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ORIGINAL ARTICLE

# Towards an efficient process planning of the V-bending process: an enhanced automated feature recognition system

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**Abstract** The process planning of V-bending involves the determination of a feasible sequence of bending tasks to achieve the final desired product shape. The feasibility of such a sequence is materialized by the absence of collision between the sheet metal and the tool set or any part of the press brake. Meanwhile, efficient process planning targets the minimization of the number of bending setup and handling tasks. This paper presents an enhanced automated feature recognition system for effectively determining part shape features that are suitable for feasible and efficient process planning of the V-bending process. The developed system automatically recognizes and reasons information of bend lines, and relations between them form STEP AP-203 format. It provides additional information regarding the relationships between bend lines based on a new classification that can facilitate efficient selection of tools and bend sequences. It also provides an easier approach for the estimation of some bend parameters compared to previous methods in the literature. An example is provided to demonstrate the benefit of applying the developed system in generating more efficient process plans.

**Keywords** Automated feature recognition · Air-bending process · Computer-aided process planning · STEP AP-203 format

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## 1 Introduction

The high level of competition among industrial organizations in today's global market demands quick product reach to consumers with competitive quality levels while keeping production costs as low as possible. This necessitates highly efficient process planning that minimizes non-value-added activities in production processes and optimally selects subtle production steps with the right process parameters. Computers have played a major role in achieving such targets via computer-aided process planning (CAPP) systems, which are the interface between computer-aided design (CAD) and computer-aided manufacturing (CAM). A major component of CAPP systems is the feature recognition module, which is responsible for interpreting alpha-numeric data stored in CAD drawing files into semantic features that can be easily used for selecting appropriate production sequences and process parameters. This paper presents an enhanced automated feature recognition system of 3D sheet metal part drawings provided in STEP AP-203 format for the V-bending process.

As identified in [1], an automated feature recognition system involves three ordered tasks: (1) extracting geometrical data from CAD file, (2) defining the method to represent the part from extracted data to be suitable for recognizing form features, and (3) identifying the required features. A considerable amount of literature exists on feature recognition [1, 2]. Since the focus of this paper is on the V-bending process, the literature on feature recognition of sheet metal parts is of main concern. The features for sheet metal parts can be classified into either deformation features or cut features, and deformation features are classified according to the type and nature of deformation [3].

For the V-bending process, the main types of deformation features are basically bend features which are characterized by bend line length, bend angle, and bend radius. For complex parts, several bend lines exist with different lengths, angles, and directions. The feature recognition function of such complex parts cannot be separated from process planning as it is necessary to identify the interrelationships between bend lines so that feasible and efficient process plans can be generated [4]. One way of recognizing features that can be correlated with the bending tasks is to reverse the bending tasks to develop corresponding part's flat pattern. The flat patterning module in [5] unfolds the part bend by bend to generate 2D flat pattern in DXF or IGES files. In [6], a method is proposed to decompose flat pattern from 3D sheet metal using face-edge graph. In [7], a flat pattern development system is proposed from the orthogonal projection of the part. That system consists of three modules, which are feature recognition from orthogonal projection, 3D wire frame model generator from recognized features, and flat pattern module.

In [8], a shearing feature recognition system of 2D sheet metal in DXF file is developed using adjacent component directional relationship (ACDR) to recognize raw material features which identify raw material type and its dimensions, boundary shearing features, and inside shearing features. In [9], a forming and shearing recognition features system is proposed for 3D wireframe sheet metal with zero thickness from DXF file. That system generates the flat pattern by unfolding and unrolling the part to recognize shearing features. A central surface with zero thickness is used in [10] to recognize deformation and cut features. The central surface is generated by that system from 3D sheet metal data from STEP file. A rule-based method is used to recognize deformation features according to adjacency graph of each feature, and Boolean logic is used to recognize the cut features. The feature reasoning system proposed in [11] takes the output in [10] as input to develop flat pattern by unfolding bent features. In contrast to [10], a deformation and cut feature recognition system is proposed in [3] for 3D sheet metal data from STEP file which is presented in constant thickness. The deformation features are divided into basic deformation and compound deformation features which are presented by a deformation graph.

In general, most of the literature in the field of automated feature recognition aims to recognize geometrical features that can be interpreted later into appropriate manufacturing steps in a suitable CAPP system. However, if the interest is to provide such features to a specific manufacturing process, it would be more beneficial to take into consideration some of the technicalities that are relevant to the manufacturing process within the feature recognition module. This will help in constructing more efficient process plans that are both faster and economical as pointed out in [12, 13]. For the V-bending process, CAPP systems not only need to recognize the bend lines of the part but also need to recognize all information of bend lines and the relationships between them that can help in reducing setup and handling times [14–16]. This paper proposes a new classification of collinear bend lines and a method to distinguish between separate and non-separate collinear bend lines. This classification is useful for efficiently selecting the bend sequence and generating more efficient process plans. Furthermore, a method for automated reasoning of the required dimensions to determine the length of the tool stage of each bend is proposed. This facilitates the reduction of the number of tool stages. Meanwhile, an easier and more accurate methods for determining the included and bend angles and the bend direction are developed, which facilitate data processing from STEP files compared to previous methods provided in [6, 10, 17].

## 2 Process planning considerations for V-bending

This section highlights some important aspects of the V-bending process that need to be considered for feasible and efficient process planning.

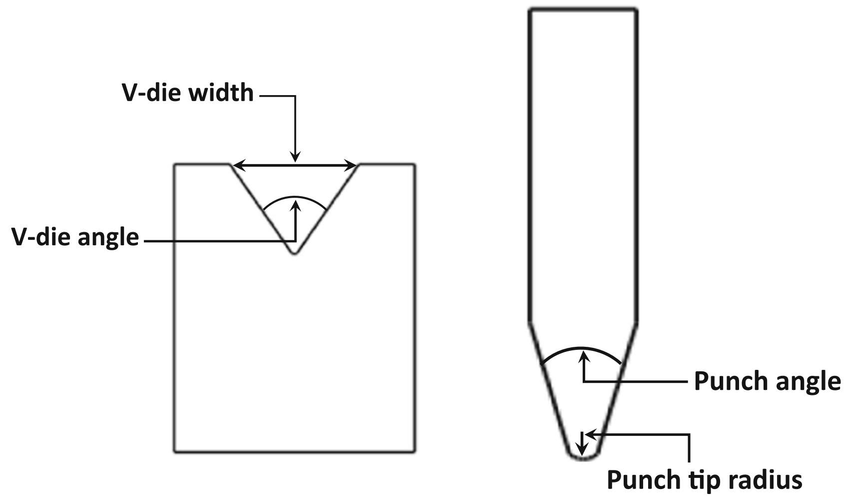
### 2.1 Process parameters and constraints

The process plan for sheet metal bending contains a sequence of bending tasks characterized by bend lines and appropriate tool list with appropriate setup length. The selected tool set to perform bending for specific bend line must firstly accommodate the technological constraints [18]. The tool set consists of a punch which is the movable component and a die which is the static component. For V-bending which is performed by either air bending or bottoming, there are technological constraints that govern the selection of the tool set. The parameters of die and punch, which are relevant to defining the technological constraints, are shown in Fig. 1. The technological constraints on die selection are (1) the angle of V-die is the lower limit of included angle of bend line and (2) the half of V-die width is the lower limit of flange length. The technological constraints on punch selection are (1) the radius of punch tip is the lower limit of bend line inner radius and (2) the angle of punch is the lower limit of included angle of bend line. Accordingly, the feature recognition system must recognize the included and bend angles and the inner radius of each bend line to select appropriate tool set.

### 2.2 Feasibility condition

A sequence of bends is infeasible if the sheet metal collides with the tool set or any part of the press brake. For instance, Fig. 2 illustrates a bending case in which collision occurs along with a possible avoidance of that collision via a

**Fig. 1** Die and punch parameters




modified tool shape. Therefore, collision detection must be checked for the proposed sequence of bends and the selected tool set. This can be done by generating the flat pattern for each bend line.

### 2.3 Tool stages and relations between bend lines

In the process planning of V-bending, more than one bend can be performed using the same punch and die combination, which is referred to as tool stage in [16]. Some geometrical constraints need to be determined on the sheet metal for which a tooling stage can be applied. For instance, the length of tool stage to bend b1 shown in Fig. 3 could be from 400 to 600 mm without any collision. Meanwhile, the tool stage length of bend b2 could be from 500 to 800 mm. Accordingly, the tool stage length which varies from 500 to 600 mm could be used to bend both b1 and b2, which will reduce the number of tool stages and setup time. Minimizing the number of tool stages is necessary for efficient process planning.

### 2.4 Bend direction

The direction of each bend line must be determined to generate correct process plans. The flat pattern of any part has two faces, up face and down face. As shown in Fig. 4, there are two bend lines that have the same included angle (90°) but they have different bend directions; the first bend line is performed on the upper face of pattern, and the second one is performed on the down face after reorienting the part to down face.

## 3 Proposed new classification of bend line relations

As shown in [19], the tool stage length is dependent on the bend sequence; therefore, it is necessary in the feature recognition system to identify the relations between different bend lines in order to be able to provide necessary data for more efficient process planning. In this paper, those relations are classified as parallelism, perpendicularity, and collinearity. The perpendicularity relation between two bend lines affects the lengths of the tool stages which are used to perform their bends. For instance, the length of a tool stage used to perform b1 of the sheet metal part shown in Fig. 5a could be equal to or greater than the length of b1 if b1 is performed before b2 and b3 as shown in Fig. 5b. However, the length of this tool stage is restricted to be equal to the length of b1 if b1 is performed after b2 and b3 as shown in Fig. 5c.

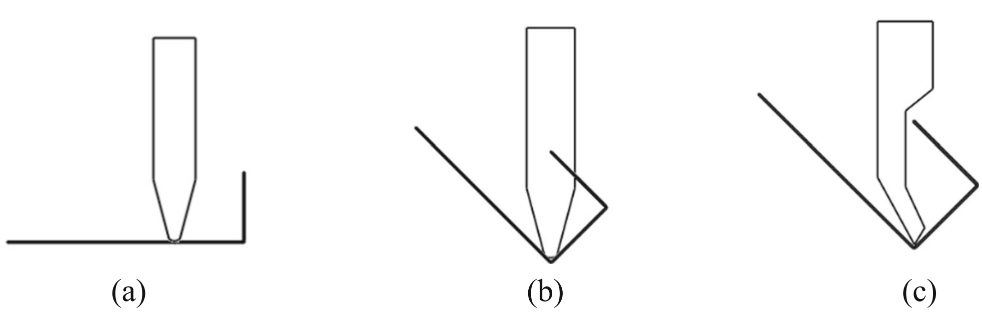
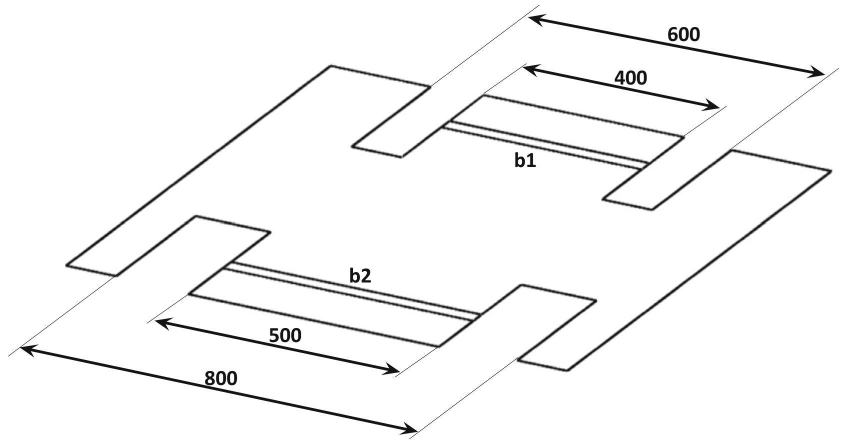



**Fig. 2** Demonstration of collision in V-bending. **a** Start of bending. **b** Collision during the process. **c** A gooseneck punch can be used to avoid collision

**Fig. 3** Length constrains of tool stage length



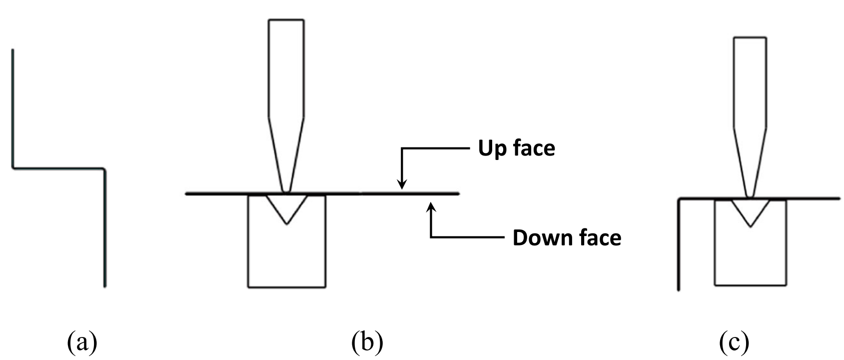

The collinear bend lines are those having same bend angle, bend direction, bend radius and bend line axis; i.e., their centers are aligned to the same axis. Such bends can be performed simultaneously, which will reduce the number of bending tasks. For instance, the collinear bend lines shown in Fig. 6a are performed simultaneously as shown in Fig. 6b. Accordingly, this paper proposes a new classification of collinear bend lines, in which the collinear bend lines are divided into non-separate collinear bend lines adjacent to same face as shown in Fig. 6a, separate collinear bend lines adjacent to same face as shown in Fig. 6c, non-separate collinear bend lines adjacent to different faces as shown in Fig. 7a, separate collinear bend lines adjacent to different faces as shown in Fig. 7b, non-separate combined collinear bend line as shown in Fig. 8a, and separate combined collinear bend lines as shown in Fig. 8b.

The proposed new classification of collinear bend lines aims to provide guidance for building more efficient bending sequence. Any two collinear bend lines are classified into separate and non-separate. The latter can be performed by the same tool, while the former cannot as different stages are required. The separate and non-separate collinear bend lines are classified into collinear bend lines adjacent to same face and collinear bend lines adjacent to different faces. The former can be performed simultaneously at any position of bending sequence, while the latter cannot as they must be performed before any perpendicular bend lines between them. For instance, b1 and b2 in the sheet metal part shown in Fig. 9a are collinear bend lines adjacent to different faces. Therefore, b1 and b2 can be bent simultaneously before any perpendicular bend lines between them such as b3 and b4 as shown in Fig. 9b. If any perpendicular bends between b1 and b2 are performed before them, they cannot be bent simultaneously as shown in Fig. 9c.

## 4 Proposed feature recognition system

As indicated in the previous sections, the generation of process plans for V-bending requires the following data: included and bend angles, inner radius, bend direction, length, left and right gaps, and left and right distances of each bend line as described in [16], in addition to the flat pattern of the part. The proposed feature recognition system aims to provide this data using a systematic method that enhances existing methods for the sake of more efficient process planning, which can be

**Fig. 4** Bend directions. **a** Final part shape. **b** Tool set for first bend. **c** Tool set for second bend



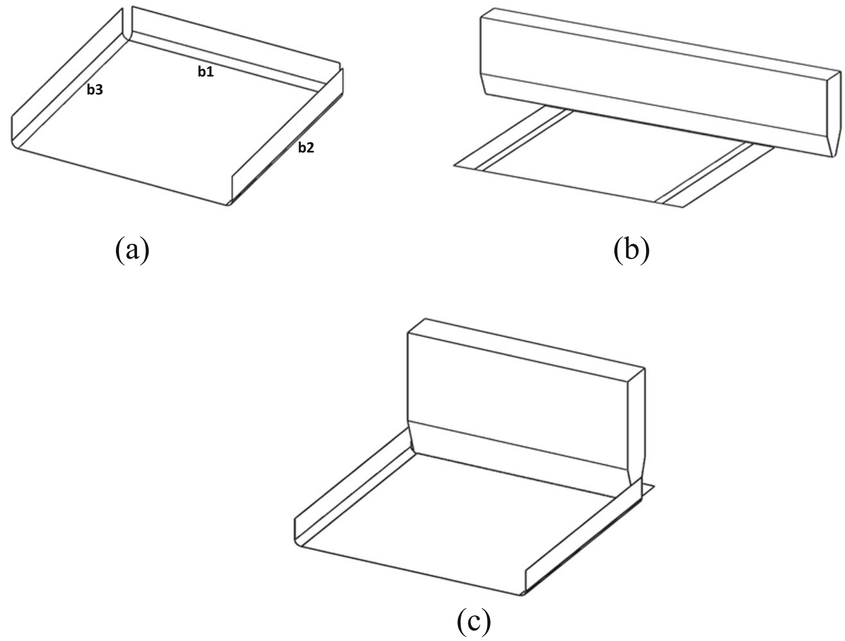



**Fig. 5** **a** Sheet metal part. **b** Performing b1 before b2 and b3. **c** Performing b1 after b2 and b3

achieved by providing more information describing the relations between bend lines. The scheme of the proposed feature recognition system is shown in Fig. 10. The input is a STEP AP203 file, which contains geometrical data of the 3D sheet metal part. The system extracts the geometrical data from STEP file, and then, the central surface of 3D sheet metal with zero thickness is generated and used to generate a face adjacency graph. The proposed system recognizes the bend and wall features and unfolds the bend lines to obtain flat pattern. Setup parameters are identified and used to determine the relations between bend lines.

### 4.1 Central surface generation

The aim of generating central surfaces is to convert solid 3D part drawing into sheet metal with zero thickness as shown in

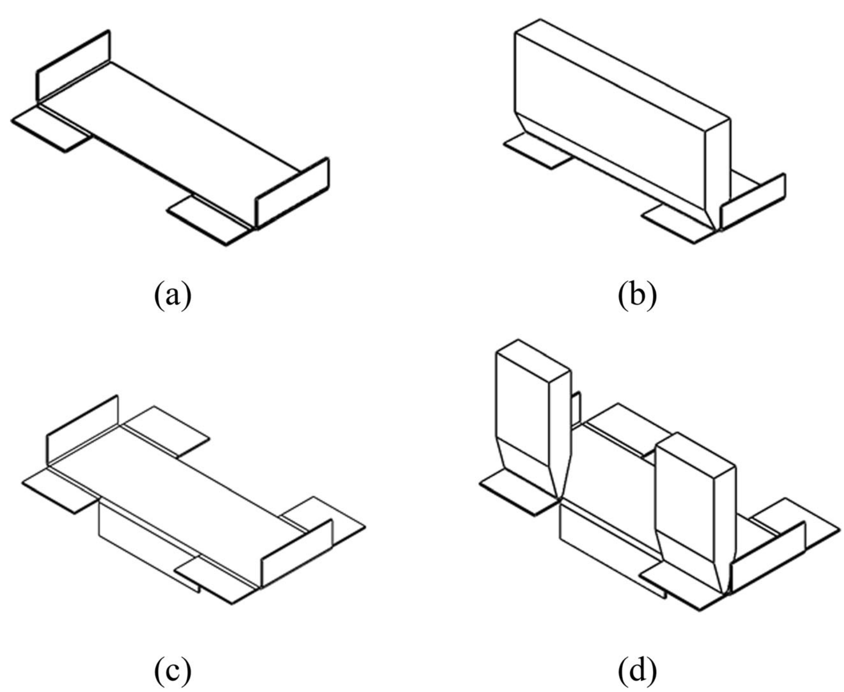
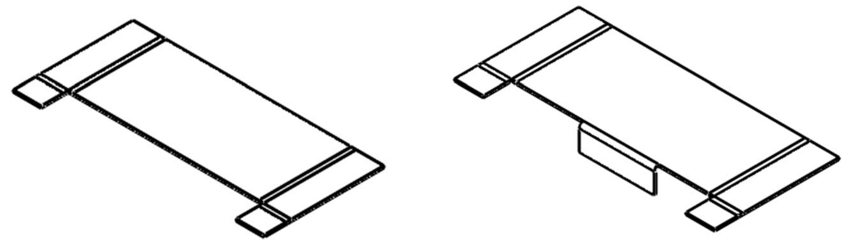



**Fig. 6** **a** Non-separate collinear bends adjacent to same face. **b** Performing bending operation of non-separate collinear bend lines by single tool. **c** Separate collinear bends adjacent to same face. **d** Performing bending operation of separate collinear bend lines by more than one tool



(a) (b)

**Fig. 7** Collinear bends adjacent to different faces. **a** Non-separate. **b** Separate

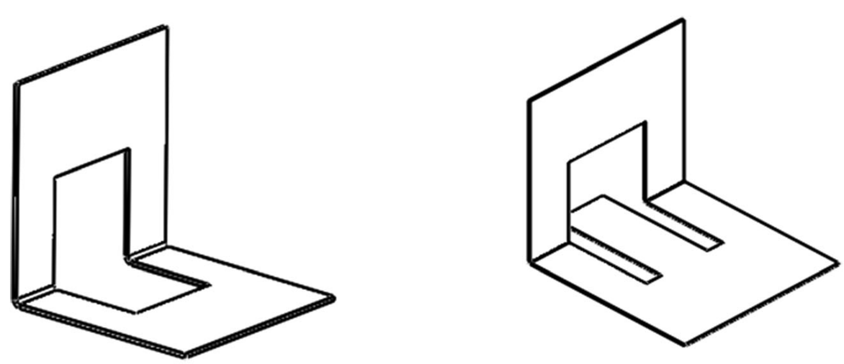
Fig. 11. The sheet metal is represented as surface model [3] or foil type [9]. This simplifies feature recognition and reduces computational loads which come from 3D sheet with more face including the thickness-defining faces [10]. The thickness is the length of the edge lying between parallel pairs of plane faces from the same type of surface and perpendicular to each faces. Thickness-defining faces are the faces which have length of edge equal to sheet thickness; these faces are identified and removed as described in [10].

The proposed system follows the central surface-generating method in [10]. In that method, central surfaces are generated by (1) removing the thickness-defining faces, (2) pairing the faces, and (3) averaging every pair to generate central surface. To pair one face with another, they must have the same type (plane surface or cylindrical surface), they must have the same number of edges, and the perpendicular distance between them is equal to the sheet thickness. In case of plane surfaces, the perpendicular distance is checked by any vertex in one face and the plane equation of the other one. In case of cylindrical surfaces, the perpendicular distance is the difference between the radii of these faces. In case of plane surfaces, the angle between the two normal vectors of these faces is equal to 0°, while in case of cylindrical surfaces, the two surfaces have the same axis.

According to previously published rules of surface pairing, surface f1 of sheet metal part which is shown in Fig. 12 could be paired with f3 because they have the same type, the same number of edges, they are parallel, and the perpendicular distance between them is equal to the sheet thickness. However, this pairing is clearly erroneous. Therefore, to pair two faces in the same level, a new rule must be added. In the proposed system, this rule stipulates that one distance of the distances between any vertex of one of these faces and every vertex in the other face must be equal to the sheet metal thickness. After adding this rule, face f2 in Fig. 12 will be paired with f1 and f3 will be paired with f4. After pairing every two faces, the coordinates of every two adjacent vertices in both faces are averaged to generate the central surface.

### 4.2 Feature recognition

Since this paper is concerned only with the V-bending process, any cylindrical surface in the central surface is identified as bend feature and any planer surface is identified as a wall. Therefore, the length of the bend line is defined as the length of any line edge of a cylindrical surface. Accordingly, by defining the coordinates of the start and end points of such a line edge, the Cartesian distance can be calculated, which defines the length of the corresponding bend line.



(a) (b)

**Fig. 8** Combined collinear bends. **a** Non-separate. **b** Separate

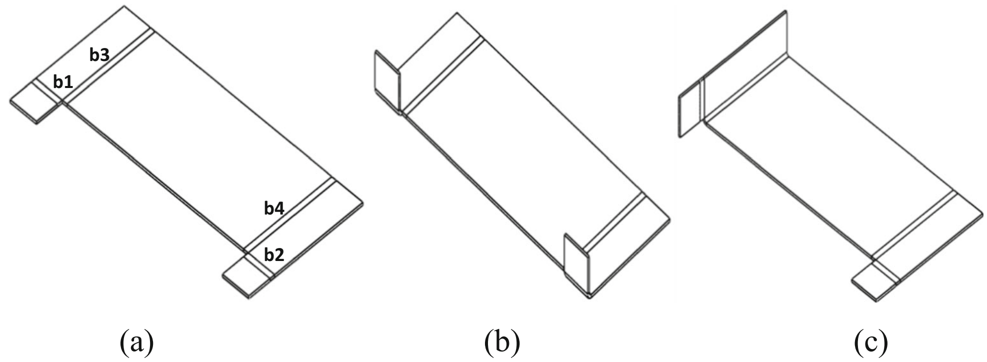



**Fig. 9** **a** Sheet metal part. **b** Bend b1 and b2 before b3 and b4. **c** Bend b3 before b1 and b2

Meanwhile, the bend radius is the inner radius which equals the radius of the cylindrical surface of the central surface defining the bend minus half of sheet metal thickness.

This paper provides an easier approach to determine the included and bend angles and the bend direction of each bend without the need to perform extra processing on the extracted data from the STEP file. In traditional methods, extra processing is required to determine the direction of each edge loop of any face in either CW or CCW direction and, accordingly, change the direction of each normal vector. For instance, the direction of each edge and normal vector of each planer surface, which are extracted from the STEP file of the sheet metal part shown in Fig. 13a, are presented in Fig. 14a. The raw data in the STEP file does not have definite direction of the edge loops (either CW or CCW), and the normal vector is independent on the edge loop direction.

Regarding the included and bend angles, there are two methods proposed in the literature to recognize them. The first one is proposed in [6], in which the angle between two adjacent faces (included angle) is calculated from the complementary angle to the angle between the normal vectors of the adjacent faces. Accordingly, the bend angle is determined as the angle between normal vectors of adjacent faces. If the normal vectors of the planer surfaces which are extracted from the STEP file are used to calculate the bend and included angles between adjacent planer surfaces using that method, there could be erroneous recognition of their values. To demonstrate that, the angle between two normal vectors is determined by Eq. (1) below.

$$\theta = \cos^{-1}\left(\frac{X_1X_2 + Y_1Y_2 + Z_1Z_2}{\sqrt{X_1^2 + Y_1^2 + Z_1^2} \times \sqrt{X_2^2 + Y_2^2 + Z_2^2}}\right) \quad (1)$$

where $X_1$, $Y_1$, and $Z_1$ are the components of the normal vector of the first face and $X_2$, $Y_2$, and $Z_2$ are the components of the normal vector of the second face.

The included angle is acute if the result of $(X_1X_2 + Y_1Y_2 + Z_1Z_2)$ is positive; otherwise, it is obtuse. If this method is used to determine bend and included angles of the central surface of the sheet metal part in Fig. 13 with the raw direction of edges and normal vectors extracted from the STEP file, the determination of the included and bend angles of each bend line will be as shown in Table 1. It can be seen that the included angles and bend angle of b2, b3, and b6 are incorrect.

The other method used for determining the bend and included angles is proposed in [10]. That method requires a transformation to make the arc edge of cylindrical surface in

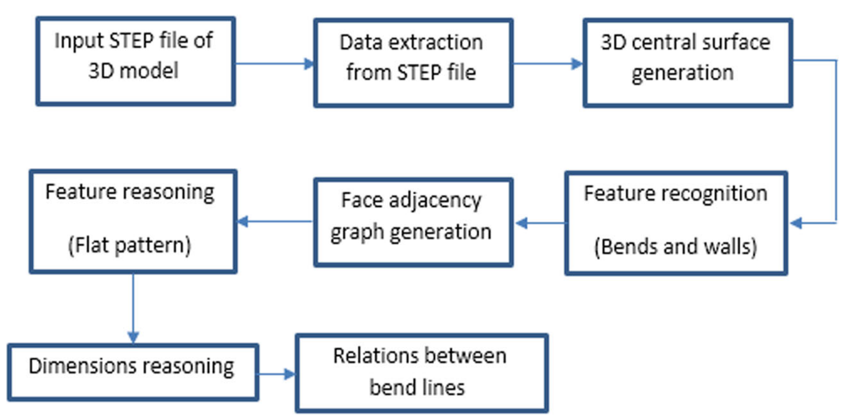



**Fig. 10** The scheme of the proposed feature recognition system

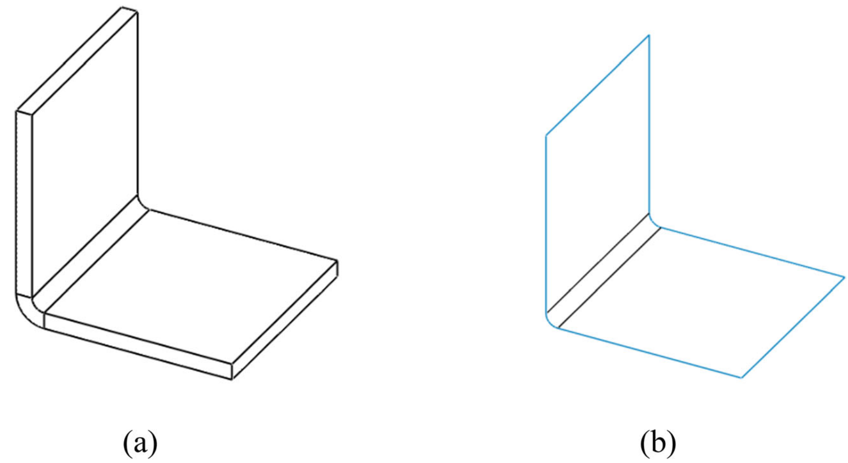



**Fig. 11** Central surface of sheet metal. **a** Original solid part. **b** Generated central surface

*X*-*Y* plane and make bend line axis aligned to *Z* axis. Then, it applies a set of rules to determine start and end angles of an arc, after which the included angle is determined.

Regarding the bend direction, there is a method presented in [6, 10, 17] to recognize it. That method depends on the direction of the vector, which is the result of the cross product of the normal vectors of adjacent planer surfaces. If the direction of that vector is in same direction of the co-edge between the faces, the bend direction is convex and vice versa. If this method is used to determine the bend direction of the central surface of the sheet metal part in Fig. 13a with the direction of edges and normal vectors as extracted from STEP file, the bend direction of each bend line will be as provided in Table 2. Evidently, the determined bend directions of b2 and b5 are incorrect.

In order to apply existing methods in the literature to determine the included and bend angles and the bend direction of each bend line, we must perform the following procedure on the data extracted from the STEP file: (1) establish the linearized face chains of adjacent planer surfaces, (2) arrange the edge loop of every planer surface in either CW or CCW direction, and (3) specify the direction of the normal vector of each planer surface according to the direction of the edge loop. A linearized face chain is the chain between planer surfaces, which are connected with bend lines with same axis direction. There are two linearized face chains in the sheet metal part of Fig. 13 {f1, f2, f5} and {f6, f3, f1, f4, f7}. To arrange the direction of edge loop first, we begin with one linearized chain and arrange the direction of edges of one face of this chain in either CW or CCW direction. Second, we arrange the direction of the edges of the next face in a linearized chain in the direction of which the co-edge is in opposite direction of previous face and so on. Third, we check the repeated face between the second chain and the first one. Fourth, we begin the second chain with the repeated face, which has arranged edge loop and arrange the edge loop of adjacent faces to this face in the direction of which the co-edge is in opposite direction with the repeated face and so on. Figure 14c shows the central surface of Fig. 13 after arranging the edge loop and specifying the normal vector of each planer surface according to edge loop direction. After performing all these processes on the data extracted from the STEP file, we can only use the previous methods to determine the included and angles and the bend direction. On the other hand, the present study proposes improved methods without the need to perform all previous extra manipulations on the extracted data from the STEP file.

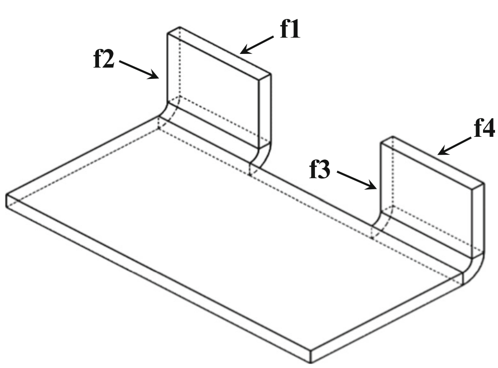



**Fig. 12** A sample part for illustrating surface pairing

This paper proposes an easier and accurate method to determine included and bend angles using the normal vectors to planer surfaces, which are extracted from the STEP file regardless the uniqueness of direction of these normal vectors and without any transformation of any edges of cylindrical surfaces. The angle between two normal vectors is determined by Eq. (2) below to get only acute angles.

$$\theta = \cos^{-1}\left(\frac{\left|X_1X_2 + Y_1Y_2 + Z_1Z_2\right|}{\sqrt{X_1^2 + Y_1^2 + Z_1^2} \times \sqrt{X_2^2 + Y_2^2 + Z_2^2}}\right) \quad (2)$$

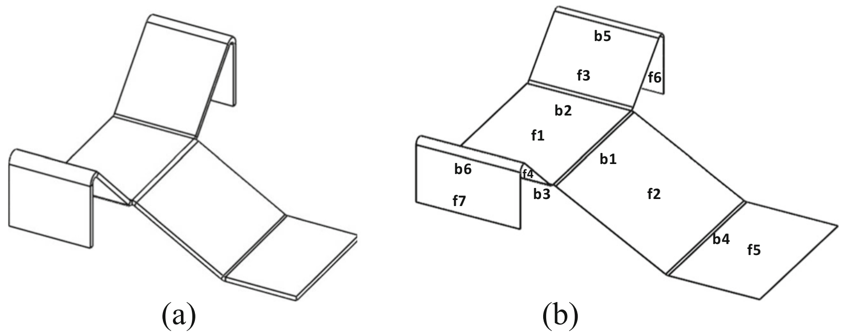



**Fig. 13** A sample sheet metal part. **a** 3D drawing. **b** Central surface and identified faces and bend lines

The distance between start and end points, denoted as $d$, of the arc of bend lines is used to determine the included and bend angles. Here, the following three cases exist:

(1) If $d$ equals the distance between the start and the end points of a quarter of a circle which has the same radius of the bend line, the included angle equals $\theta$ and the bend angle is $(180° - \theta)$.

(2) If $d$ is less than the distance between the start and the end points of a quarter of a circle which has the same radius of the bend line, the included angle equals $(180° - \theta)$, and the bend angle is $\theta$.

(3) If $d$ is greater than the distance between the start and the end points of a quarter of a circle which has the same radius of the bend line, the included angle equals $\theta$ and the bend angle is $(180° - \theta)$.

### 4.3 Face adjacency graph generation

To generate the face adjacency graph which is needed to present the part in feature reasoning, the proposed system firstly generates bend lines chain matrix and plane adjacency matrix [10] and identifies the base face of the part. The base face of the sheet metal part is used in this paper to generate the face adjacency graph. There are other benefits of identifying the base face, such as using it to distinguish different types of bend lines [20]. There are rules to identify base face of the part which are mentioned in [6, 20]. One such a rule is that the base face is the face with the largest area of the part to increase stability during sheet metal working. Another rule defines the base face as the most adjacent to other faces. According to the latter rule, the base face of the part shown in Fig. 13 is f1 as it is the most adjacent to other faces.

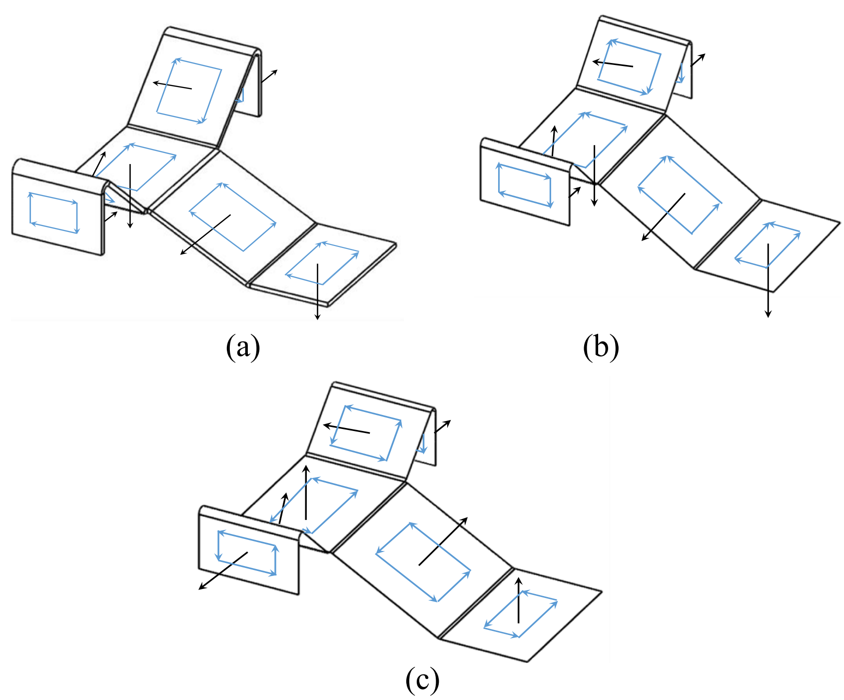



**Fig. 14** **a** Extracted normal vectors and direction of edges from STEP file of the part shown in Fig. 13. **b** Normal vectors and direction of edges of central surface of Fig. 13. **c** Normal vectors and direction of edges of central surface of Fig. 13 after performing extra processing to identify the direction of edge loop and normal vectors

**Table 1** Included and bend angles of the bends of the sheet metal part shown in Fig. 13 by using other methods

| | Bend line | | | | | |
|---|---|---|---|---|---|---|
| | b1 | b2 | b3 | b4 | b5 | b6 |
| Included angle | 150° | 45° | 45° | 150° | 45° | 135° |
| Bend angle | 30° | 135° | 135° | 30° | 135° | 45° |

The face adjacency graph is a graph that represents the adjacency between faces. The faces are represented as nodes and bend lines are represented as links between nodes. The root face (root node) of face adjacency graph is the base face of the part, adjacent face to base face is identified from plane adjacency matrix, and the bend line between adjacent faces is identified from bend line chain matrix. The face adjacency graph of the part shown in Fig. 13 is presented in Fig. 15.

### 4.4 Feature reasoning

The flat pattern of the 3D central surface is the output of the feature-reasoning module. Feature reasoning is conducted by unfolding bend lines and converting them into plane surface while taking into consideration bend allowances. As shown in Fig. 16b, the unfolding of bend lines is performed by rotating the vertices of each face so that it will be parallel to the plane of the flat pattern. Every vertex is rotated by bend angle about the axis of bend line.

In order to obtain the flat pattern, cylindrical surfaces are converted to planer surfaces with taking into consideration bend allowances. The arc edges in any cylindrical surface are converted to line edges with length equal to bend allowance which is calculated as described in [7]. This is done by translating the portion of the part connecting with these edges into the difference between bend allowance and arc coordinates; then, the new faces are maintained to be in the same plane as shown in Fig. 16c.

An important element of feature reasoning is the identification of bend direction. This paper proposes a new technique to determine the bend direction during flat pattern generation. Bend direction can be UP or DOWN. UP direction means that

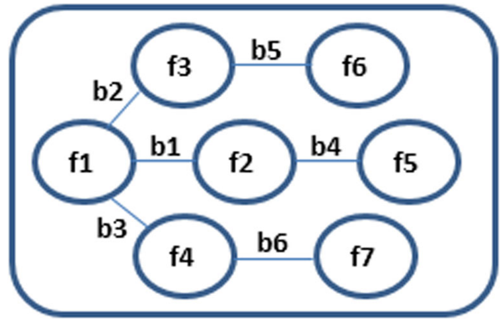



**Fig. 15** Face adjacency graph of the part shown in Fig. 13

bending is performed on the upper face of sheet metal. DOWN direction means reorienting the sheet on down face to perform bending. The proposed technique uses the face adjacency graph of the part to identify bend directions and to develop a flat pattern of the part. To illustrate that, the flat pattern generation of the sheet metal shown in Fig. 13 using the face adjacency graph shown in Fig. 15 is performed according to the following steps:

(1) Rotate the base face f1 to be parallel to *X-Z* plane as shown in Fig. 17a.
(2) Check the *Y* coordinates of non-common vertices of bend lines adjacent to f1. If the *Y* coordinates of non-common vertices are less than the *Y* coordinate of f1, the bend direction is DOWN, and if the *Y* coordinates of non-common vertices are greater than the *Y* coordinate of f1, the bend direction is UP. Accordingly, the bend direction of b1 is DOWN and of b2 and b3 is UP.
(3) Rotate the adjacent faces to f1 by bend angle of each bend line, rotate f3 by bend angle of b2, rotate f4 by bend angle of b3, and rotate f2 by bend angle of b1. f2, f3, and f4 are parallel to *X-Z* plane.
(4) Convert cylindrical surfaces of bend line (b1, b2, b3) to plane surfaces according to bend allowances as shown in Fig. 17b.
(5) Check the *Y* coordinates of non-common vertices of b4 to determine the direction to b4.
(6) According to face adjacency graph, the system identifies the bend direction of b4, unfolds f5 to be parallel to *X-Z* plane, and converts cylindrical surface of bend line b4 to plane surface according to bend allowances as shown in Fig. 17c.

**Table 2** Bend direction of sheet metal part in Fig. 13 by using existing methods in the literature

| | Bend line | | | | | |
|---|---|---|---|---|---|---|
| | b1 | b2 | b3 | b4 | b5 | b6 |
| Bend direction | Concave | Concave | Convex | Convex | Convex | Concave |

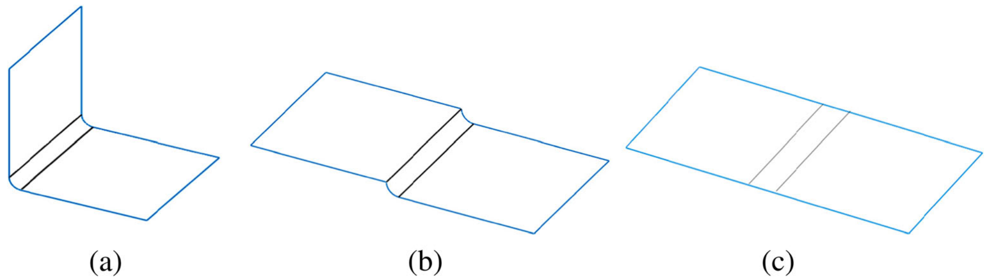



**Fig. 16** Illustration of unfolding of one face. **a** A bend. **b** Unfolded face. **c** Converting bend line to plane surface

(7) Check the *Y* coordinates of non-common vertices of b6 to determine the direction of b6.

(8) According to the face adjacency graph, the system identifies the bend direction of b6 and unfolds f7 to be parallel to *X-Z* plane and converts cylindrical surface of bend b6 to plane surface according to bend allowances as shown in Fig. 17d.

(9) Check the *Y* coordinates of non-common vertices of b5 to determine the direction of b5.

(10) According to the face adjacency graph, the system identifies the bend direction of b6 and unfolds f6 to be parallel to *X-Z* plane and converts cylindrical surface of bend b5 to plane surface according to bend allowances as shown in Fig. 17e.

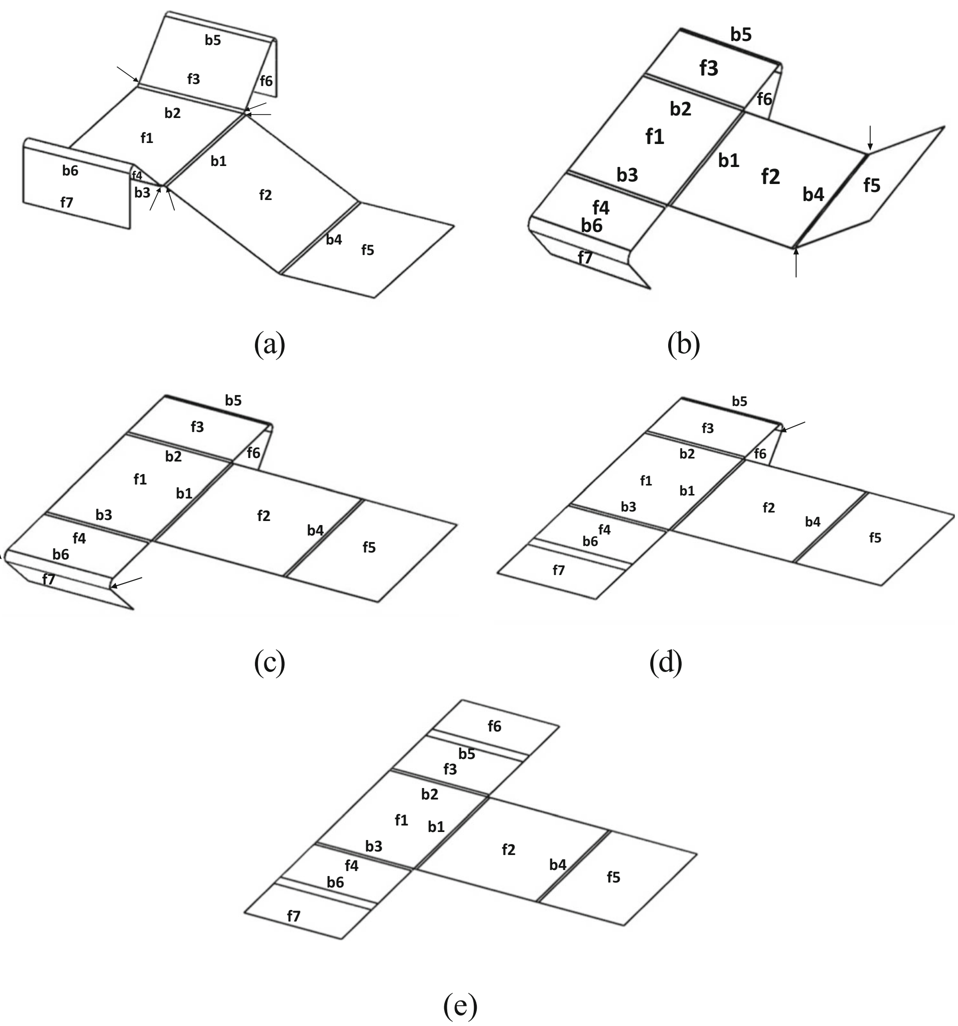



**Fig. 17** Flat pattern development process

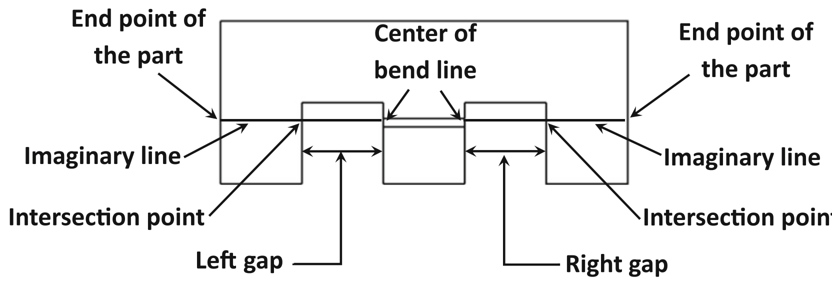



**Fig. 18** Right and left gaps of bend lines

### 4.5 Dimension reasoning

The purpose of dimension reasoning is to identify the left and right gaps and left and right distances of each bend line. This paper proposes a method using the intersection between two lines in 2D. To identify right or left gaps, the proposed system establishes imaginary line whose start point is the center of bend line (plane surface) and end point is the end point of this part as shown in Fig. 18. Checking the intersection is performed between this new line and every line edge in this part. If there are intersections between new imaginary line and other lines, the proposed system selects the nearest intersection point to the start point (center of bend line) and the gap is the distance between start point of new line and the nearest intersection point. If there is no intersection between the imaginary line and any line edge in flat pattern, the gap is infinity. The left or right distances are the distances between center points of the bend line to the end points of the part as shown in Fig. 19.

### 4.6 Relations between bend lines

The relations between bend lines as mentioned earlier in this paper are parallelism, perpendicularity, and collinearity between bend lines. The latter is divided into collinear bend lines in same face, collinear bend lines in different faces, and combined collinear bend lines. The proposed method to identify these relations between bend lines is presented herein.

To identify parallelism between two bend lines, the angle between their axes has to be 0°. To identify perpendicularity between two bend lines, the angle between their axes has to be 90°. To identify collinearity between two bend lines, the two bend lines must have similar included and bend angles, bend radius, bend direction, and bend line axis (i.e., the centers of bend lines are aligned to the same axis).

After identifying collinearity between two bend lines, the system checks if the two collinear bend lines are adjacent to a same face or adjacent to different faces by investigating the face adjacency graph of the part. In the part shown in Fig. 20a, bend lines b1 and b2 are collinear and have similar included angle, bend direction, radius, and bend line axis. Moreover, they are both adjacent to f1. Also, bend lines b3 and b5 have similar characteristics.

The bend lines are non-separately collinear, for instance b1 and b2 shown in Fig. 20, if the left gap of one bend line is equal to the right gap of the other one or the right gap of one bend line is equal to the left gap of the other one and there is no intersection between the imaginary line with the two bend lines and any line edge of the part. The bend lines are separately collinear, for instance b3 and b5 shown in Fig. 20, if there is intersection between the imaginary line with the two bend lines and any line edge of the part.

As shown in Fig. 21, the bend lines b4 and b5 are collinear and have similar included angle, bend line direction, radius, and bend line axis. They are adjacent to different faces f2 and f3.

As shown in Fig. 22, the bend lines b1 and b2 are combined collinear, and their corresponding radii, included angles, bend line directions, and bend line axes are the same. These bend lines are adjacent to the same faces, f1 and f2.

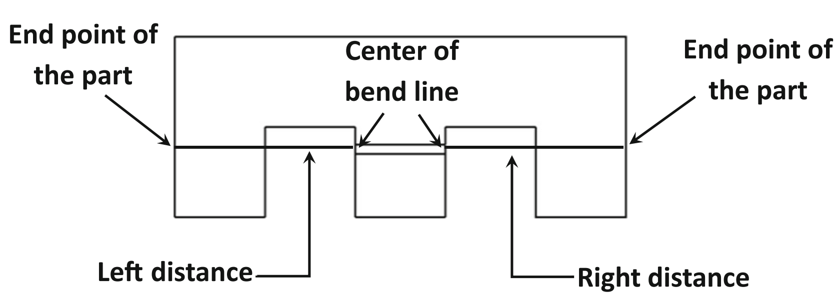



**Fig. 19** Bend line left and right distances

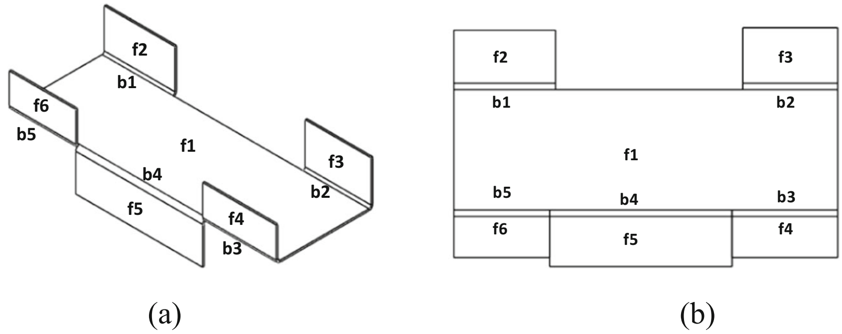



**Fig. 20** Sample bent sheet metal part. **a** Final shape. **b** Unfolded sheet

### 4.7 Implementation

The proposed feature recognition system is implemented using the C++ programming language under Windows operating system. In order to validate its output, 40 different sample 3D parts of complex shapes (some of them are available in literature and the others are from the industry) are drawn using a commercial solid modeling CAD software. Figure 23 shows elected five parts of them. For these sample parts, the bend lines are known a priori and they are compared to the output of the developed system. For all parts, the developed system is found to be capable of successfully producing results that are in 100% compliance with the known bend lines.

## 5 Demonstrative example and practical application

For a detailed demonstration of the output of the proposed feature recognition system and its practical application, a sample 3D part is shown in Fig. 24. The generated face adjacency graph is shown in Fig. 25, and a sketch of the generated flat pattern is presented in Fig. 26. The included angles, inner radius, and direction of each bend line are provided in Table 3, along with the length, left and right gaps, and left and right distances of each bend line. The relationships between bend lines are provided in Table 4.

As a comparison with other methods in the literature, using the methods provided in [6, 10, 17] to determine bend and included angles and bend direction based on raw STEP file data would lead to incorrect results. For the part shown in Fig. 24, the included angles and bend direction generated by using those methods are shown in Table 5. It can be easily recognized that the bend directions for b2, b3, b8, b9, b10, b11, and b13 are not correct. This requires some additional processing of the raw STEP file data prior to applying those methods in order to be able to obtain the correct features as described in section 4.2. On the other hand, the proposed method determines correct features directly based on the raw data in the STEP file without any additional processing.

The remaining part of this section discusses how the proposed classifications and feature recognition system will help in generating more efficient process plans. A validation of the generated process plans is done using a practical application, which is performed using 1-mm cold rolled mild steel sheet metal on DURMA PBF 2560 hydraulic press brake. The springback effect is taken into consideration when performing the practical application. The initial bend angles are calculated as described in [21]. The initial bend angles and back gauge of each bend lines are shown in Table 6. The inside radius, the flange

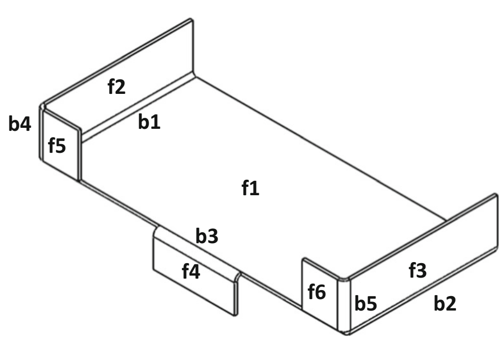



**Fig. 21** Sample bent part

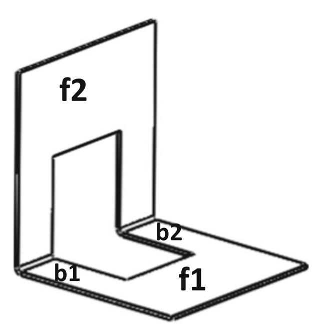



**Fig. 22** Sample bent part

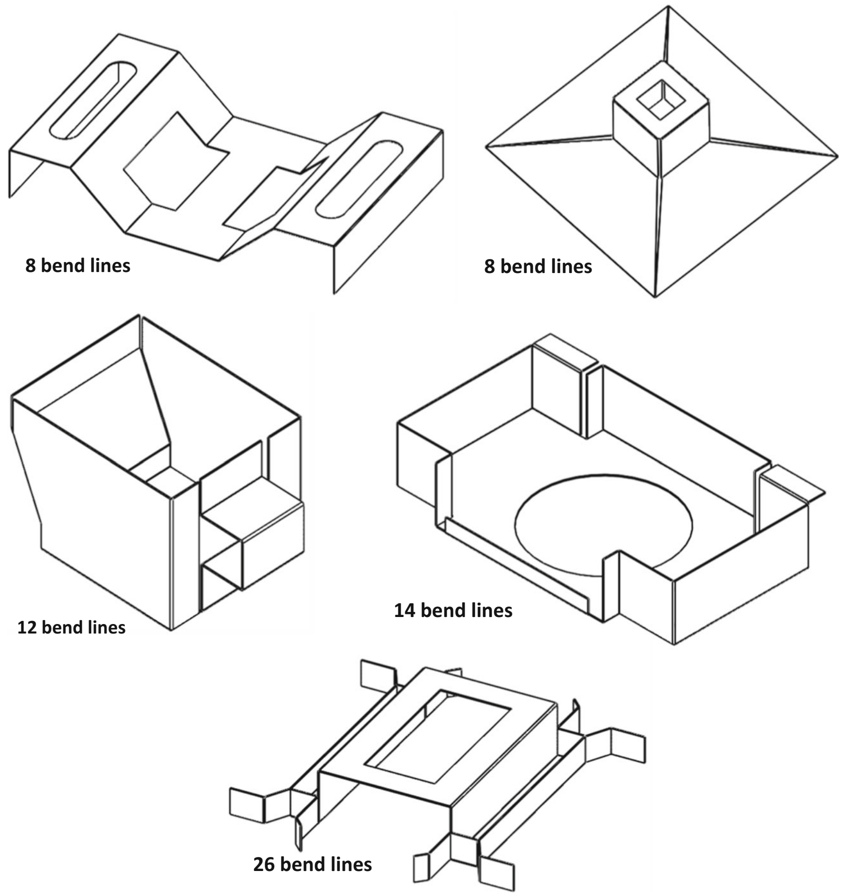



**Fig. 23** Samples of successful implementations of the proposed system

lengths, and included angles of bend lines are considered in the selection of bending tools. The selected tools are shown in Fig. 27. The width of the V-die is selected according to the empirical rules $r_i = 0.16 \times V$ and minimum flange length $= (0.5 \times V) + 2 \times t$, where $r_i$ is the inside radius of bend line, $V$ is the width of the V-die, and $t$ is the sheet metal thickness.

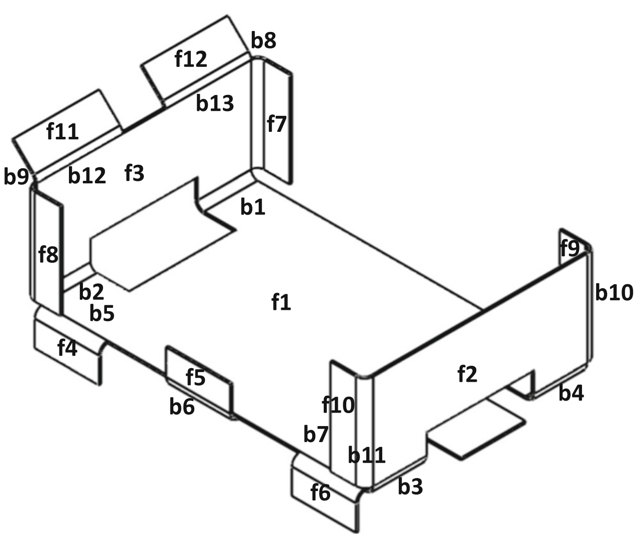



**Fig. 24** Sample sheet metal bent part and identified faces and bend lines

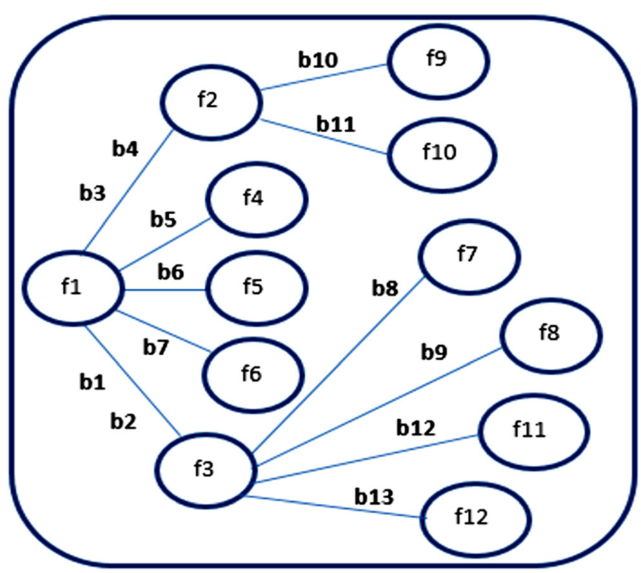



**Fig. 25** Face adjacency graph for the sample part shown in Fig. 24

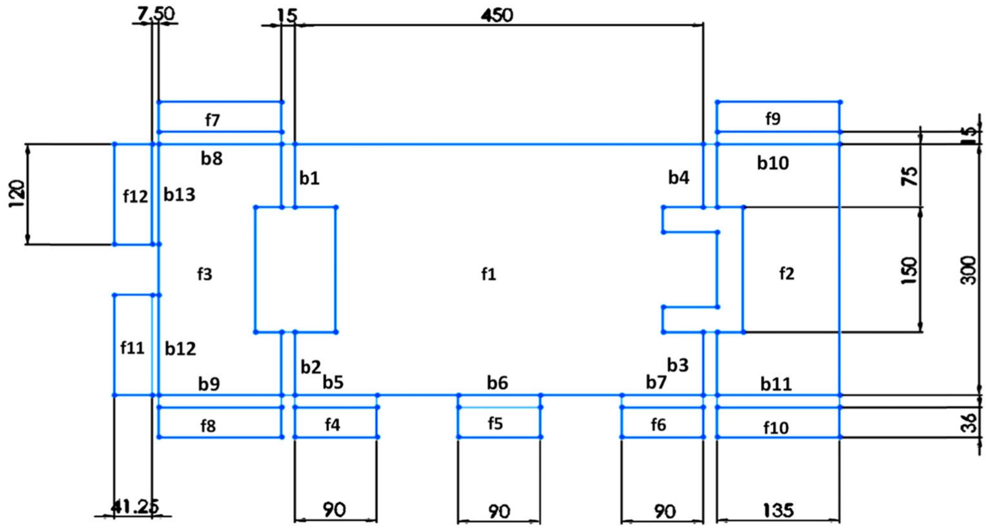



**Fig. 26** A sketch of the flat pattern generated for the sample part shown in Fig. 24 (all dimensions in mm)

The punch is selected to avoid collision during bending.

It is known that the number of all possible bend sequences for any part is evaluated as $n! \times 2^n$, where $n$ is the number of bend lines [15]. Accordingly, the number of all possible bend sequences of the part shown in Fig. 24 is huge. Some of these sequences are infeasible due to geometric and dimension tolerance constraints [4] or due to collision that would occur during bending. Some of the feasible sequences outperform others as they have less number of bending tasks and tool setups. The proposed feature recognition system and bend line classifications help in quickly finding such efficient bending sequences.

Here, a comparison between some bending sequences, based on the part shown in Fig. 24, is performed to demonstrate the benefit of using the proposed classification of collinear bend lines and the recognized relations between them. Starting with the sequence (b8, b1, b11, b10, b12, b6, b9, b7, b13, b3, b5, b2, b4), it is evident that this sequence is infeasible as presented by the practical application shown in Fig. 28, because as shown in Table 4, the groups {b1, b2} and {b3, b4} are combined collinear bend lines and the bends of each group must be conducted simultaneously. Now, if the combined collinear bend lines are taken into consideration in the selection of the bending sequence, one can obtain the sequence ({b12, b13}, {b1, b2}, {b3, b4}, b6, {b5, b7}, b8, b10, b9, b11), which

**Table 3** Identified bend lines information for the sample part in Fig. 24

| Bend | Included angle | Bend direction | Bend radius | Length | Right gap | Left gap | Right distance | Left distance |
|---|---|---|---|---|---|---|---|---|
| b1 | 90° | UP | 9 | 75 | 150 | ∞ | 276 | 51 |
| b2 | 90° | UP | 9 | 75 | ∞ | 150 | 51 | 276 |
| b3 | 90° | UP | 9 | 75 | ∞ | 30 | 51 | 276 |
| b4 | 90° | UP | 9 | 75 | 30 | ∞ | 276 | 51 |
| b5 | 90° | DOWN | 9 | 90 | 90 | 15 | 510 | 198.75 |
| b6 | 90° | UP | 9 | 90 | 90 | 90 | 330 | 378.75 |
| b7 | 90° | DOWN | 9 | 90 | 15 | 90 | 150 | 558.75 |
| b8 | 90° | UP | 9 | 135 | 480 | ∞ | 615 | 48.75 |
| b9 | 90° | UP | 9 | 135 | 15 | ∞ | 615 | 48.75 |
| b10 | 90° | UP | 9 | 135 | ∞ | 480 | 0 | 663.75 |
| b11 | 90° | UP | 9 | 135 | ∞ | 15 | 0 | 663.75 |
| b12 | 135° | DOWN | 9 | 120 | ∞ | 60 | 51 | 231 |
| b13 | 135° | DOWN | 9 | 120 | 60 | ∞ | 231 | 51 |

**Table 4** Identified relationships between bend lines for the part shown in Fig. 24

| Bends | Relation between bends | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | b1 | b2 | b3 | b4 | b5 | b6 | b7 | b8 | b9 | b10 | b11 | b12 | b13 |
| b1 | | 8 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 |
| b2 | 8 | | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 |
| b3 | 1 | 1 | | 7 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 |
| b4 | 1 | 1 | 7 | | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 |
| b5 | 2 | 2 | 2 | 2 | | | 3 | 1 | 1 | 1 | 1 | 2 | 2 |
| b6 | 2 | 2 | 2 | 2 | | | | 1 | 5 | 1 | 5 | 2 | 2 |
| b7 | 2 | 2 | 2 | 2 | 3 | | | 1 | 1 | 1 | 1 | 2 | 2 |
| b8 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | | 1 | 6 | 1 | 2 | 2 |
| b9 | 2 | 2 | 2 | 2 | 1 | 5 | 1 | 1 | | 1 | 5 | 2 | 2 |
| b10 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 6 | 1 | | 1 | 2 | 2 |
| b11 | 2 | 2 | 2 | 2 | 1 | 5 | 1 | 1 | 5 | 1 | | 2 | 2 |
| b12 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | | 4 |
| b13 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 4 | |

*1* parallelism, *2* perpendicularity, *3* separatily collinear in same face, *4* non-separately collinear in same face, *5* separately collinear in different faces, *6* non-separately collinear in different faces, *7* separately combined collinear, *8* non-separately combined collinear

has nine bends as the groups of collinear bend lines {b12, b13}, {b1, b2}, {b3, b4}, and {b5, b7} are bent simultaneously. However, according to the proposed classification of collinear bend lines, bends b8 and b10 are separate collinear adjacent to different faces. Both b8 and b10 could have been combined to be done simultaneously; yet, as the perpendicular groups of bend lines {b1, b2} and {b3, b4} are performed before them, this cannot be achieved as demonstrated by the practical application shown in Fig. 29. Accordingly, the bending sequence can be improved by performing the groups of bend lines {b8,b10} and {b9, b6, b11} earlier, which results in the bending sequence ({b12, b13}, {b8, b10}, {b9, b6, b11}, {b5, b7}, {b1, b2}, {b3, b4}), for which there are only six bends. To validate this result, Fig. 30 shows the camera shots of a practical application of this bending sequence. The above demonstrative examples show the importance of the proposed classification of collinear bend lines, which is obtained as an output of the proposed feature recognition system, in guiding the selection of the bending sequence. This eventually leads to minimizing the number of bending tasks and, therefore, generating more efficient process plans.

**Table 5** Features recognized using other methods in [6, 10, 17] for the part shown in Fig. 24

| Bend | Included angle | Bend direction |
|---|---|---|
| b1 | 90° | Convex |
| b2 | 90° | Concave[a] |
| b3 | 90° | Concave[a] |
| b4 | 90° | Convex |
| b5 | 90° | Concave |
| b6 | 90° | Convex |
| b7 | 90° | Concave |
| b8 | 90° | Concave[a] |
| b9 | 90° | Concave[a] |
| b10 | 90° | Concave[a] |
| b11 | 90° | Concave[a] |
| b12 | 135° | Concave |
| b13 | 135° | Convex[a] |

[a] Incorrect results

**Table 6** Initial bend angles and back gauges of bend lines

| Bend | Included angle | Final bend angle | Initial bend angle | Back gauge |
|---|---|---|---|---|
| b1 | 90° | 90° | 92.7° | 142.5 |
| b2 | 90° | 90° | 92.7° | 142.5 |
| b3 | 90° | 90° | 92.7° | 142.5 |
| b4 | 90° | 90° | 92.7° | 142.5 |
| b5 | 90° | 90° | 92.7° | 43.5 |
| b6 | 90° | 90° | 92.7° | 43.5 |
| b7 | 90° | 90° | 92.7° | 43.5 |
| b8 | 90° | 90° | 92.7° | 43.5 |
| b9 | 90° | 90° | 92.7° | 43.5 |
| b10 | 90° | 90° | 92.7° | 43.5 |
| b11 | 90° | 90° | 92.7° | 43.5 |
| b12 | 135° | 45° | 46.4° | 45 |
| b13 | 135° | 45° | 46.4° | 45 |

Another important aspect for efficient process planning is the minimization of the number of tool stages. Due to the new classification of collinear bend lines and the dimension reasoning followed by the proposed feature recognition system, the lengths of tool stages of the part shown in Fig. 24 based on the sequence ({b12, b13}, {b8, b10}, {b9, b6, b11}, {b5, b7}, {b1, b2}, {b3, b4}) are provided in Table 7. This table shows the setup length of tool stages of collinear bend lines in the case of using a single tool stage (for non-separate collinear bend lines) or in the case of using more than one tool stage. In addition, it shows the stage length setup constraints which must be respected to determine the tool stage length. These constraints define both the minimum length of tool stage required to conduct collinear bends and the allowable range for the distance between tool stages. The former is the summation of bend lines lengths and distances between them in case of using more than one tool stages. The latter is especially important in case of separate collinear bends. The data shown in Table 7 indicates that any tool stage

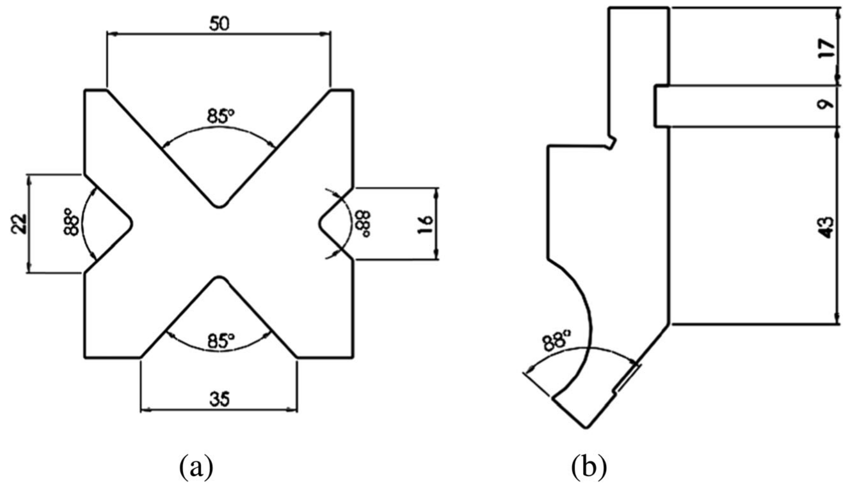



**Fig. 27** Selected tool set for practical application. **a** Die. **b** Punch

with length ≥750 or two tool stages with length ≥750 and a range of the distance between them from 0 to 60 could be used to bend both {b12, b13} and {b8, b10}. In addition, two tool stages with lengths of 150 and 150 with a distance of 150 between them can be used to perform {b5, b7}, {b1, b2}, and {b3, b4}. Using the same tool stage or tool stages for more than one bending operation will reduce the setup times and consequently increase the production output rate.

## 6 Conclusions

In this paper, an enhanced feature recognition system is developed for the sheet metal V-bending process using geometric data stored in STEP AP-203 format files. The developed system is shown to treat some erroneous interpretations in previously developed approaches and to provide easier identification of bending parameters. Furthermore, the developed system provides additional information that is amenable to more efficient process planning such as the relationships between bend lines and their relative orientations. The developed system has been tested on 40 different 3D parts elected from the literature and from industrial cases. By comparing the output of the developed system represented by the generated flat patterns and the identified bend lines and their relationships with the bend line information known a priori from the 3D solid modeling software, it is proven that the developed system is capable of producing accurate and valid interpretations.

The developed feature recognition system is a first step towards the design of an efficient CAPP system for the V-bending process. The recognized information and bend line relations, along with the generated flat pattern, are the inputs to such a CAPP system. However, in order for a CAPP system to be efficient, the sequence by which bends are to be conducted needs to be optimized for minimizing the number of handling and tool setup tasks and to make sure that the selected sequence is collision free. This should

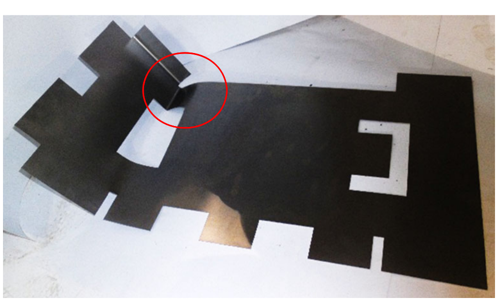


**Fig. 28** Infeasible bending sequence due to separating combined collinear bend lines

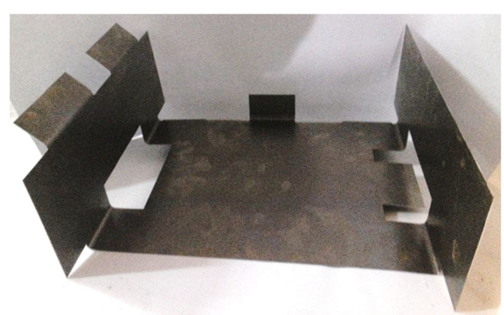


**Fig. 29** Incomplete part demonstrating the case of collinear bend lines adjacent to different faces that could not be bent simultaneously after bending the perpendicular bend lines between them

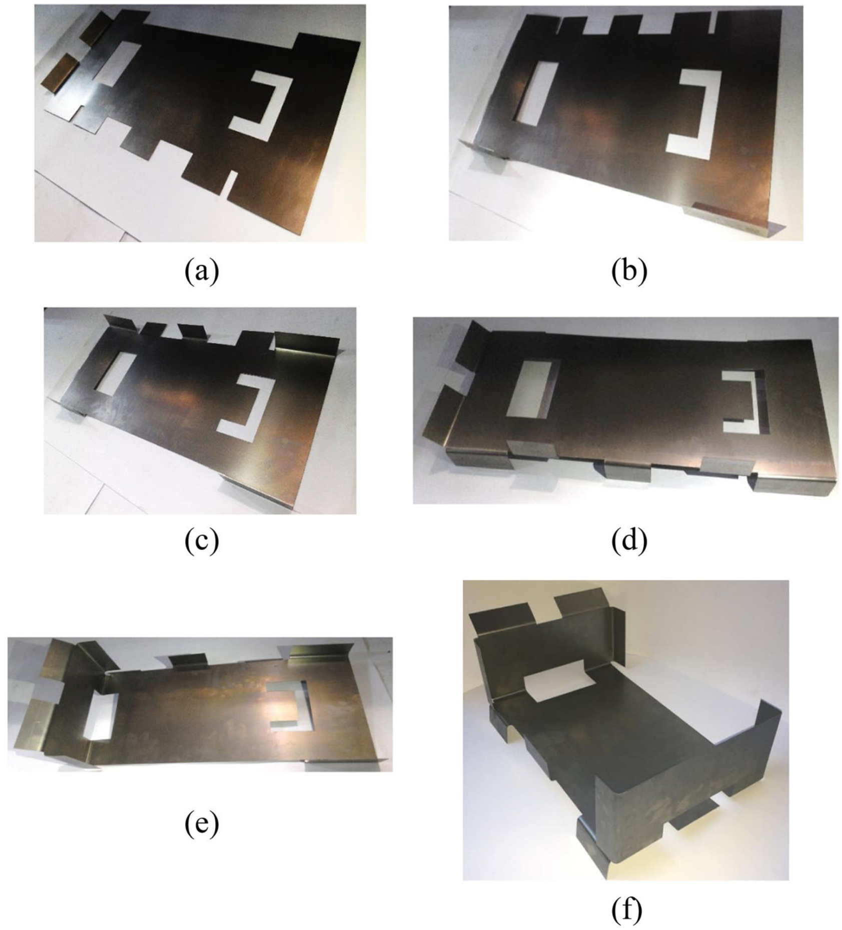



**Fig. 30** Camera shots of the optimized bending sequence of the sample part. **a** Performing bends b12 and b13. **b** Performing bends b8 and b10. **c** Performing bends b9, b6, and b11. **d** Performing bends b5 and b7. **e** Performing bends b1 and b2. **f** Performing bends b3 and b4 and final part

also include appropriate selection of bending tools. It is demonstrated through a sample part with a practical application how the proposed system can provide useful information to CAPP systems which can help in achieving that target.The conducted practical application, which show how the proposed classification of bend line relations facilitates quick determination of efficient sequences of bending tasks with the minimum number of bends. In addition to that, the consideration of the identified relations can rule out process plans that will result in bad or incomplete products. The future work will include the utilization of a suitable optimization technique to search for an optimized bend sequence.

**Table 7** Tool stages and related dimensions for a selected process plan for the part shown in Fig. 24

| Collinear bend lines | Single tool stage | | More than one tool stage | | | | | | Length setup considerations | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Minimum length | Maximum length | Length of first tool | | Length of second tool | | Length of third tool | | Minimum length of tool stage | Range for the distance between tool stages |
| | | | Minimum | Maximum | Minimum | Maximum | Minimum | Maximum | | |
| [b12, b13] | 300 | ∞ | 120 | ∞ | 120 | ∞ | N/A | N/A | ≥300 | 0 to 60 |
| [b8, b10] | 750 | ∞ | 135 | ∞ | 135 | ∞ | N/A | N/A | ≥750 | 0 to 480 |
| [b9, b6, b11] | N/A | N/A | 135 | ∞ | 90 | 270 | 135 | ∞ | ≥750 | 90 to 195 |
| [b5, b7] | N/A | N/A | 90 | 195 | 90 | 195 | N/A | N/A | ≥450 | 90 to 270 |
| [b1, b2] | 300 | ∞ | 75 | ∞ | 75 | ∞ | N/A | N/A | ≥300 | 0 to 150 |
| [b3, b4] | N/A | N/A | 75 | ∞ | 75 | ∞ | N/A | N/A | ≥300 | 90 to 150 |

*N/A* not applicable

## References


1. Babic B, Nesic N, Miljkovic Z (2008) A review of automated feature recognition with rule-based pattern recognition. Comput Ind 59:321–337. doi:10.1016/j.compind.2007.09.001
2. Subrahmanyam S, Wozny M (1995) An overview of automatic feature recognition techniques for computer-aided process planning. Comput Ind 26:1–21. doi:10.1016/0166-3615(95)80003-4
3. Gupta RK, Gurumoorthy B (2013) Classification, representation, and automatic extraction of deformation features in sheet metal parts. Comput Des 45:1469–1484. doi:10.1016/j.cad.2013.06.010
4. Rui W, Thimm GL, Yongsheng M (2010) Review: geometric and dimensional tolerance modeling for sheet metal forming and integration with CAPP. Int J Adv Manuf Technol 51:871–889. doi:10.1007/s00170-010-2663-x
5. See Toh KH, Loh HT, Nee AYC, Lee KS (1995) A feature-based flat pattern development system for sheet metal parts. J Mater Process Technol 48:89–95. doi:10.1016/0924-0136(94)01637-G
6. Chuang SH, Huang S (1996) Feature decomposition from solid models for automatic flattening. Comput Des 28:473–481. doi:10.1016/0010-4485(95)00051-8
7. Shunmugam MS, Kannan TR (2002) Automatic flat pattern development of sheet metal components from orthographic projections. Int J Mach Tools Manuf 42:1415–1425. doi:10.1016/S0890-6955(02)00071-8
8. Jagirdar R, Jain VK, Batra JL, Dhande SG (1995) Feature recognition methodology for shearing operations for sheet metal components. Comput Integr Manuf Syst 8:51–62. doi:10.1016/0951-5240(95)92813-A
9. Jagirdar R, Jain V, Batra J (2001) Characterization and identification of forming features for 3-D sheet metal components. Int J Mach Tools Manuf 41:1295–1322
10. Kannan TR, Shunmugam MS (2009) Processing of 3D sheet metal components in STEP AP-203 format. Part I: feature recognition system. Int J Prod Res 47:941–964. doi:10.1080/00207540701510055
11. Kannan TR, Shunmugam MS (2009) Processing of 3D sheet metal components in STEP AP-203 format. Part II: feature reasoning system. Int J Prod Res 47:1287–1308. doi:10.1080/00207540701510063
12. Han JH, Han I, Lee E, Yi J (2001) Manufacturing feature recognition toward integration with process planning. IEEE Trans Syst man, Cybern Part B, Cybern 31:373–380. doi:10.1109/3477.931522
13. Garcia F, Lanz M, Jarvenpaa E, Tuokko R (2011) Process planning based on feature recognition method. Proc −2011 I.E. Int Symp Assem Manuf ISAM 2011. doi:10.1109/ISAM.2011.5942296
14. Wagner S, Sathe M, Schenk O (2014) Optimization for process plans in sheet metal forming. Int J Adv Manuf Technol 71:973–982. doi:10.1007/s00170-013-5515-7
15. Zhang L, Zhang Y, Zhou Q, He F (2011) Robust sheet metal bend sequencing method based on A-star algorithm. Proc −2011 I.E. Int Conf Comput Sci Autom Eng CSAE 2:711–715. doi:10.1109/CSAE.2011.5952603
16. Gupta S, Rajagopal D (2002) Sheet metal bending: forming part families for generating shared press-brake setups. J Manuf Syst 2
17. Abouel Nasr ES, Kamrani AK (2006) A new methodology for extracting manufacturing features from CAD system. Comput Ind Eng 51:389–415. doi:10.1016/j.cie.2006.08.004
18. Duflou JR, Nguyen THM, Kruth J-P (2004) Intelligent tool preselection: a contribution to automatic process planning for sheet metal bending. In: Proc. TMCE 2004, April 13–17. Lausanne, Switzerland, pp 671–682
19. Kannan TR, Shunmugam MS (2008) Planner for sheet metal components to obtain optimal bend sequence using a genetic algorithm. Int J Comput Integr Manuf 21:790–802. doi:10.1080/09511920701678833
20. Ong S, de Vin L, Nee A, Kals H (1997) Fuzzy set theory applied to bend sequencing for sheet metal bending. J Mater Process Technol 69:29–36
21. Chandrasekaran P (2015) A review on springback effect in sheet metal forming process. Int Conf Syst Sci Control Commun Eng Technol 2015:43–49