aims to quickly search all feasible solutions and select the best planning from among them.

3.1 *Procedure of sequence planning for progressive dies*

(Figure 2) shows the procedure of sequence planning for progressive dies used in this research. It consists of three steps: preparation of the strip, punch layout, and layout evaluation, which are discussed individually below.

(1) Preparation of the strip

The preparation of the strip is the setup work of the entire research, including first searching the bend line and bend plate from the 3D CAD model of the sheet metal part, and saving information about associated geometries and features in a proper format, then unfolding the sheet metal part and designing the punches corresponding to the bending and shearing features. The basic assumption in this research is that the design work of all the needed punches is complete. Hence, this step focuses on how to record the feature information of the CAD model.

(2) Punch layout

Punch layout involves placing all the designed punches into the sequencing and generating the strip layout. The object of this research is a sheet metal part with bending and shearing features. Bending operations, however, cause localised plastic deformation of the sheet metal part which results in ruptures and wear-outs of other shearing punches. Thus, punches for bending or shearing are not placed in the same work stage. In this research, the two types of punches are planned separately and then merged into different work stages. The procedures for planning both types of punches are identical, and follow seven processes.

(a) Clustering of punches: According to each punch's features, the ones for bending operations are classified as simultaneous use, sequential use, and exclusive use, while others for shearing operations are grouped as prior use, posterior use, simultaneous use, sequential use, and exclusive use. All the compatible punch sets are then obtained after punch grouping.
(b) Expansion of punch number: According to the total number of punches and expansion rules, find all possible numbers of stages and number of punches for every stage.
(c) Sequencing of punches: Place bending and shearing punches into every stage according to their characteristics of punch clustering.
(d) Merge of planning: All the generated sequences of both bending and shearing punches are merged into a complete strip layout.

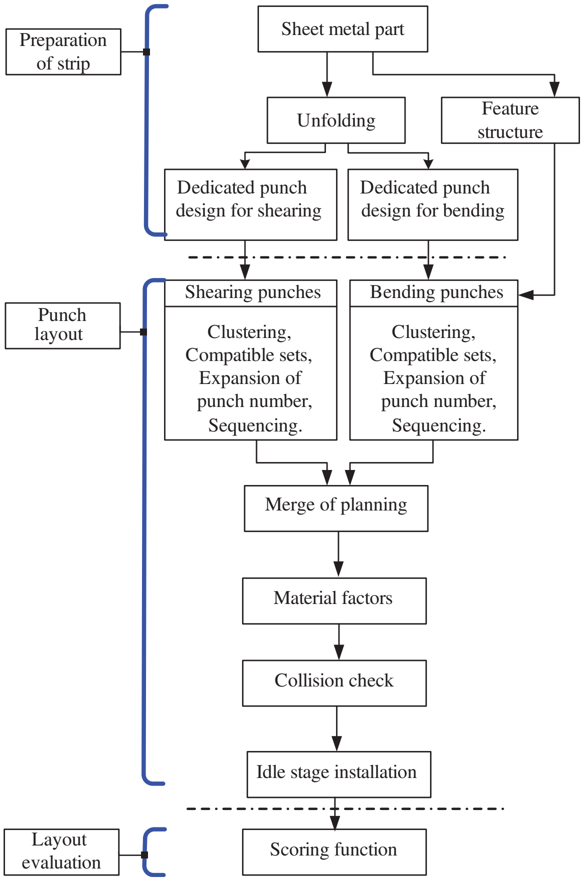


Figure 2. Procedure of sequence planning for progressive dies.

(e) Material factors: Material properties such as thickness, type of material, and springback effect may affect the sequence generated from previous processes and are treated during this process.
(f) Collision check: Examine the merged planning to see if there is a self-collision during bending processes or not; if yes, the planning has to be eliminated.
(g) Idle stage installation: If interference of punches occurred between adjacent stages, an idle stage must be inserted in between to separate the interfering punches.

(3) Layout evaluation

From previous step of punch layout, many feasible layouts are obtained, but only some of them can meet the requirements such as cost-effectiveness, low wear rate of dies, and high accuracy. Therefore, this research introduces a multiple-criteria decision-making approach with four criteria, including number of stages, moment balancing, strip stability, and feeding height, to form the scoring function which grades each feasible solution and helps designers determine the best sequencing plans.

The remainder of this paper is organised as follows: the strip preparation is described in Section 3.2. The punch layout for bending operations and its procedure is explained in Section 3.3. Section 3.4 presents the results of the punch layout for shearing operations. The merging of sequences, material factors, collision check, and idle stage installation are discussed in Sections 3.5, 3.6, 3.7, and 3.8, respectively. The layout evaluation and case studies are depicted in Sections 4 and 5. Finally, the conclusion is in Section 6.

3.2 *Preparation of strips*

The preparation of the strips includes three parts: sheet metal part unfolding, dedicated punch design, and tree structure diagram of features. This research takes a sheet metal part as an example – see (Figure 3). (Figure 4) shows

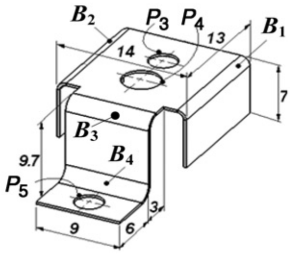


Figure 3. Sheet metal part.

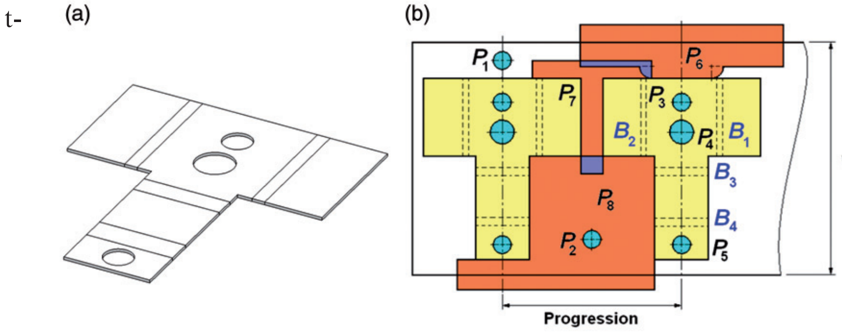


Figure 4. (a) Unfolded sheet metal, (b) Punch designs.

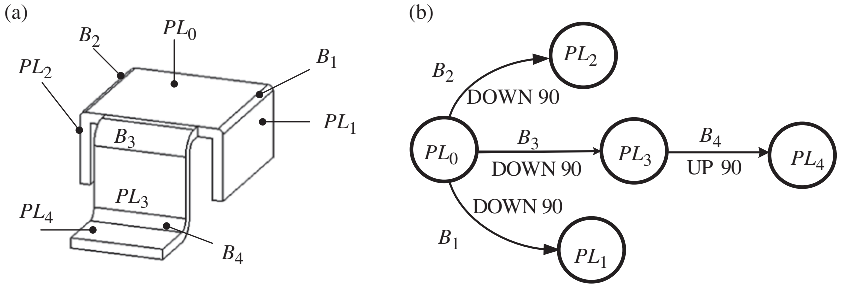


Figure 5. (a) Sheet metal part, (b) Tree structure of features.

he unfolding drawing and designed punches of the example part. In the dedicated punch design, the punches for bending operations are designed according to bend lines which need four punches (B_1–B_4), while the punch design for shearing operations is based on the internal and external shape of the unfolded sheet metal part which results in a total of eight punches (P_1–P_8). In addition, this research applies a tree diagram to depict the feature structure of bending operations. This tree diagram sets the reference plane as the root node and the bend plane as a node; the link represents the bend line between the two bend planes. Bending direction and bending angle are also recorded as link information. The reference plane is important and is defined as a fixed plane that does not rotate throughout the bending operations. The rules for selecting a reference plane were discussed in detail in Farsi and Arezoo's (2009) paper. Taking the sheet metal part in (Figure 5a) as an example, its feature tree diagram is shown in (Figure 5b). In this figure, PL_0 is selected as the reference plane, thus it is the root node of the tree diagram. Moreover, there are three bend planes linking with PL_0: PL_1, PL_2, and PL_3. Thus, PL_1, PL_2, and PL_3 are three nodes. The bend line between PL_0 and PL_1 is B_1 and the bending direction is downwards with a 90° bending angle (noted as DOWN 90°). Therefore, the link between PL_0 and PL_1 should be recorded as "B_1 and DOWN 90°". Plane PL_3 links with another bend plane PL_4. Assuming PL_3 is horizontal, the bending direction and angle are UP and 90° respectively, thus, the link between PL_3 and PL_4 should be noted as "B_4 and UP 90°". The rest of the notation can be done in the same manner.

3.3 *Bending punch layouts*

The following subsections explain the procedure of bending punch layouts, including topics such as types of bending operations, generation of bending punch clusterings and compatible sets, expansion of number of bending punches, and bending punch sequencing.

3.3.1 *Types of bending operations*

Four of the most frequently used bending types in progressive dies are the L-bend, Z-bend, U-bend, and V-bend. A part with complex bends can usually be created by combining these standard features (Li *et al.* 2002).

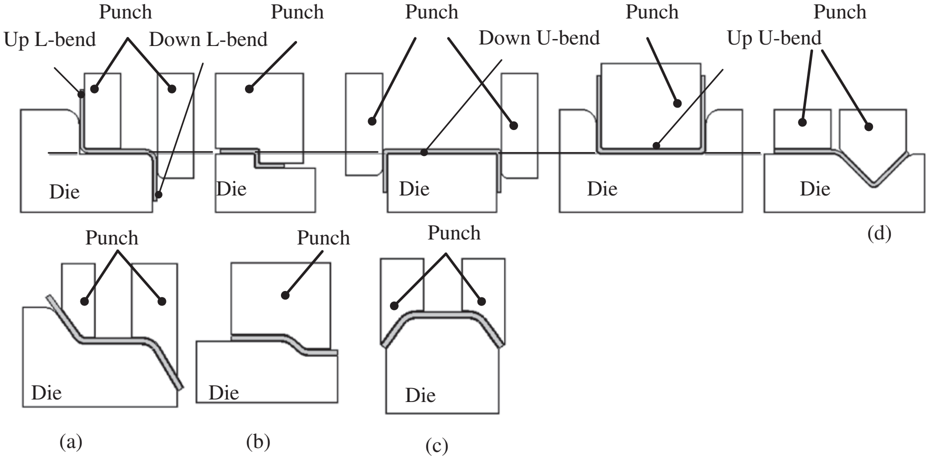


Figure 6. Four types of bends: (a) L-bend, (b) Z-bend, (c) U-bend, and (d) V-bend.

(Figure 6a) illustrates an L-bend, which can be sub-grouped into Up L-bend and Down L-bend. (Figure 6b) shows a Z-bend, an operation where the flat metal sheet is bent into a step fracture plane; note that the depth of the step cannot exceed five sheets' thicknesses, as too large a depth of step causes damage at bent corners (Yamaguchi 2001). (Figure 6c) displays a U-bend that simultaneously performs two symmetrical bends, where a Down U-bend uses two punches, and an Up U-bend uses only one punch. Finally, (Figure 6d) illustrates a V-bend, which uses two punches, one for pressing the metal sheet and the other for creating the V-shape.

3.3.2 *Bending punch clustering*

Bending punch clustering considers the characteristics of punches as well as the relationship between punches, and classifies the punches for simultaneous use, sequential use, and exclusive use in order to follow a punch layout. The clustering rules and methods for each group are discussed in detail as follows:

(1) Punches for simultaneous use

If several bending features have to be performed in one work stage, the associated punches should be placed in the same work stage. This rule can be used under three circumstances: collinear bend, U-bend, and Z-bend, explained separately below.

(a) Collinear bend: If the bend line is collinear with several bend features and it can be performed in one work stage, then the bending operation is defined as a ''collinear bend''. For example, in (Figure 7a), bending features B_1, B_2, B_3, and B_4 are collinear, thus, the punches for these two features should be placed at same work stage, noted as $[B_1, B_2]$ and $[B_3, B_4]$.

(b) U-bend: When parallel bend lines are symmetrical with respect to the reference plane, and their bending directions are the same, the bending operations should be completed at the same work stage. (Figure 7b) shows two types of U-bends, where (B_5, B_6) and (B_7, B_8) are Up U-bends and Down U-bends, respectively. Hence, the associated bending operations are performed at one stage, noted as $[B_5, B_6]$ and $[B_7, B_8]$.

(c) Z-bend: This type of bend consists of two bend lines whose depth of bend does not exceed five times the sheet's thickness. Its bending operation should be arranged at the same work stage. As shown in (Figure 7c), the Z-bend, where B_9 and B_{10} bends should be assigned at one stage, is noted as $[B_9, B_{10}]$.

When planning bending sequences, there are two basic constraints: (a) during the bending process, collisions cannot occur between sheet metal planes; and (b) restricted to the structure of progressive dies, bending operations should be performed on the die block surface. In order to simultaneously meet the above two constraints, the sequence planning is based on the reference plane of the sheet metal part, and starts from the outer-most bending surface, continuing sequentially from outside to inside. For instance, the sheet metal part shown in (Figure 8a) has a reference plane PL_0, bend lines B_1, B_2, B_3, and B_4, and bend planes PL_1, PL_2, PL_3, and PL_4. Its tree diagram is displayed in (Figure 8b). (Figure 9) illustrates the bending sequence of the sheet metal part, which starts from the

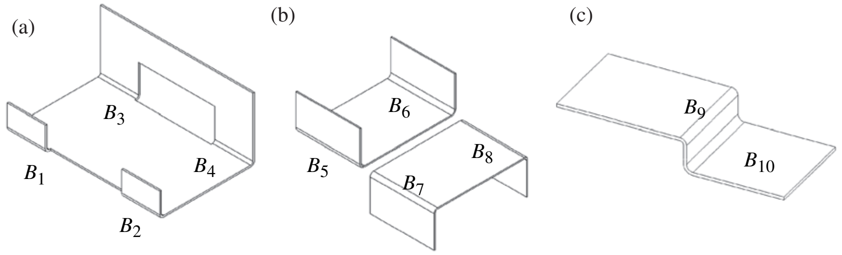


Figure 7. Punches for simultaneous use.

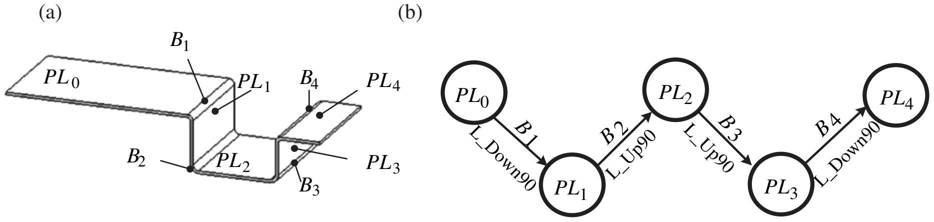


Figure 8. (a) Sheet metal part and (b) Its feature tree.

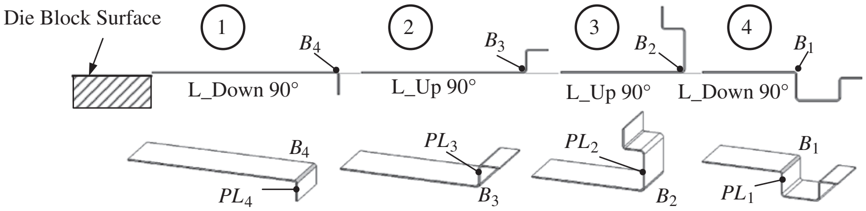


Figure 9. Bending sequence.

outer-most plane PL_4, followed by PL_3, PL_2, and PL_1. L_Down 90° and L_Up 90° represent the L-bends, whose bending directions are down and up, respectively, and bending angles 90°. This procedure thus forms the rules for bending sequence planning.

(2) Punches for sequential use

If different bend features have to be placed sequentially at different stages, the punches should be placed in the same sequence at each stage. The rules of bending sequence are stated as follows:

> In the tree diagram of bend features, the bending sequence on the same branch should start from the bend surface at the furthest node, and then follow the sequence of the branch from the outside to the inside until reaching the reference plane.

Taking the sheet metal part shown in (Figure 5) as an example, PL_1 and PL_2 define the U-bend according to the rules for simultaneous use, thus punches for bend lines B_1 and B_2 have to be placed in the same work stage, noted as $[B_1, B_2]$. See (Figure 10a). Moreover, according to the structure of the feature tree diagram, bend planes PL_0, PL_3, and PL_4 have sequential relationships, so the punches for bend lines B_3 and B_4 should be placed in the sequence from the outside node to the inside, noted as $(B_4 \rightarrow B_3)$. See (Figure 10b).

(3) Punches for exclusive use

If any two or more bend features cannot be allocated in one work stage, then the punches used cannot be placed in the same work stage. The exclusive relationship in bend planning is from the punches for sequential use, because those punches need to be placed in sequential stages; in other words, they cannot be placed in one stage. In the example in (Figure 5), the punches used form the punch set $\mathrm{B} = \{[B_1, B_2], B_3, B_4\}$, in which there is only one

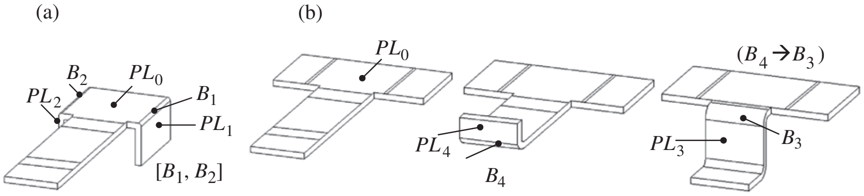


Figure 10. (a) Simultaneous use, (b) Sequential use.

sequential relationship ($B_4 \rightarrow B_3$). So the exclusive sets for punch B_i can be written as $E(B_i)$, where E denotes exclusive, as listed separately below:

$$\begin{aligned} E([B_1, B_2]) &= \{\Phi\} \\ E(B_3) &= \{B_4\} \\ E(B_4) &= \{B_3\} \end{aligned}$$

$E([B_1, B_2]) = \{\Phi\}$ means the exclusive set for simultaneous use punches and $[B_1, B_2]$ is an empty set Φ. In other words, $[B_1, B_2]$ can be placed with any other punches for simultaneous use. Compatible sets of B_i mean the set of all punches which can be placed with B_i in the same work stage, noted as $C(B_i)$, where C denotes compatible. The compatible sets can be derived by subtracting exclusive members of B_i and itself from the set B, as illustrated in Equation (1).

$$C(B_i) = B - E(B_i) - B_i \tag{1}$$

In the punch set $B = \{[B_1, B_2], B_3, B_4\}$, the compatible sets for each punch are computed below:

$$\begin{aligned} C([B_1, B_2]) &= \{B_3, B_4\} \\ C(B_3) &= \big\{[B_1, B_2]\big\} \\ C(B_4) &= \big\{[B_1, B_2]\big\} \end{aligned}$$

Based on the compatible sets, the punch set B can be converted into different combinations of punches which can be placed in one stage, as listed below:

$$\begin{aligned} \text{One-punch compatibility} &= (B_3), (B_4) \\ \text{Two-punch compatibility} &= ([B_1, B_2]) \\ \text{Three-punch compatibility} &= ([B_1, B_2], B_4), ([B_1, B_2], B_3) \end{aligned}$$

When planning the punch layout, designers need to consider two problems. The first is how many punches can be placed in one stage. Although many punches can be theoretically placed at one stage, in practice, just a few of them can be placed together due to the sequential rules or exclusive relationships among punches. In this case, the maximum number of punches which can be located in one bending stage is three (three-punch compatibility), which means it is not feasible to have four punches in one stage. Based on this result, solutions which contain four punches in one single stage can be eliminated, which results in a reduction of computation and search space. The other problem is determining the maximum number of bending stages, N_{bend_max}, and the minimum number of bending stages, N_{bend_min}. The punch layout should place every punch into a stage only once, and the planning can be obtained by considering the maximum and minimum number of punches which show compatibility. For the aforementioned case, the maximum number of punch compatibilities is three, and they are $((B_1, B_2), B_4)$, $((B_1, B_2), B_3)$, thus the minimum number of bending stages, N_{bend_min}, is two:

Two-stage design: $([B_1, B_2], B_4)$, (B_3) and $([B_1, B_2], B_3)$, (B_4).

In addition, the minimum number of punch compatibilities is one, and they are (B_3), (B_4), so the maximum number of bending stages, N_{bend_max}, is three:

Three-stage design: (B_3), (B_4), $([B_1, B_2])$.

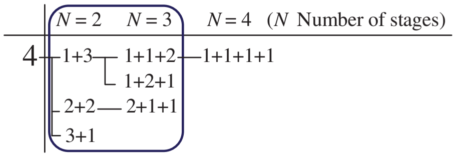


Figure 11. Expansion of four bending punches.

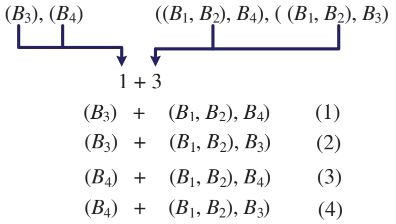


Figure 12. Bending punch sequencing for a $1+3$ case.

3.3.3 *Expansion of the number of bending punches*

The expansion of the number of punches aims to derive the number of stages and the number of punches at each stage in every possible solution, when there are n punches. If the idle stage is excluded, n punches can be located in at least two stages (Groover 2001), and at most n stages. The next question is how many punches are in each stage, and this can be answered by an expansion of the number of punches. When placing n punches into two stages, the number of punches at each stage can be expanded as:

$$1+(n-1), 2+(n-2), 3+(n-3), \ldots, (n-2)+2, (n-1)+1, \quad \text{in total } n-1 \text{ types of combinations.}$$

If the punch number is five, the expansion of number of punches at two stages results in a total of four types of expansions, which are $1+4$, $2+3$, $3+2$, and $4+1$. $1+4$ means one punch is located at the first stage and four punches are placed in the second stage. If these five punches need to be placed into three stages, it can be achieved by continuing the expansion of the number of punches at the last stage. For example, the last stage of $2+3$ has three punches, which can be expanded as $1+2$ and $2+1$. Therefore, the three-stage expansion can be arranged as $2+1+2$ and $2+2+1$. Based on the above discussion, the rules for the expansion of the number of punches are as follows:

1. If there are k stages, and the number of punches at the kth stage is m, and $m>1$, then the expansion can be continued to $k+1$ stages.
2. If the number of punches at the last stage is m, and if $m>1$, then there are $m-1$ ways to expand to the next stage: $1+(m-1)$, $2+(m-2), \ldots, (m-1)+1$.

During the expansion of the number of punches, if the number of bending punches at one stage exceeds the maximum number of punches which can be located in one bending stage, this solution is infeasible.

In the case of the sheet metal part in (Figure 5), there are four bend lines and four corresponding punches, which can be located in two, three, or four stages. The diagram of the expansion of number of punches is illustrated in (Figure 11). However, according to the discussion in Section 3.3.2, the minimum number of bending stages $N_{bend\_min}=2$, and the maximum number of bending stages $N_{bend\_max}=3$; thus, the four-stage solution, $1+1+1+1$ can be eliminated so that a total of $4!=24$ possible solutions are eliminated without requiring detailed calculations.

3.3.4 *Bending punch sequencing*

Bending punch sequencing, based on the results of the expansion of the number of punches, locates each punch cluster into an appropriate stage. There are three basic rules for punch sequencing:

1. According to the expansion of the number of punches, to locate each punch, start with the maximum number of punches which can show compatibility, followed by the second maximum number of punches, and so on.
2. Sequence should meet the clustering rules for simultaneous use, compatible use, and sequential use.
3. Each punch can be placed only once.

In the case of the sheet metal part in (Figure 5), taking the two-stage sequence $1+3$ as an example, there are two compatible sets with three punches, $((B_1, B_2), B_4)$ and $((B_1, B_2), B_3)$, leaving two single punches, (B_3) and (B_4), respectively. The sequencing procedure and its results are shown in (Figure 12).

In the four sequencing results shown in (Figure 12), (2) and (3) violate the rule that each punch can be placed only once, thus they are abandoned. The first sequence $(B_3)+([B_1, B_2], B_4)$ conflicts with the sequential rule

($B_4 \rightarrow B_3$), which is infeasible. Hence, only the sequence $(B_4)+([B_1, B_2], B_3)$ is correct. As a result, the case of (Figure 5) has only five feasible bending punch sequences:

$$\begin{array}{ll}
1+3 & (B_4)+([B_1,B_2],B_3) \\
3+1 & ([B_1,B_2],B_4)+(B_3) \\
1+1+2 & (B_4)+(B_3)+([B_1,B_2]) \\
1+2+1 & (B_4)+([B_1,B_2])+(B_3) \\
2+1+1 & ([B_1,B_2])+(B_4)+(B_3)
\end{array}$$

3.4 *Shearing punch layout*

The method of sequence planning for shearing operations has been published previously (Lin and Sheu 2011). This paper does not repeat the same detailed explanation, but presents the results only. The case of the sheet metal part in (Figure 3) uses eight shearing punches. They are $P_1 - P_8$, in which P_1 and P_2 are pilot punches belonging to prior use and P_6 is a parting punch which belongs to posterior use. The punches for simultaneous use are $[P_1, P_2]$ for punching pilot holes and $[P_3, P_4]$ for punching internal holes. When punching holes, internal hole punching is usually performed before external shearing. Thus, punches $[P_3, P_4]$ should be located before P_7, P_8, which yields the sequential relationship $[P_3, P_4] \rightarrow P_7$, P_8. (Figure 4b) shows that there is significant overlap between punch P_7 and P_8, so they cannot be placed in one stage and thus fall under exclusive use. According to the exclusive relationship, the compatibility sets for the eight punches can be arranged as:

$$\begin{aligned}
\text{One-shearing punch compatibility} &= P_5, P_6, P_7, P_8 \\
\text{Two-shearing punch compatibility} &= ([P_1, P_2]), ([P_3, P_4]), (P_5, P_7), (P_5, P_8) \\
\text{Three-shearing punch compatibility} &= ([P_3, P_4], P_5)
\end{aligned}$$

According to the above compatibility sets, the maximum number of punches which can be placed at one stage is three, while the minimum number of shearing stages, N_{shear_min}, is five, and maximum number of stages, N_{shear_max}, is six. Then the expansion of the number of shearing punch produces 42 solutions in total, of which 14 are feasible, as listed below:

Five-stage design:

$$\begin{gathered}
([P_1,P_2])+(P_3,P_4)+(P_7)+(P_5,P_8)+(P_6) \\
([P_1,P_2])+([P_3,P_4])+(P_8)+(P_5,P_7)+(P_6) \\
([P_1,P_2])+([P_3,P_4])+(P_5,P_8)+(P_7)+(P_6) \\
([P_1,P_2])+([P_3,P_4])+(P_5,P_7)+(P_8)+(P_6) \\
([P_1,P_2])+([P_3,P_4],P_5)+(P_7)+(P_8)+(P_6) \\
([P_1,P_2])+([P_3,P_4],P_5)+(P_8)+(P_7)+(P_6)
\end{gathered}$$

Six-stage design:

$$\begin{gathered}
([P_1,P_2])+(P_5)+([P_3,P_4])+(P_7)+(P_8)+(P_6) \\
([P_1,P_2])+(P_5)+([P_3,P_4])+(P_8)+(P_7)+(P_6) \\
([P_1,P_2])+([P_3,P_4])+(P_8)+(P_7)+(P_5)+(P_6) \\
([P_1,P_2])+([P_3,P_4])+(P_8)+(P_5)+(P_7)+(P_6) \\
([P_1,P_2])+([P_3,P_4])+(P_7)+(P_8)+(P_5)+(P_6) \\
([P_1,P_2])+([P_3,P_4])+(P_7)+(P_5)+(P_8)+(P_6) \\
([P_1,P_2])+([P_3,P_4])+(P_5)+(P_7)+(P_8)+(P_6) \\
([P_1,P_2])+([P_3,P_4])+(P_5)+(P_8)+(P_7)+(P_6)
\end{gathered}$$

3.5 *Merging of bending and shearing planning*

The merging of bending and shearing planning combines the punch layouts obtained in Sections 3.3 and 3.4 and locates every punch into different stages to determine the strip layout. The procedure is to first cluster both types of punches into groups of prior use, posterior use, and sequential use, and then to merge the layouts. The rules for the three clusters are:

(1) Punches for prior use

Pilot punches for shearing operations should be placed at the very beginning. In the case shown in (Figure 4), punch set $[P_1, P_2]$ belongs to the prior use group.

(2) Punches for posterior use

Shearing punches corresponding to carrier or bridge cut-off should be located at the last stage. In the case in (Figure 4), P_6 belongs to the punch for posterior use.

(3) Punches for sequential use

   (a) Bending operations should be arranged after the surrounding area has been removed by shearing operations. In the example in (Figure 4b), shearing punch P_7 must be placed before bending punches $[B_1, B_2]$, denoted as $P_7 \rightarrow ([B_1, B_2])$. Moreover, punch P_8 should be located before bending punches $[B_1, B_2]$, B_3, and B_4, denoted as $P_8 \rightarrow ([B_1, B_2])$, B_3, B_4.
   (b) Punching holes requiring a high degree of positional accuracy should be arranged after bending operations. In the case in (Figure 4), punch P_5 for punching holes should be located after bending punch B_3, denoted as $B_3 \rightarrow P_5$.

The procedure and rules for merging bending and shearing planning are explained below:

(1) Separate punches for prior use and posterior use from other punches, and exclude for planning in order to reduce the computation load.
(2) Merge new sequence planning according to the sequential rules of bending and shearing planning.
(3) When merging, the original sequence of bending and shearing punches cannot be modified.

In (Figure 13), taking three-stage bending punches $(B_4) + (B_3) + ([B_1, B_2])$ and six-stage shearing punches $([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + (P_5) + (P_6)$ as an example of merging. First, the punches for prior use $[P_1, P_2]$ and for posterior use P_6 are separated from the others and will be excluded for merging. Then, according to sequential rules, the insert points of bending punches are checked. Based on the sequential relationship $P_7 \rightarrow [B_1, B_2]$, there are two insert points for bending punch set $[B_1, B_2]$, which is after either P_7 or P_5. In addition, the rules $(P_8 \rightarrow B_3)$ and $(B_3 \rightarrow P_5)$ allow two insert points for punch B_3, which is after either P_8 or P_7. $(P_8 \rightarrow B_4)$ allows three insert points for punch B_4, which are after P_8, P_7, and P_5. However, its insert point after P_5 changes the post bending sequence $(B_3) + ([B_1, B_2])$ behind punch P_5, which violates the rule $B_3 \rightarrow P_5$, so this insert point is cancelled.

According to each insert point in (Figure 13), the merger of two plannings produces the following six solutions:

$$\begin{gathered}
([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (B_4) + (B_3) + (P_7) + ([B_1, B_2]) + (P_5) + (P_6) \\
([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (B_4) + (B_3) + (P_7) + (P_5) + ([B_1, B_2]) + (P_6) \\
([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (B_4) + (P_7) + (B_3) + ([B_1, B_2]) + (P_5) + (P_6) \\
([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (B_4) + (P_7) + (B_3) + (P_5) + ([B_1, B_2]) + (P_6) \\
([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + (B_4) + (B_3) + ([B_1, B_2]) + (P_5) + (P_6) \\
([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + (B_4) + (B_3) + (P_5) + ([B_1, B_2]) + (P_6)
\end{gathered}$$

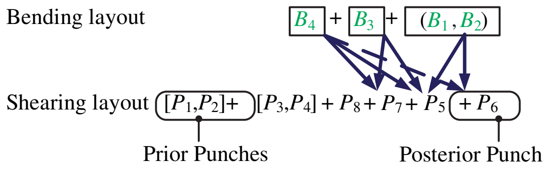


Figure 13. Merging of bending and shearing planning.

Based on the analysis in Section 3, the minimum number of bending stages, N_{bend_min}, for the case in (Figure 4) is two, while the maximum number of bending stages, N_{shear_min}, is three. On the other hand, the minimum number of shearing stages, N_{shear_min}, is five, whereas the maximum number of shearing stages, N_{shear_max}, is six. When merging both bending and shearing plannings, there are four overall combinations of total stage numbers, which are: seven stages (two bending stages and five shearing stages), eight stages (three bending stages and five shearing stages), eight stages (two bending stages and six shearing stages), and nine stages (three bending stages and six shearing stages). According to above merging rules, the case in (Figure 4) produces 17 feasible solutions. Apart from above six solutions, the rest are listed below:

Eight-stage design (two bending stages and six shearing stages):

$$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + (B_4) + ([B_1, B_2], B_3) + (P_5) + (P_6)$$
$$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (B_4) + (P_7) + ([B_1, B_2], B_3) + (P_5) + (P_6)$$
$$([P_1, P_2]) + ([P_3, P_4]) + (P_7) + (P_8) + (B_4) + ([B_1, B_2], B_3) + (P_5) + (P_6)$$
$$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + ([B_1, B_2], B_4) + (B_3) + (P_5) + (P_6)$$
$$([P_1, P_2]) + ([P_3, P_4]) + (P_7) + (P_8) + ([B_1, B_2], B_4) + (B_3) + (P_5) + (P_6)$$

Eight-stage design (three bending stages and five shearing stages):

$$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (B_4) + (B_3) + (P_5, P_7) + ([B_1, B_2]) + (P_6)$$

Nine-stage design (three bending stages and six shearing stages):

$$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + (B_4) + ([B_1, B_2]) + (B_3) + (P_5) + (P_6)$$
$$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (B_4) + (P_7) + ([B_1, B_2]) + (B_3) + (P_5) + (P_6)$$
$$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + ([B_1, B_2]) + (B_4) + (B_3) + (P_5) + (P_6)$$
$$([P_1, P_2]) + ([P_3, P_4]) + (P_7) + (P_8) + (B_4) + (B_3) + P_5 + ([B_1, B_2]) + (P_6)$$
$$([P_1, P_2]) + ([P_3, P_4]) + (P_7) + (P_8) + (B_4) + (B_3) + ([B_1, B_2]) + (P_5) + (P_6)$$

3.6 *Material factors*

The method of sequence generation from previous processes is more geometric in nature, but the material properties usually play another role affecting sequences. For example, the requirement of bending allowance and the effect of material springback may necessitate an extra bending stroke in order to meet dimensional considerations. Therefore, this study also takes material factors into consideration. One rule regarding bending allowance and sequence planning is listed as follows: If the bending angle allowance is within $+/- 0.5^\circ$, an extra bending stroke is needed to fulfil this requirement (Chu 2000).

3.7 *Collision check*

During bending operations, every process changes the shape of the sheet metal. Collisions between bending planes may occur in some of the solutions, which means they are infeasible and should be deleted. However, the problem here is that sequence planning contains a huge amount of possible solutions, and it is difficult to check every one of them. To solve this problem, this research uses two approaches: (1) using the removing rule to remove already discovered collision solutions and similar ones, which would reduce computation; and (2) performing collision checks after the merging step, since previous procedures can significantly reduce the amount of possible solutions. For example, the case presented in this paper has a total of 12 punches, which can produce $12! = 479{,}001{,}600$ possible solutions for only 12-stage planning. But actually there are only 17 feasible solutions obtained after the above planning.

3D solid modelling software is able to accurately calculate model volume. Volumetric intersection can be used to examine whether or not there will be a collision between sheet metal planes. The removing rule is demonstrated with the sheet metal part shown in (Figure 14a). The structure diagram of its features is shown in (Figure 14b). (Figure 14c) shows that, during bending operation B_4, collision occurs between plane PL_5 and PL_2. According to the

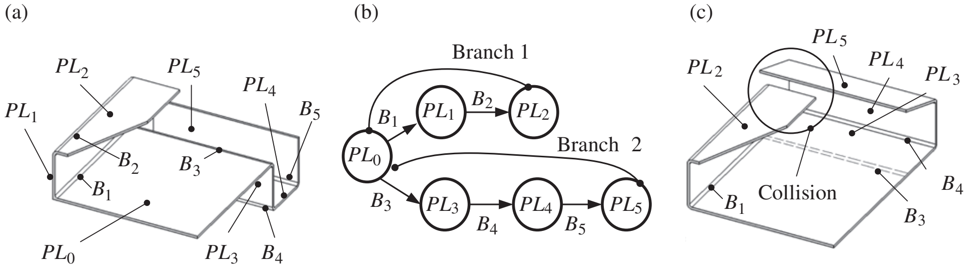


Figure 14. Collision check for bending operation.

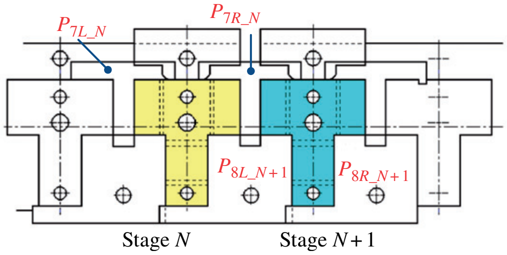


Figure 15. Installation of idle stage.

bending sequence rules, bending operations are arranged based on the feature tree diagram from the outside of the bend plane to the inside. When collision occurs, bends B_1 and B_2 on branch 1 have been completed, as has bend B_5 on branch 2, while bend B_4 is in the process of being completed. When recording the finished bend on both branches at the same time, if B_4 and B_1 appear together, then this solution is not feasible. Applying this recording method, if same situation happens, the solution should be deleted immediately.

3.8 *Installation of idle stages*

After the merging of the planning, there is another issue to address, namely, interference between punches of two adjacent stages. Interference occurs when the positions of punches at one stage and the next stage are too close or even overlapping. For instance, an arrangement such that P_7 is at the right side of stage N (P_{7R_N}) and P_8 is at the left side of stage $N+1$ (P_{8L_N+1}) has the problem of overlapping interference. The solution here is to install an idle stage in between, which increases the total stage number by one.

Rule for idle stage installation:

When planning punches, if the punch footprints on the strip at stage N and stage $N+1$ are too close, overlap, or interfere, an idle stage should be installed during operations.

This research uses an idle stage matrix to assist designers in deciding whether to install an idle stage. The idle stage matrix seeks first to identify the possible interference among each punch at the next two stages. In the matrix, if interference does not occur and an idle stage is not necessary, the associated relationship is denoted as 0. If interference does occur and an idle stage is necessary, the corresponding relationship is noted as 1, and the symbol "–" means not applicable. For an external profile shearing punch, there are two possible positions at the stage: the position is recorded as L if at the left side of the stage, and R if at the right side. See (Table 1)

Based on the above analysis, several solutions of the initial 17 sequencing plans should install an idle stage, represented by the symbol "***I***". The final completed stage numbers and punch planning sequences are listed as follows:

Eight-stage planning:

$$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + (B_4) + ([B_1, B_2], B_3) + (P_5) + (P_6)$$

Table 1. Idle stage matrix.

		$N+1$										
Stage		$[P_1, P_2]$	$[P_3, P_4]$	P_5	P_6	P_{7_L}	P_{7_R}	P_{s_L}	P_{s_R}	$[B_1, B_2]$	B_3	B_4
N	$[P_1, P_2]$	–	0	0	0	0	0	1	0	0	0	0
	$[P_3, P_4]$	–	–	0	0	0	0	0	0	0	0	0
	P_5	–	0	–	0	0	0	0	0	0	0	0
	P_6	–	–	–	–	–	–	–	–	–	–	–
	P_{7_L}	–	0	0	0	–	–	0	0	0	0	0
	P_{7_R}	–	0	0	1	–	–	1	0	1	0	0
	P_{s_L}	–	0	0	0	0	0	–	–	0	0	0
	P_{s_R}	–	0	0	0	1	0	–	–	1	1	1
	$[B_1, B_2]$	–	0	0	0	–	–	–	–	–	0	0
	B_3	–	0	0	0	0	0	–	–	0	–	–
	B_4	–	0	0	0	0	0	–	–	0	0	–

Nine-stage planning:

$$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + \boldsymbol{I} + (B_4) + (P_7) + ([B_1, B_2], B_3) + (P_5) + (P_6)$$
$$([P_1, P_2]) + ([P_3, P_4]) + (P_7) + (P_8) + \boldsymbol{I} + (B_4) + ([B_1, B_2], B_3) + (P_5) + (P_6)$$
$$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + \boldsymbol{I} + ([B_1, B_2], B_4) + (B_3) + (P_5) + (P_6)$$
$$([P_1, P_2]) + ([P_3, P_4]) + (P_7) + (P_8) + \boldsymbol{I} + ([B_1, B_2], B_4) + (B_3) + (P_5) + (P_6)$$
$$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + \boldsymbol{I} + (B_4) + (B_3) + (P_5, P_7) + ([B_1, B_2]) + (P_6)$$
$$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + (B_4) + ([B_1, B_2]) + (B_3) + (P_5) + (P_6)$$
$$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + (B_4) + (B_3) + (P_5) + ([B_1, B_2]) + (P_6)$$
$$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + (B_4) + (B_3) + ([B_1, B_2]) + (P_5) + (P_6)$$

Ten-stage planning:

$$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + \boldsymbol{I} + (B_4) + (P_7) + ([B_1, B_2]) + (B_3) + (P_5) + (P_6)$$
$$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + \boldsymbol{I} + ([B_1, B_2]) + (B_4) + (B_3) + (P_5) + (P_6)$$
$$([P_1, P_2]) + ([P_3, P_4]) + (P_7) + (P_8) + \boldsymbol{I} + (B_4) + (B_3) + (P_5) + ([B_1, B_2]) + (P_6)$$
$$([P_1, P_2]) + ([P_3, P_4]) + (P_7) + (P_8) + \boldsymbol{I} + (B_4) + (B_3) + ([B_1, B_2]) + (P_5) + (P_6)$$
$$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + \boldsymbol{I} + (B_4) + (P_7) + (B_3) + ([B_1, B_2]) + (P_5) + (P_6)$$
$$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + \boldsymbol{I} + (B_4) + (B_3) + (P_7) + ([B_1, B_2]) + (P_5) + (P_6)$$
$$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + \boldsymbol{I} + (B_4) + (B_3) + (P_7) + (P_5) + ([B_1, B_2]) + (P_6)$$
$$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + \boldsymbol{I} + (B_4) + (P_7) + (B_3) + (P_5) + ([B_1, B_2]) + (P_6)$$

4. Layout evaluation

When all feasible punch sequences have been found by the previous procedures, the next step is to find the most suitable solutions from among them. Various firms usually have their own special considerations and varying levels of expertise, and they thus make decisions based mainly on their own criteria and needs. A better choice for one company may not work well for another. An approach called multiple-criteria decision making, which is a sub-discipline of operation research, is used in this study. MCDM is concerned with structuring and solving decision and planning problems involving multiple criteria. Typically, there is no unique optimal solution for such problems, and using the decision-maker's preferences to differentiate between solutions is indispensable. An MCDM model called weighted sums (Gass and Saaty 1955) or the scoring model (Anderson *et al.* 2004), which has criteria and weights in its objective equation, is used to evaluate and select the best alternatives.

The weighted sums model (WSM) can be represented as Equation (2):

$$A_i^{WSM} = \sum_{j=1}^{n} w_j a_{ij} \quad \text{for} \quad i = 1, 2, 3, \ldots m \tag{2}$$

In the equation, the problem is defined based on m alternatives and n decision criteria. All the criteria are benefit criteria, which means higher values are better. The relative weight of importance of the criterion C_j is denoted by w_j, and a_{ij} is the performance value of alternative A_i when it is evaluated in terms of criterion C_j.

The chosen criteria should be closely related to the scoring equation. The weight values are chosen based on the designers' preferences and reflect their own concerns. In this study, many field experts have been consulted for their preferred criteria. They suggested several criteria, but only four were consistently approved, and the rest were only significant to individual experts in their own way. The final evaluation model thus consists of four factors: stage number factor F_N, moment balancing factor F_B, strip stability factor F_S, and feeding height factor F_L. The evaluation score E_V is calculated based on Equation (3).

$$\text{Evaluation score } E_V = w_1 \times F_N + w_2 \times F_B + w_3 \times F_S + w_4 \times F_L \tag{3}$$

where $w_1 + w_2 + w_3 + w_4 = 1$ and $0 \leq w_1, w_2, w_3, w_4 \leq 1$.

In the above equation, w_1, w_2, w_3, and w_4 are weights which can be adjusted according to the designer's experience and product requirements. This research sets each weighting value as $w_1 = 0.3$, $w_2 = 0.2$, $w_3 = 0.3$, $w_4 = 0.2$. The calculated values of those four factors range from 10 to 100. A score of 10 indicates the worst design while 100 indicates the best. Therefore the evaluation score E_V, computed from Equation (3), should also range between 10 and 100.

As mentioned previously, firms usually have their own concerns. The evaluation function in this study reflects only part of the real process for selecting the best solutions. However, this methodology could give the designer an opportunity to add/delete criteria and to tune the weight values to fit his/her needs.

4.1 *Stage number factor F_N*

The punch layout for n punches in progressive dies can be organised into at least two stages (Groover 2001), and at most n stages, while the actual number of stages is normally somewhere in between. From a manufacturing point of view, more stages result in a bigger die and higher costs. This results in the limitation of machinery selection due the bed size. Thus, using fewer stages has the advantages of cost effectiveness and flexibility of use. The stage number factor, F_N, ranges from 10 to 100. The factor is 100 for a two-stage planning and is 10 when stage number is n. For any N-stage planning, the factor can be obtained by means of linear interpolation. Equation (4) and its explanation are shown in (Figure 16).

$$\text{Stage number factor } F_N = 100 - 90 \times (N - 2)/(n - 2) \tag{4}$$

where N is the number of stages including idle stages and n is total number of punches.

4.2 *Moment balancing factor F_B*

Progressive dies use more than one stage. When each stage performs a task, the reaction force from punching acts simultaneously on different spots of the die block. If the centre of the resultant reaction force is mismatched with the centre of the dies, a force imbalance occurs and this eventually causes misalignment of the die, wearing out of the punch and leading to a shorter die life. Therefore, a good design has to consider the force distribution on the dies during operation. In other words, it is strongly suggested to design a die with the appropriate punch layout that will result in an evenly distributed load over the press bed (Wilson 1963). In order to achieve this, the centre of the resultant force should be near the centre of the die. The moment balancing factor is a measurement of how closed the distance between the centre of resultant reaction force and the centre of the die block.

Moment equilibrium equations are used for calculating the centre of the resultant reaction force (Lin and Chang 2001, Lin and Chen 2003). The punching force for bending and shearing operations can be calculated based

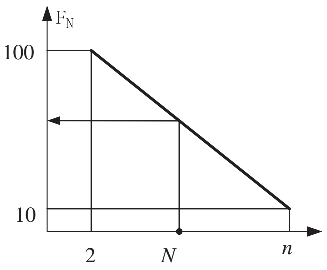


Figure 16. Number of stages N – factor F_N.

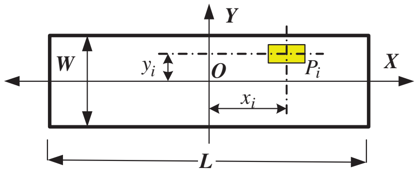


Figure 17. Punch P_i and its punching distance.

on the following equations, where l is the bending or shearing length, t is sheet metal thickness, δ_B is the tensile strength, and C_u, C_L, and C_u are the material coefficients which can be found in the handbook of engineering materials.

$$\text{U-bend force } F_{U\_bend} = (C_u/3) \times l \times t \times \delta_{\mathrm{B}} \tag{5}$$

$$\text{L-bend force } F_{L\_bend} = (C_L/6) \times l \times t \times \delta_{\mathrm{B}} \tag{6}$$

$$\text{Shearing force } F_{Shear} = Cs \times l \times t \times \delta_{\mathrm{B}} \tag{7}$$

The length L and width W of the die can be determined by the number of stages and strip width. Then the die centre O can be calculated by L and W. For example, there are n punches in total, where f of them are U-bend punches, m of them are for L-bends, and s of them are shearing punches. Moreover, x_i, x_j, and x_k are the distances of forces generated along the X direction by the U-bend punch P_i, the L-bend punch P_j, and the shearing punch P_k, respectively. Likewise, y_i, y_j, and y_k are the distances of the above forces along the Y direction. (Figure 17) uses punch P_i as an example to illustrate the relationship between the distance of the force and die centre O. The resultant force on the die can be computed according to Equations (8) and (9).

$$F = \sum_{i=1}^{f} F_{Ubend\_i} + \sum_{j=1}^{m} F_{Lbend\_j} + \sum_{k=1}^{s} F_{shear\_k} \tag{8}$$

$$\begin{aligned} &= \sum_{i=1}^{f}\left(C_U \times L_i \times t \times \frac{\delta_B}{3}\right) + \sum_{j=1}^{m}\left(C_L \times L_j \times t \times \frac{\delta_B}{6}\right) + \sum_{k=1}^{s}(C_S \times L_k \times t \times \delta_B) \\ &= t \times \delta_B \times \left(\sum_{i=1}^{f} C_U \times L_i \times \frac{1}{3} + \sum_{j=1}^{m} C_L \times L_j \times \frac{1}{6} + \sum_{k=1}^{s} C_S \times L_k\right) \end{aligned} \tag{9}$$

The centre of the resultant reaction force at n-punch die $(\bar{x}, \bar{y})$ can be found through Equations (10) and (11).

$$\begin{aligned} \bar{x} &= \left(\sum_{i=1}^{f} x_i \times F_{Ubend\_i} + \sum_{j=1}^{m} x_j \times F_{Lbend\_j} + \sum_{k=1}^{s} x_k \times F_{shear\_k}\right)\Big/F \\ &= t \times \delta_B \times \left(\sum_{i=1}^{f} x_i \times C_U \times L_i \times \frac{1}{3} + \sum_{j=1}^{m} x_j \times C_L \times L_j \times \frac{1}{6} + \sum_{k=1}^{s} x_k \times C_S \times L_k\right)\Big/F \\ &= \left(\sum_{i=1}^{f} x_i \times C_U \times L_i \times \frac{1}{3} + \sum_{j=1}^{m} x_j \times C_L \times L_j \times \frac{1}{6} + \sum_{k=1}^{s} x_k \times C_S \times L_k\right) \\ &\quad \div \left(\sum_{i=1}^{f} C_U \times L_i \times \frac{1}{3} + \sum_{j=1}^{m} C_L \times L_j \times \frac{1}{6} + \sum_{k=1}^{s} C_S \times L_k\right) \end{aligned} \tag{10}$$

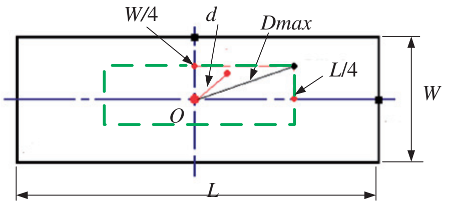


Figure 18. Range of deviation.

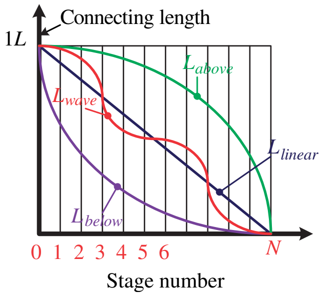


Figure 19. Patterns of connecting length decrease.

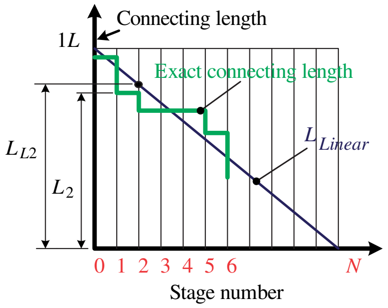


Figure 20. Variation of connecting length.

$$\bar{y} = \left(\sum_{i=1}^{f} y_i \times C_U \times L_i \times \frac{1}{3} + \sum_{j=1}^{m} y_j \times C_L \times L_j \times \frac{1}{6} + \sum_{k=1}^{s} y_k \times C_S \times L_k \right) \div \left(\sum_{i=1}^{f} C_U \times L_i \times \frac{1}{3} + \sum_{j=1}^{m} C_L \times L_j \times \frac{1}{6} + \sum_{k=1}^{s} C_S \times L_k \right) \tag{11}$$

The moment balancing factor considers how close the centre of the resultant reaction force is to the centre of the die. (Figure 18) shows a die of length L and width W. The centre of the resultant reaction force seldom deviates from the die block centre by more than $L/4$ and $W/4$, so the maximum deviation D_{max} and actual deviation d are defined in Equations (12) and (13):

$$D_{\max} = \sqrt{(L/4)^2 + (W/4)^2} \tag{12}$$

$$d = \sqrt{\bar{x}^2 + \bar{y}^2} \tag{13}$$

The moment balancing factor can be calculated using Equation (14). When $d = 0$, $F_B = 100$. When $d = D_{max}$, $F_B = 10$. Although in most cases $d < D_{max}$, if $d > D_{max}$ occurs, it would affect the score of the overall evaluation, so the worst case is assigned to $d = D_{max}$.

$$\text{Moment balancing factor } F_B = 100 \times (1 - 0.9 \times d/D_{\max}) \tag{14}$$

4.3 *Strip stability factor F_S*

When the strip moves from one stage to another, the connecting length between the part and the strip is reduced. As the connecting length becomes shorter, the part attached to the strip vibrates more intensely during operation. This is highly undesirable for sheet metal parts, which usually require high accuracy and precision. The connecting length between the part and strip is $1L$ at the beginning, but with the punching operations at following stages, it becomes

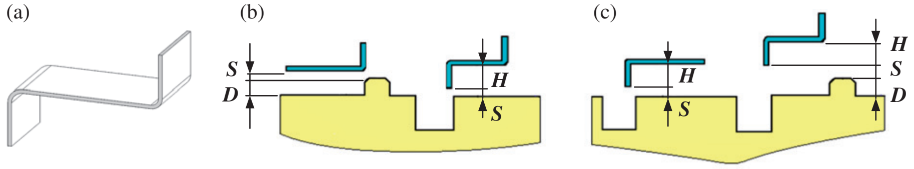


Figure 21. Feeding heights.

shorter and shorter, and eventually at the last stage becomes zero. In other words, the connecting length decreases with increasing stage numbers. As shown in (Figure 19), there are four types of length reducing patterns: L_{linear}, L_{above}, L_{below}, and L_{wave}. When connecting length decreases linearly with an increasing number of stages, the trend is the linear type L_{linear}. This type seldom appears, however it is a desirable trend. The L_{above} type is the most desirable type; the decreasing trend is gentle, so the accuracy is better. In contrast, type L_{below} is the worst case; the connecting length is reduced rapidly and the parts become shaky. The last type, L_{wave}, is the most common one; the connection length reduction is sometimes higher than L_{linear} and sometimes lower than L_{linear}.

There are two considerations for the evaluation of strip stability. (1) The connecting length of one stage is the residual length after the punching operation of the stage. (2) The connecting length at later stages has a more important impact on the stability of the strip. This is because the shaking becomes more serious at the last stages. The equation for the strip stability factor of N stages refers to the linear trend L_{linear}. See (Figure 20). The linear trend is considered to be a good one, and if one length-decreasing pattern fits the linear type, a score of 70 out of 100 is assigned. The equation for calculating the strip stability factor is listed below:

$$\begin{aligned} F_S &= 70 \times \{1 \times (L_1/L_L 1) + 2 \times (L_2/L_L 2) + \cdots + k \times (L_k/L_{Lk}) + \cdots + (N-1) \\ &\quad \times (L_N{-}1/L_{LN}{-}1)\}/(1 + 2 + \cdots + N - 1) \\ &= 70 \times \left\{ \sum_{k=1}^{N-1} k \times (L_k \,/\, L_{Lk}) \right\} \Big/ \sum_{k=1}^{N-1} k \end{aligned} \tag{15}$$

N is the number of stages,
L_k is the exact connecting length at the kth stage,
L_{Lk} is the connecting length at the kth stage in the L_{linear} pattern, and
k is the weighting for the stage number k.

In Equation (15), the real connecting length L_k of the attached part at stage k is divided by the length of linear pattern L_{Lk}. For example, L_2 is the residual connecting length at the second stage, and L_{L2} is the length of the linear decreasing pattern at this stage. If the ratio of L_2/L_{L2} is greater than one, this implies the stability at this stage is better than the linear pattern layout. On the other hand, a smaller ratio implies a worse case than the linear one. In Equation (15), the ratio at each stage is multiplied by a weighting value of its own stage number, which gives the ratios of later stages more influence on the total score. Moreover, if the connecting length shows a wave-reducing pattern, the length decreases rapidly at later stages, the average final value is still close to L_{linear}, but it is unfavourable. With weighting factors, this situation can be avoided.

4.4 *Feeding height factor F_L*

During bending operations, the movement of the strip can easily cause collisions with other parts of the dies, thus the strip is normally lifted in order to avoid this type of collision or interference. For example, the sheet metal part in (Figure 21a) has two sequencing plans. The first one, as shown in (Figure 21b), bends the front end of the strip upwards at the first stage, then bends the rear end downwards at the second stage. In order to pass the stage and avoid possible collision, the strip needs to be lifted with a safety height S above the top of the die at that stage. Normally, the feeding height refers to the bottom of the reference plane of the strip, so for the first plan the feeding height at these two stages is:

$$fh_1 = S + D$$
$$fh_2 = S + H$$

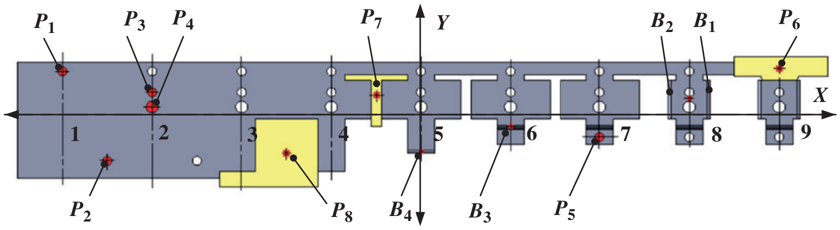


Figure 22. Calculation of the centre of the resultant reaction force.

The overall feeding height of the sheet metal part is the maximum value of fh_1 and fh_2, or $FH = \text{MAX}\ (fh_1, fh_2)$. (Figure 21c) shows the second plan, which first bends the rear end of the strip downward, and then bends the front end upward at the second stage, so the feeding height at the two stages is:

$$fh_1 = S + H$$
$$fh_2 = D + S + H$$

The above example indicates that different sequencing plans for the same product can result in different feeding heights. However, a higher feeding height usually causes more shaking when moving strip, and adds to the difficulty of die design. Therefore, a lower feeding height results in a better sequencing plan.

For an N-stage sequencing plan in progressive dies, the feeding heights at each stage are $fh_1, fh_2, fh_3, \ldots, fh_N$, and then the overall feed height is:

$$FH = \text{MAX}(fh_1, fh_2, fh_3, \ldots, fh_N) \tag{16}$$

Bending operations certainly require a feeding height. In this research, the reference feeding heights are defined as follows:

$$\text{Minimum feeding height } FH_{MIN} = S \tag{17}$$

$$\text{Maximum feeding height } FH_{MAX} = H_m + S \tag{18}$$

Where S is the safety height, and its value is determined by the material and thickness of the sheet metal part (the safety height is normally four to eight times the thickness of the part) and H_m is the maximum length of the imaginary rectangle that can enclose the entire sheet metal part. The equation for calculating the factor of feeding heights is illustrated in Equation (19):

$$F_L = 100 - 90 \times (FH - FH_{MIN})/(FH_{MAX} - FH_{MIN}) \tag{19}$$

4.5 *Calculation of the evaluation scores*

The 17 sequencing plan candidates are found in Section 3. The next problem is to determine the desirability of these plans, so they need to be tested by the evaluation function. In the following paragraph, a nine-stage layout of $([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + (B_4) + (B_3) + (P_5) + ([B_1, B_2]) + (P_6)$ will be used as an example for demonstrating the calculation process.

(1) Stage number factor F_N

The value of F_N for 12 punches ($N = 12$) and a nine-stage layout ($n = 9$) is calculated using Equation (4), as shown below.

$$F_N = 100 - 90 \times (N - 2)/(n - 2) = 100 - 90 \times (9 - 2)/(12 - 2) = 37$$

(2) Moment balancing factor F_B

The centre of the resultant reaction force $(\bar{x}, \bar{y})$ is calculated with Equations (10) and (11). As shown in (Figure 22), a nine-stage design should have a total of 270 units of strip length processing in the die set, and the centre of die block is located 135 units from both ends. The material coefficients C_U, C_L, and C_S depend on many

Table 2. Connecting length.

Stage no.	0	1	2	3	4	5	6	7	8	9
L_{LK}	114.16	101.47	88.79	76.11	63.42	50.74	38.05	25.37	12.684	0
L_K	114.16	114.16	114.16	78.92	31.33	10	10	10	10	0

Table 3. Feeding heights for stages.

Stage no.	1	2	3	4	5	6	7	8	9
FH	2	2	2	2	2	2	2	9	9

factors such as clearance between the punch and die, punching speed, and radius of punch, so their values are chosen to be 1.2, 1.2, and 1.0, respectively (Chu 2000).

$$\begin{aligned}
\bar{x} = &\left(\sum_{i=1}^{f} x_i \times C_U \times L_i \times \frac{1}{3} + \sum_{j=1}^{m} x_j \times C_L \times L_j \times \frac{1}{6} + \sum_{k=1}^{s} x_k \times C_S \times L_k\right) \\
&\div \left(\sum_{i=1}^{f} C_U \times L_i \times \frac{1}{3} + \sum_{j=1}^{m} C_L \times L_j \times \frac{1}{6} + \sum_{k=1}^{s} C_S \times L_k\right) \\
&= \big[(C_U \times L_{B_{1-B2}} \times X_8)/3 + C_L \times (L_{B_4} \times X_5 + L_{B_3} \times X_6)/6 + C_S \times (L_{P_{1-P2}} \times X_1 \\
&\quad + L_{P_{3-P4}} \times X_2 + L_{P_8} \times X_3 + L_{P_7} \times X_4 + L_{P_5} \times X_7 + L_{P_6} \times X_9)]/[C_U \times L_{B_{1-B2}}/3 \\
&\quad + C_L \times \big(L_{B_4} + L_{B_3}\big)/6 + C_S \times \big(L_{P_{1-P2}} + L_{P_{3-P4}} + L_{P_8} + L_P 7 + L_{P_5} + L_{P_6}\big)\big] \\
&= [(1.2 \times 26 \times 90/3) + 1.2 \times (9 \times 0 + 9 \times 30)/6 + 1 \times (18.85 \times -127.5 + 21.99 \times -90 \\
&\quad +70.41 \times -46.34 + 68.67 \times -15 + 9.42 \times 60 + 16 \times 120)]/(1.2 \times 26/3 + 1.2 \times (9+9)/6 \\
&\quad + 18.85 + 21.99 + 70.41 + 68.67 + 9.42 + 16) = -23.708
\end{aligned}$$

$$\begin{aligned}
\bar{y} = &\left(\sum_{i=1}^{f} y_i \times C_U \times L_i \times \frac{1}{3} + \sum_{j=1}^{m} y_j \times C_L \times L_j \times \frac{1}{6} + \sum_{k=1}^{s} y_k \times C_S \times L_k\right) \\
&\div \left(\sum_{i=1}^{f} C_U \times L_i \times \frac{1}{3} + \sum_{j=1}^{m} C_L \times L_j \times \frac{1}{6} + \sum_{k=1}^{s} C_S \times L_k\right) \\
&= [(C_U \times L_{\mathrm{B1-B2}} \times Y_8) + C_L \times (L_{\mathrm{B4}} \times Y_5 + L_{\mathrm{B3}} \times Y_6) + C_S \times (L_{\mathrm{P1-P2}} \times Y_1 + L_{\mathrm{P3-P4}} \times Y_2 + L_{\mathrm{P8}} \times Y_3 \\
&\quad + L_{\mathrm{P7}} \times Y_4 + L_{\mathrm{P5}} \times Y_7 + L_{\mathrm{P6}} \times Y_9)]/[C_U \times L_{\mathrm{B1-B2}}/3 + C_L \times (L_{\mathrm{B4}} + L_{\mathrm{B3}})/6 \\
&\quad + C_S \times (L_{\mathrm{P1-P2}} + L_{\mathrm{P3-P4}} + L_{\mathrm{P8}} + L_{\mathrm{P7}} + L_{\mathrm{P5}} + L_{\mathrm{P6}})]
\end{aligned}$$

$$\begin{aligned}
&= [(1.2 \times 26 \times 7/3) + 1.2 \times (9 \times -11.12 + 9 \times -2.06)/6 + 1 \times (18.85 \times 1.5 + 21.99 \times 6.66 \\
&\quad + 70.41 \times -9.9 + 68.67 \times 11.65 + 9.42 \times -6.2 + 16 \times 17.04)]/(1.2 \times 26/3 + 1.2 \times (9+9)/6 \\
&\quad + 18.85 + 21.99 + 70.41 + 68.67 + 9.42 + 16) = 2.46
\end{aligned}$$

$$d = \sqrt{\bar{x}^2 + \bar{y}^2} = \sqrt{(-23.708)^2 + (2.46)^2} = 23.84$$

$$D_{\max} = \sqrt{(L/4)^2 + (W/4)^2} = \sqrt{67.5^2 + 9.77^2} = 68.20$$

$$F_B = 100 \times (1 - 0.9 \times d/D_{\max}) = 100 \times (1 - 0.9 \times 23.84/68.20) = 68.54$$

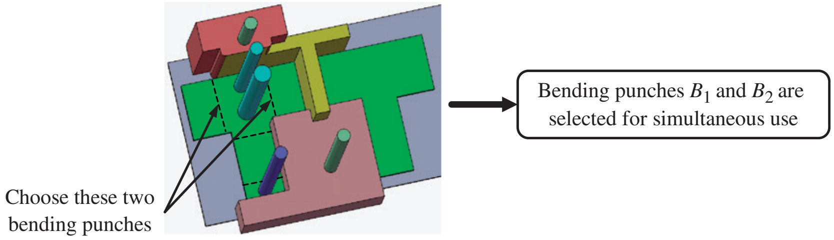


Figure 23. Selecting punches for simultaneous use.

(3) Strip stability factor F_S

The total shearing length of the sheet metal part in (Figure 4) is 114.16 units, and this value will be reduced gradually by punching operations performed at every stage. The connecting length of the linear reduction L_{LK} and its remaining L_k at each stage are shown in (Table 2).

$$\begin{aligned} F_S &= 70 \times \{1 \times \left(L_1/L_{L_1}\right) + 2 \times \left(L_2/L_{L_2}\right) + \cdots + k \times (L_k/L_{Lk}) + \cdots + (N-1) \\ &\quad \times (L_N{-}1/L_{LN}{-}1)\}/(1 + 2 + \cdots + N - 1) \\ &= 70 \times \{(1 \times 114.16/101.47 + 2 \times 114.16/88.79 + 3 \times 78.92/76.11 \\ &\quad + 4 \times 31.33/63.42 + 5 \times 10/50.74 + 6 \times 10/38.05 + 7 \times 10/25.37 \\ &\quad + 8 \times 10/12.684)\}/(1+2+3+4+5+6+7+8) = 39.69 \end{aligned}$$

(4) Feeding height factor F_L

The processing strip is lifted and moved to the next stage when in bending operation in order to avoid collision or interference with die fixtures. A higher feeding height usually causes more shaking and eventually deteriorating part accuracy, and this may even complicate the die structure. Therefore a designer is more likely to select a lower feeding height for the sequencing plan required. The feeding height required for every stage in this case is shown in (Table 3)

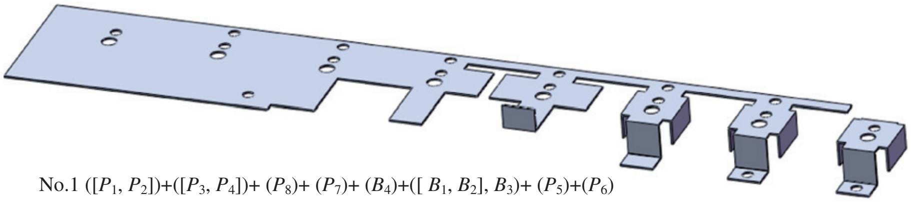
$$\begin{aligned} &\text{Minimum feeding height } FH_{MIN} = S = 2 \\ &\text{Maximum feeding height } FH_{MAX} = H_m + S = 24, \quad \text{where} = H_m = 22 \\ &F_L = 100 - 90 \times (FH - FH_{MIN})/(FH_{MAX} - FH_{MIN}) = 100 - 90 \times (9-2)/(24-2) = 71.36 \end{aligned}$$

Summarising these four criteria, the evaluation score E_V is obtained using Equation (3).

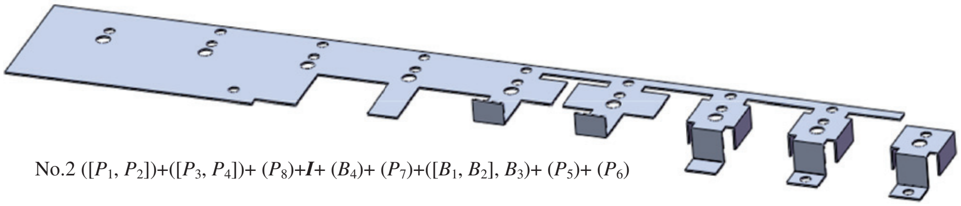
$$\begin{aligned} \text{Evaluation score } E_V &= w_1 \times F_N + w_2 \times F_B + w_3 \times F_S + w_4 \times F_L \\ &= 0.3 \times 37 + 0.2 \times 68.54 + 0.3 \times 39.69 + 0.2 \times 71.36 = 50.99 \end{aligned}$$

5. Implementation of pilot system

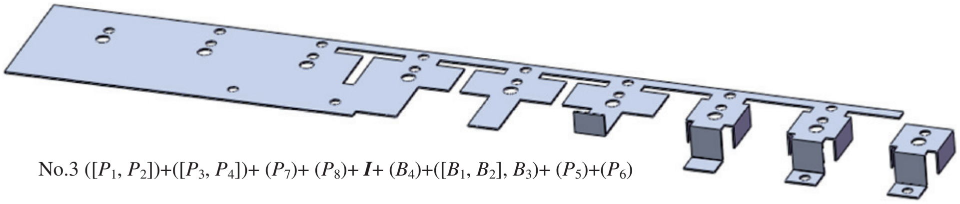
In this study, a pilot computer-aided system has been developed. The system works using Pro/ENGINEER®, utilising Pro/TOOLKIT subroutines written in Visual C++. The input of the system is the 3D CAD model of the sheet metal part and its superimposed punches, which are shown in (Figures 3 and 4b). These input data are used for processing in the three primary modules of the system: preparation of the strip, punch layouts, and layout evaluation. The incorporation of the proposed rules and how the user must make responses to the system are all explained below.



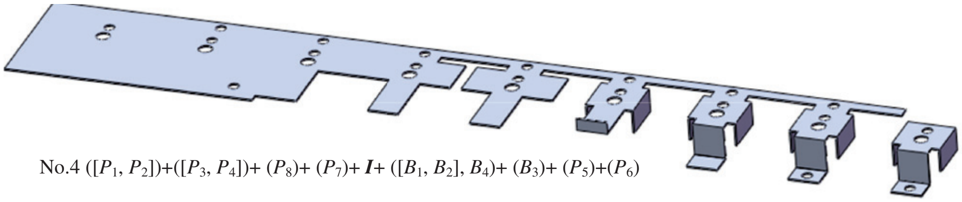
No.1 $([P_1, P_2])+([P_3, P_4])+(P_8)+(P_7)+(B_4)+([B_1, B_2], B_3)+(P_5)+(P_6)$



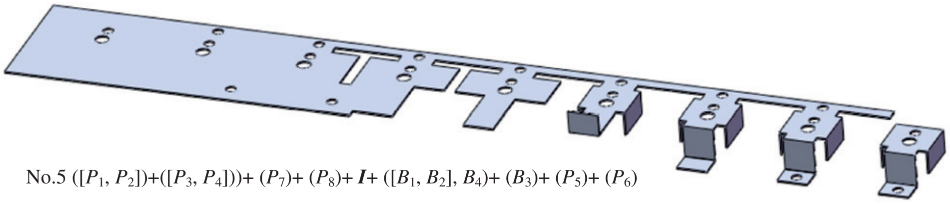
No.2 $([P_1, P_2])+([P_3, P_4])+(P_8)+\boldsymbol{I}+(B_4)+(P_7)+([B_1, B_2], B_3)+(P_5)+(P_6)$



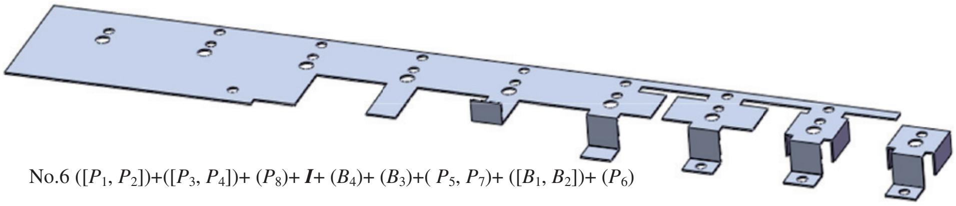
No.3 $([P_1, P_2])+([P_3, P_4])+(P_7)+(P_8)+\boldsymbol{I}+(B_4)+([B_1, B_2], B_3)+(P_5)+(P_6)$



No.4 $([P_1, P_2])+([P_3, P_4])+(P_8)+(P_7)+\boldsymbol{I}+([B_1, B_2], B_4)+(B_3)+(P_5)+(P_6)$



No.5 $([P_1, P_2])+([P_3, P_4]))+(P_7)+(P_8)+\boldsymbol{I}+([B_1, B_2], B_4)+(B_3)+(P_5)+(P_6)$



No.6 $([P_1, P_2])+([P_3, P_4])+(P_8)+\boldsymbol{I}+(B_4)+(B_3)+(P_5, P_7)+([B_1, B_2])+(P_6)$

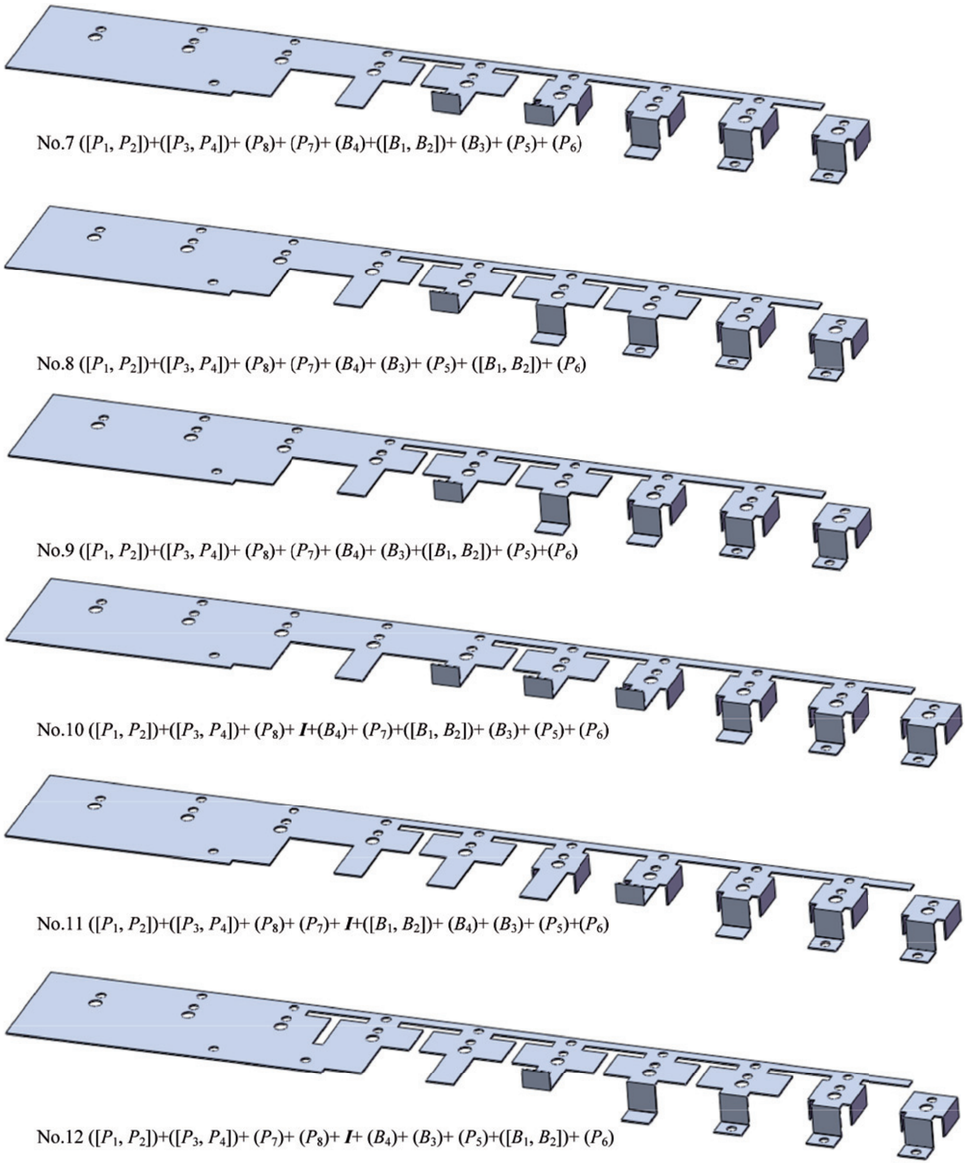
Figure 24. Seventeen models of punch layouts.

Module 1: Preparation of the strip

In this module, the user needs to define the sheet metal part, the punches, and the dimensions of the strip used in the operation. The system will search through the part's CAD model and then generate the tree structure of the bending features.

Module 2: Generation of punch layouts

This module has the following six functions: punch clustering, expansion of number of punches, punch layout, merging of bending and shearing planning, collision check, and installation of idle stages.



No.7 $([P_1, P_2])+([P_3, P_4])+(P_8)+(P_7)+(B_4)+([B_1, B_2])+(B_3)+(P_5)+(P_6)$

No.8 $([P_1, P_2])+([P_3, P_4])+(P_8)+(P_7)+(B_4)+(B_3)+(P_5)+([B_1, B_2])+(P_6)$

No.9 $([P_1, P_2])+([P_3, P_4])+(P_8)+(P_7)+(B_4)+(B_3)+([B_1, B_2])+(P_5)+(P_6)$

No.10 $([P_1, P_2])+([P_3, P_4])+(P_8)+\boldsymbol{I}+(B_4)+(P_7)+([B_1, B_2])+(B_3)+(P_5)+(P_6)$

No.11 $([P_1, P_2])+([P_3, P_4])+(P_8)+(P_7)+\boldsymbol{I}+([B_1, B_2])+(B_4)+(B_3)+(P_5)+(P_6)$

No.12 $([P_1, P_2])+([P_3, P_4])+(P_7)+(P_8)+\boldsymbol{I}+(B_4)+(B_3)+(P_5)+([B_1, B_2])+(P_6)$

Figure 24. Continued.

As discussed in Section 3.3, there are three types of rules for clustering the bending punches, as listed below:

(1) Rules for simultaneous use

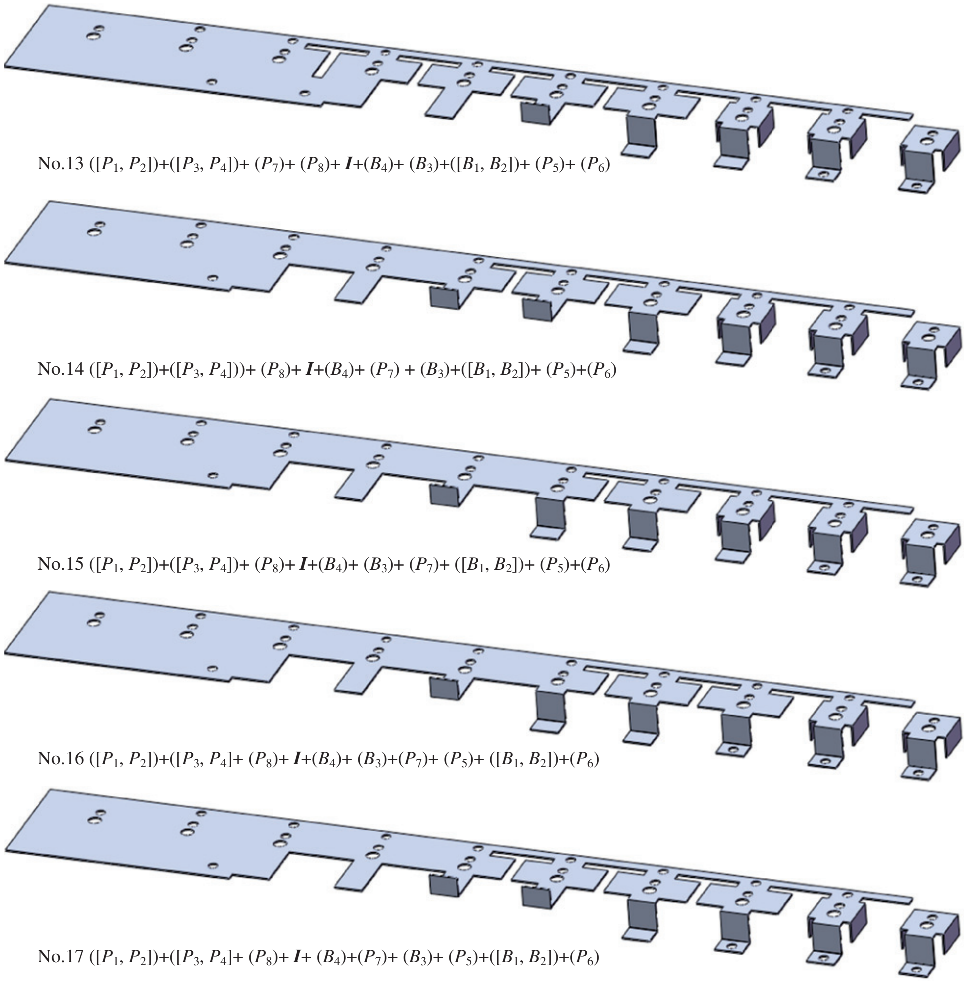
There are some types of bending operations that require punches to be used simultaneously. The system user selects all the punches required to be used together and clusters them as a set. For example, in (Figure 23), the system user chooses bending punches $[B_1, B_2]$ for simultaneous usage.

(2) Rules for sequential use

The sequential relationship of bending features is primarily based on their feature structure. The system can automatically trace through the feature tree and identify their sequence for every bend. For example, the bending punch of B_4 must be ahead of B_3.

(3) Rules for exclusive use

Exclusiveness for bending punches is the result of their sequential relationship. Any two bending punches required to be placed in sequence are not allowed to be arranged in the same stage; they are exclusive. This



No.13 ([P_1, P_2])+([P_3, P_4])+ (P_7)+ (P_8)+ $\boldsymbol{I}$+(B_4)+ (B_3)+([B_1, B_2])+ (P_5)+ (P_6)

No.14 ([P_1, P_2])+([P_3, P_4]))+ (P_8)+ $\boldsymbol{I}$+(B_4)+ (P_7) + (B_3)+([B_1, B_2])+ (P_5)+(P_6)

No.15 ([P_1, P_2])+([P_3, P_4])+ (P_8)+ $\boldsymbol{I}$+(B_4)+ (B_3)+ (P_7)+ ([B_1, B_2])+ (P_5)+(P_6)

No.16 ([P_1, P_2])+([P_3, P_4]+ (P_8)+ $\boldsymbol{I}$+(B_4)+ (B_3)+(P_7)+ (P_5)+ ([B_1, B_2])+(P_6)

No.17 ([P_1, P_2])+([P_3, P_4]+ (P_8)+ $\boldsymbol{I}$+ (B_4)+(P_7)+ (B_3)+ (P_5)+([B_1, B_2])+(P_6)

Figure 24. Continued.

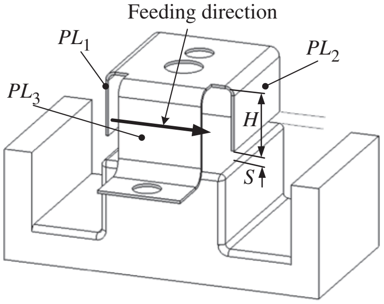


Figure 25. Feed height of the part.

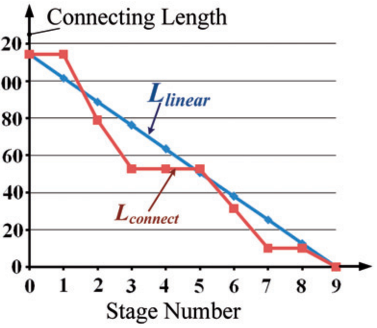


Figure 26. L_{linear} and $L_{connect}$ for case 6.

relationship can be checked against the feature tree of the part by the system. As a result, the bending punches B_4 and B_3 are classified as exclusive.

When all three groups of bending punches are selected and defined, the compatible sets of punch are also defined according to Equation (1) in Section 3.3.

The expansion of number of bending punches and bending punch layouts are quite calculation-based with very clear rules to follow. The rules governing their processes and the results of the expansion of the number of punches

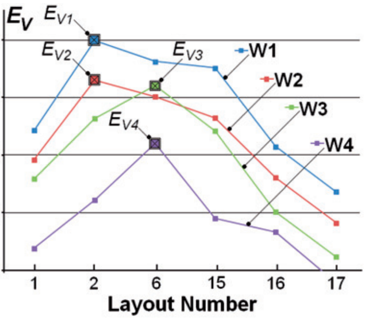


Figure 27. Weights and values of E_V.

Table 4. Results of the layout evaluation.

No.	Layouts	F_N	F_B	F_S	F_L	E_V
1	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + (B_4) + ([B_1, B_2], B_3) + (P_5) + (P_6)$	46	78.62	43.75	71.36	**56.92**
2	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + \boldsymbol{I} + (B_4) + (P_7) + ([B_1, B_2], B_3) + (P_5) + (P_6)$	37	94.97	57.93	71.36	**61.74**
3	$([P_1, P_2]) + ([P_3, P_4]) + (P_7) + (P_8) + \boldsymbol{I} + (B_4) + ([B_1, B_2], B_3) + (P_5) + (P_6)$	37	65.93	41.35	71.36	**50.97**
4	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + \boldsymbol{I} + ([B_1, B_2], B_4) + (B_3) + (P_5) + (P_6)$	37	65.06	39.69	71.36	**50.29**
5	$([P_1, P_2]) + ([P_3, P_4])) + (P_7) + (P_8) + \boldsymbol{I} + ([B_1, B_2], B_4) + (B_3) + (P_5) + (P_6)$	37	63.90	41.36	71.36	**50.56**
6	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + \boldsymbol{I} + (B_4) + (B_3) + (P_5, P_7) + ([B_1, B_2]) + (P_6)$	37	90.72	75.01	71.36	**66.02**
7	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + (B_4) + ([B_1, B_2]) + (B_3) + (P_5) + (P_6)$	37	64.68	39.69	71.36	**50.22**
8	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + (B_4) + (B_3) + (P_5) + ([B_1, B_2]) + (P_6)$	37	68.15	39.69	71.36	**50.99**
9	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + (B_4) + (B_3) + ([B_1, B_2]) + (P_5) + (P_6)$	37	66.41	39.69	71.36	**50.56**
10	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + \boldsymbol{I} + (B_4) + (P_7) + ([B_1, B_2]) + (B_3) + (P_5) + (P_6)$	28	80.20	49.49	71.36	**53.56**
11	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + \boldsymbol{I} + ([B_1, B_2]) + (B_4) + (B_3) + (P_5) + (P_6)$	28	54.34	37.37	71.36	**44.75**
12	$([P_1, P_2]) + ([P_3, P_4]) + (P_7) + (P_8) + \boldsymbol{I} + (B_4) + (B_3) + (P_5) + ([B_1, B_2]) + (P_6)$	28	56.36	38.63	71.36	**45.53**
13	$([P_1, P_2]) + ([P_3, P_4]) + (P_7) + (P_8) + \boldsymbol{I} + (B_4) + (B_3) + ([B_1, B_2]) + (P_5) + (P_6)$	28	56.19	38.63	71.36	**45.50**
14	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + \boldsymbol{I} + (B_4) + (P_7) + (B_3) + ([B_1, B_2]) + (P_5) + (P_6)$	28	81.73	49.48	71.36	**53.86**
15	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + \boldsymbol{I} + (B_4) + (B_3) + (P_7) + ([B_1, B_2]) + (P_5) + (P_6)$	28	93.26	60.63	71.36	**59.51**
16	$([P_1, P_2]) + ([P_3, P_4] + (P_8) + \boldsymbol{I} + (B_4) + (B_3) + (P_7) + (P_5) + ([B_1, B_2]) + (P_6)$	28	87.32	60.63	71.36	**58.33**
17	$([P_1, P_2]) + ([P_3, P_4] + (P_8) + \boldsymbol{I} + (B_4) + (P_7) + (B_3) + (P_5) + ([B_1, B_2]) + (P_6)$	28	81.91	49.48	71.36	**53.90**

are described in Section 3.3.3, and punch layouts are described in Section 3.3.4. All five feasible bending punch layouts are easily found by the system.

The only difference between sequencing the bending punches and shearing punches is the need to cluster the shearing punches into five groups, and the rest of the processes are similar. The 14 feasible shearing punch layouts are all listed in Section 3.4, and the rules for merging the two sequencing results are explained in Section 3.5. The system will generate the 17 layouts as an input for the next move. Material factors are considered in this study because they may affect the sequence of the obtained layouts. The system will go through the CAD model of the sheet metal part and check its dimensional requirements for different bends. Since the bending allowance is not of great concern for the part, the system will not change the sequence. A collision check is crucial for the bending sequence planning, and the 17 layouts are found to be free from self-collision. Since overlapping between adjacent punch footprints is easily detected using the 3D CAD models, the system can check all the combinations of different shearing and bending punches to create an idle stage matrix as shown in (Table 1). When all layouts are then checked again for the requirement of an idle stage, the 17 feasible sequencing plans for this sheet metal part are then finally decided. Their 3D layout models are also generated by Pro/ENGINEER®, as shown in (Figure 24). These 3D CAD models will be used as input for the next module.

Module 3: Layout evaluation

It is certain that some of these 17 feasible sequencing plans will perform better than others, and their superiority is verified by the evaluation module. These 17 layouts are all evaluated by the four criteria, and the results are shown

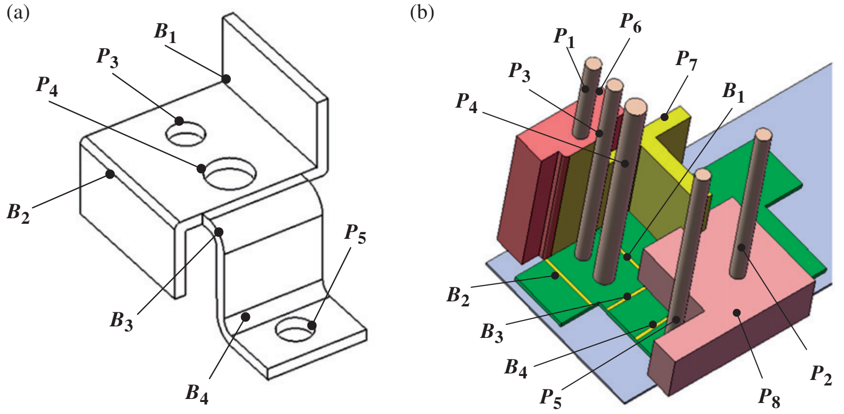


Figure 28. A part and its dedicated punches. (a) Part for case 2 (b) Dedicated punch designs.

in (Table 2). The scores of the 17 layouts are explained in the following three points: (1) although the 17 plans contain different sequences, the feeding height of each plan is all determined by the same bend plane PL_1 and PL_2 – refer to (Figure 25) – and since bend plane PL_3 is parallel to the feeding direction, a groove is inserted in the die to allow the movement of PL_3, so the lifted height is only the safety height S and H, and the feeding height factors for the 17 plans are thus identical; (2) the difference between the maximum and minimum score is greater than 20, which indicates the actual difference in operational performance among the 17 plans; (3) layout number 6 – see (Figure 24) – has the best score; the computation indicates the superior moment balancing because the distance between centre of resultant force and centre of the die is only six mm. Also, the strip stability is the best among all the plans. (Figure 26) shows a comparison between the connecting length at each stage ($L_{connect}$) and the linear pattern (L_{linear}) of the nine-stage plan.

5.1 *Change of weights for different results*

Various firms usually have different expectations for a good sequence layout. A good choice for one company may not work well for another and, in that regard, an MCDM model and the weighted sums function can help the designer choose some of the best alternatives. The basic elements for a weighted sums function are criteria and weights, and they all affect the final result. There are four criteria selected in this study, however, a designer may alter or add to them to fit his/her firm's own interests. The weights are also crucial factors that influence outcomes, and in this study, they are chosen to be 0.3, 0.2, 0.3, and 0.2. An analysis of how varying the weights may actually reshape the value of E_V is covered in this paragraph.

In (Figure 27), the four weight groups are set as:

$$\begin{array}{lllll}
\text{W1:} & w_1 = 0.2, & w_2 = 0.5, & w_3 = 0.1, & w_4 = 0.2 \\
\text{W2:} & w_1 = 0.3, & w_2 = 0.5, & w_3 = 0.1, & w_4 = 0.1 \\
\text{W3:} & w_1 = 0.2, & w_2 = 0.3, & w_3 = 0.2, & w_4 = 0.3 \\
\text{W4:} & w_1 = 0.3, & w_2 = 0.2, & w_3 = 0.3, & w_4 = 0.2 \text{ (used herein)}
\end{array}$$

Out of the 17 feasible layouts, only six of them in (Table 4) with the highest E_V values are chosen for examination, namely layout numbers 1, 2, 6, 15, 16, and 17. When the weights are changed, the E_V values for each layout are modified accordingly. The highest E_V values appear in layout 2 (E_{V1} and E_{V2}) for the W1 and W2 cases, and in layout 6 (E_{V3} and E_{V4}) for the W3 and W4 cases. This means that if a designer chooses the weights to be the same as W1 or W2, he/she probably prefers layout 2; on the other hand, for the W3 and W4 cases, layout 6 could be the most desirable candidate.

Table 5. Results of layout evaluation.

No.	Layouts	F_N	F_B	F_S	F_L	E_V
1	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + (B_4,\ B_1) + (B_2,\ B_3) + (P_5) + (P_6)$	46	75.7	43.7	71.4	**56.34**
2	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + (B_4) + B_1 + (B_2,\ B_3) + (P_5) + (P_6)$	37	63.3	39.7	71.4	**49.94**
3	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + (B_2) + (B_4,\ B_1) + (B_3) + (P_5) + (P_6)$	37	62.6	39.7	46.8	**44.89**
4	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + (B_4,\ B_1) + (B_3) + (B_2) + (P_5) + (P_6)$	37	62.4	39.7	71.4	**49.76**
5	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + (B_4,\ B_1) + (B_2) + (B_3) + (P_5) + (P_6)$	37	62.2	39.6	71.4	**49.72**
6	$([P_1, P_2]) + ([P_3, P_4]) + (P_7) + (P_8) + I + (B_4,\ B_1) + (B_2,\ B_3) + (P_5) + (P_6)$	37	62.5	41.4	71.4	**50.28**
7	$([P_1, P_2]) + ([P_3, P_4]) + (P_7) + (P_8) + (B_1) + (B_4) + (B_2,\ B_3) + (P_5) + (P_6)$	37	62.0	41.3	71.4	**50.18**
8	$([P_1, P_2]) + ([P_3, P_4]) + (P_7) + (P_8) + (B_2) + (B_4,\ B_1) + (B_3) + (P_5) + (P_6)$	37	61.5	41.4	46.8	**45.17**
9	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + I + (B_4) + (B_3) + (P_5, P_7) + (B_1) + (B_2) + (P_6)$	28	81.9	60.6	71.4	**57.25**
10	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + I + (B_4) + (B_3) + (P_5, P_7) + (B_2) + (B_1) + (P_6)$	28	81.3	60.7	48.8	**52.34**
11	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + (B_4) + (B_1) + (B_2) + (B_3) + (P_5) + (P_6)$	28	52.6	37.3	71.4	**44.40**
12	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + (B_4) + (B_2) + (B_1) + (B_3) + (P_5) + (P_6)$	28	52.4	37.4	46.8	**39.35**
13	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + (B_4) + (B_3) + (B_1) + (B_2) + (P_5) + (P_6)$	28	52.8	37.3	71.4	**44.46**
14	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + (B_4) + (B_3) + (B_2) + (B_1) + (P_5) + (P_6)$	28	52.3	37.3	46.8	**39.55**
15	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + (B_4) + (B_2) + (B_3) + (B_1) + (P_5) + (P_6)$	28	52.1	37.4	46.8	**39.50**
16	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + (B_4) + (B_1) + (B_3) + (B_2) + (P_5) + (P_6)$	28	52.7	37.4	71.4	**44.43**
17	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + (B_1) + (B_2) + (B_4) + (B_3) + (P_5) + (P_6)$	28	52.3	37.3	71.4	**44.34**
18	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + (B_2) + (B_1) + (B_4) + (B_3) + (P_5) + (P_6)$	28	52.3	37.4	46.8	**39.40**
19	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + (B_2) + (B_4) + (B_1) + (B_3) + (P_5) + (P_6)$	28	52.4	37.4	46.8	**39.46**
20	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + (P_7) + (B_1) + (B_4) + (B_2) + (B_3) + (P_5) + (P_6)$	28	52.3	37.3	71.4	**44.37**
21	$([P_1, P_2]) + ([P_3, P_4]) + (P_7) + (P_8) + I + (B_4) + (B_2,\ B_3) + (B_1) + (P_5) + (P_6)$	28	52.4	38.6	46.8	**39.82**
22	$([P_1, P_2]) + ([P_3, P_4]) + (P_7) + (P_8) + I + (B_4,\ B_1) + (B_3) + (B_2) + (P_5) + (P_6)$	28	52.1	38.6	71.4	**44.68**
23	$([P_1, P_2]) + ([P_3, P_4]) + (P_7) + (P_8) + I + (B_4,\ B_1) + (B_2) + (B_3) + (P_5) + (P_6)$	28	51.7	38.6	71.4	**44.60**
24	$([P_1, P_2]) + ([P_3, P_4]) + (P_7) + (P_8) + (B_1) + (B_2) + (B_4) + (B_3) + (P_5) + (P_6)$	28	51.2	38.7	71.4	**44.49**
25	$([P_1, P_2]) + ([P_3, P_4]) + (P_7) + (P_8) + (B_2) + (B_1) + (B_4) + (B_3) + (P_5) + (P_6)$	28	51.2	38.7	46.8	**39.59**
26	$([P_1, P_2]) + ([P_3, P_4]) + (P_7) + (P_8) + (B_2) + (B_4) + (B_1) + (B_3) + (P_5) + (P_6)$	28	51.3	38.6	46.8	**39.60**
27	$([P_1, P_2]) + ([P_3, P_4]) + (P_7) + (P_8) + (B_1) + (B_4) + (B_2) + (B_3) + (P_5) + (P_6)$	28	51.3	38.6	71.4	**44.52**
28	$([P_1, P_2]) + ([P_3, P_4]) + (P_7) + (P_8) + I + (B_4) + (B_1) + (B_2,\ B_3) + (P_5) + (P_6)$	28	52.7	38.6	71.4	**44.80**
29	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + I + (B_4) + (P_7) + (B_2) + (B_1) + (B_3) + (P_5) + (P_6)$	19	67.7	45.0	46.8	**42.11**
30	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + I + (B_4) + (P_7) + (B_1) + (B_2) + (B_3) + (P_5) + (P_6)$	19	67.7	45.1	71.4	**47.02**
31	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + I + (B_4) + (P_7) + (B_1) + (B_3) + (B_2) + (P_5) + (P_6)$	19	67.8	45.0	71.4	**47.04**
32	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + I + (B_4) + (P_7) + (B_3) + (B_1) + (B_2) + (P_5) + (P_6)$	19	67.9	45.1	71.4	**47.07**
33	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + I + (B_4) + (B_3 + (P_7) + (B_1) + (B_2) + (P_5) + (P_6)$	19	79.1	52.7	71.4	**51.60**
34	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + I + (B_4) + (P_7) + (B_3 + (B_2) + (B_1) + (P_5) + (P_6)$	19	73.5	45.0	46.8	**43.27**
35	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + I + (B_4) + (B_3) + (P_7) + (B_2) + (B_1) + (P_5) + (P_6)$	19	79.1	52.7	46.8	**46.69**
36	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + I + (B_4) + (P_7) + (B_2) + (B_3) + (B_1) + (P_5) + (P_6)$	19	70.8	45.0	46.8	**42.73**
37	$([P_1, P_2]) + ([P_3, P_4]) + (P_8) + I + (B_4) + (P_7) + (B_1) + (B_3) + (B_2) + (P_5) + (P_6)$	19	75.9	77.7	71.4	**58.49**
38	$([P_1, P_2]) + ([P_3, P_4]) + (P_7) + (P_8) + I + (B_4) + (B_1) + (B_2) + (B_3) + (P_5) + (P_6)$	19	43.9	37.0	71.4	**39.86**
39	$([P_1, P_2]) + ([P_3, P_4]) + (P_7) + (P_8) + I + (B_4) + (B_2) + (B_1) + (B_3) + (P_5) + (P_6)$	19	43.8	37.0	46.8	**34.93**
40	$([P_1, P_2]) + ([P_3, P_4]) + (P_7) + (P_8) + I + (B_4) + (B_3) + (B_1) + (B_2) + (P_5) + (P_6)$	19	44.2	37.1	71.4	**39.91**
41	$([P_1, P_2]) + ([P_3, P_4]) + (P_7) + (P_8) + I + (B_4) + (B_3) + (B_2) + (B_1) + (P_5) + (P_6)$	19	44.1	37.0	46.8	**35.00**
42	$([P_1, P_2]) + ([P_3, P_4]) + (P_7) + (P_8) + I + (B_4) + (B_2) + (B_3) + (B_1) + (P_5) + (P_6)$	19	44.0	37.0	46.8	**34.97**
43	$([P_1, P_2]) + ([P_3, P_4]) + (P_7) + (P_8) + I + (B_4) + (B_1) + (B_3) + (B_2) + (P_5) + (P_6)$	19	43.0	37.1	46.8	**34.85**

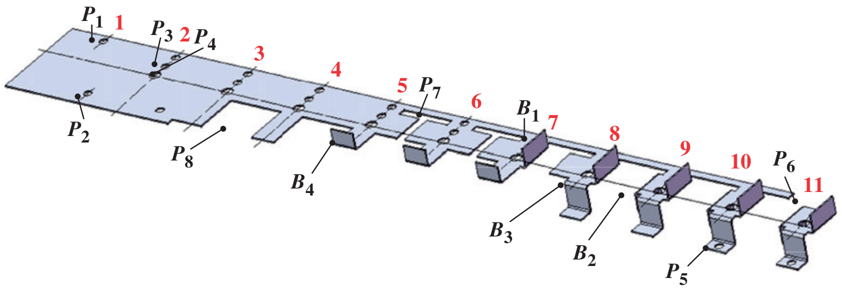


Figure 29. $([P_1, P_2]) + ([P_3, P_4]) + (P_8) + I + (B_4) + (P_7) + (B_1) + (B_3) + (B_2) + (P_5) + (P_6)$.

5.2 *Case study*

The part for case 2 is shown in (Figure 28a), and its punch designs are shown in (Figure 28b). Although the part looks very similar to the previous case, a slight change of upright bend B_1 has unexpectedly altered the final results. The punch layout module has generated a group of completely different sequencing plans, and the feeding heights required for each plan are also very different.

In the punch layout step, the rules governing the sequence are listed as follows:

Punches for prior use: $[P_1, P_2]$ (pilot holes)
Punch for posterior use: P_6 (carrier cut-off)
Punches for simultaneous use: $[P_1, P_2]$, $[P_3, P_4]$ (accuracy concern)
Punches for sequential use: $B_4 \rightarrow B_3$ (bending sequence)
$B_3 \rightarrow P_5$ (positional accuracy for hole P_5)
$P_8 \rightarrow B_1, B_2, B_3, B_4$ (to remove surrounding area for bending)
$P_7 \rightarrow B_1, B_2$ (to remove surrounding area for bending)
$[P_3, P_4] \rightarrow P_7, P_8$ (punching from inside out)

A total of 43 feasible sequencing plans are found by the punch layout step, and they are then tested and evaluated using Equation (3). The weights $w_1 = 0.3$, $w_2 = 0.2$, $w_3 = 0.3$, and $w_4 = 0.2$ and their calculation results are shown in (Table 5). The highest E_V value is found in layout 37 and its CAD model is shown in (Figure 29). In this case, the value of the feeding height factor F_L varies because of different bending sequences.

6. Conclusion

Bending sequence planning for progressive dies is a design problem involving the placement of punches into a die block. It is a tedious task and requires experienced designers to handle it. The real challenge is that there are many possible combinations, or possible solutions. The designer must use his/her expertise to screen all of the possible solutions to find the feasible ones. However, there are still two concerns here: (1) with such a large amount of possible solutions, it is impossible for the designer to check them all and it is easy to ignore some very good solutions, and (2) the number of feasible solutions is too large for designers to choose from, and it becomes difficult to quickly produce a good layout. In this study, a new approach to solve superimposed bending layout problems is presented. The method uses a strategy to cluster the punches based on rules that are widely accepted in industry and that can first reduce the search space then, with the help of the weighted Sum equation, formulate the four evaluation criteria and weights associated with them to help find the most appropriate layouts in a very rapid manner. This study is not only a solution to the bending sequencing problem but it also demonstrates how bending sequencing plans can be integrated with shearing plans, which is the most common problem in progressive die applications.

Sequence planning for forming operations is not covered in this study because there are many different types of forming operations involved in progressive die design. Each operation requires the formulation and organisation of its own specific design rules, which is beyond the scope of this paper and can be included in future work. Also, forming operations cause very dramatic plastic deformation on the sheet metal surface. To avoid damage to other punches, the designer needs to determine the sequence planning for each type of operation and merge them with the other plans later. This task can be treated in the same way that the bending and shearing operations are dealt with in this paper, so the methodology used in this paper provides a very suitable framework for future work.

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