

# A VIRTUAL SHEET METAL BENDING SETUP PLANNER

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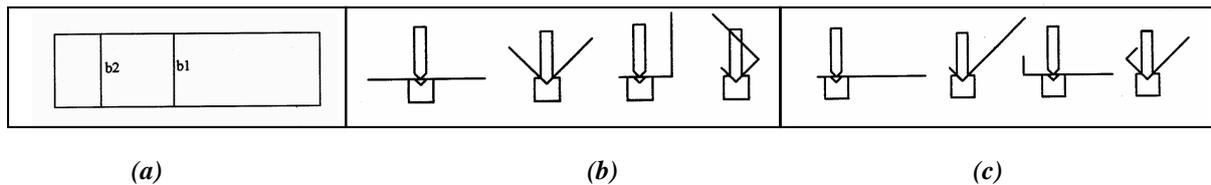
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## ABSTRACT

*Manufacturing of sheet metal component varies to a vast extent in terms of the forming methods and in turn the manufacturing planning when compared with prismatic or cylindrical components. Sheet metal bending is one of the widely used methods in sheet metal processing. During progressive bending to form a 3D component from the flat pattern, any arbitrary bending sequence cannot be adopted as there is a possibility of tool-part collision. Normally, physical try-outs are done to arrive at a feasible bending sequence. Apart from a feasible bending sequence, part positioning, part reorientation and tool stacking details for each bend are also required for developing sheet metal bending setup plan. If the bending operations are tried out in a virtual environment, it will render setup planning easier and will save a great deal of time and money. Such a virtual sheet metal bending setup planner that determines all possible feasible sequences and chooses the optimal sequence requiring minimal number of tool changes is proposed in this paper.*

## INTRODUCTION

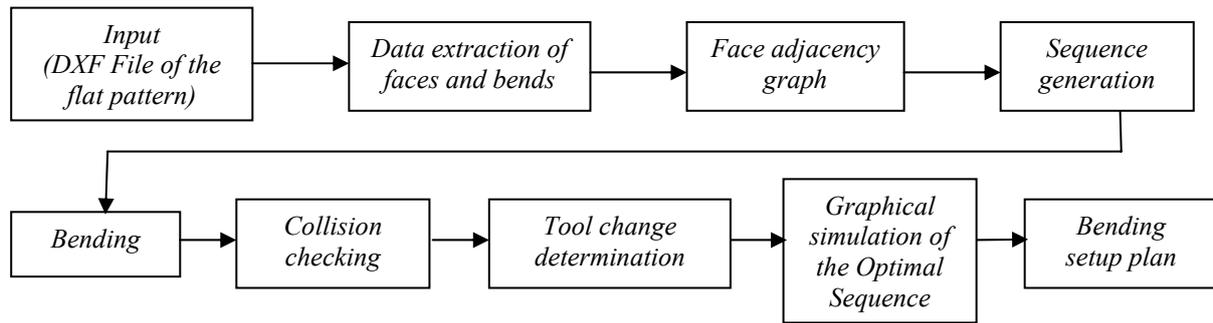
Sheet metal components find their use in a variety of products. Sheet metal bending is a common process that is being widely used for manufacturing sheet metal components. Flat sheet metal blanks are progressively bent to form 3D components using press brakes. During progressive bending, there is a possibility of tool-part collision i.e. the previously bent faces or a portion of the component might collide with the tool hindering effective bending or forming of the component. For example, the component shown in Fig 1(a) has two bends. If the bending sequence  $b1, b2$  is adopted, then there will be tool-part collision while performing the bend  $b2$  as shown in Fig 1(b). Instead, if the bend sequence  $b2, b1$  is adopted then there will not be any tool-part collision as shown in Fig 1(c). Hence, it is not always possible to adopt any arbitrary bending sequence for a given component.



**Fig 1. (a) Flat Pattern of a Component, (b) Step by Step Bending of the Component using Bending Sequence  $b1, b2$ , (c) Step by Step Bending of the Component using Bending Sequence  $b2, b1$**

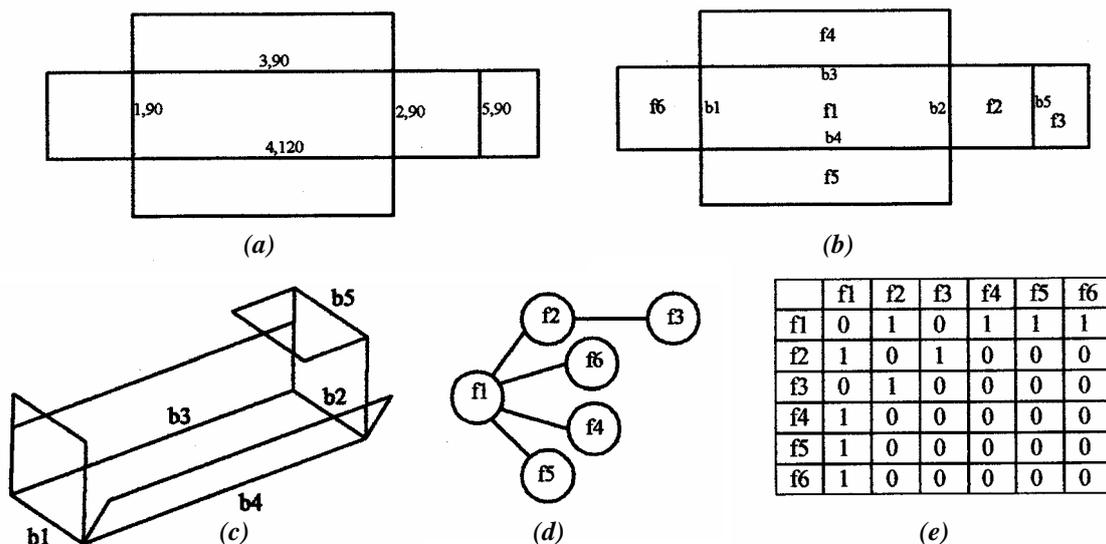
In order to arrive at a feasible bending sequence, physical try-out is adopted to check for any possible tool-part collision. The number of tryouts grows exponentially with the number of bends. If there are  $n$  bends in a given component, then the number of alternate sequences will be  $n!$ . Performing such a large number of physical try-outs is tedious. Moreover, physical try-outs are time consuming and in batch manufacturing units, it will have an adverse impact on the productivity as the effective utilization of the machine is reduced. In industries, feasible sequences are crudely determined using certain heuristics [1] and physical try-outs. Such feasible sequences may not be optimal in terms of the number of tool changes. If the bending operations are tried out in a virtual environment, it will save a great deal of time and money. All the possible sequences can be tried out and all possible feasible sequences can be determined. Among these feasible sequences, the solution with

minimal number of tool changes can be determined as an optimal sequence. Such a virtual sheet metal bending setup planner is proposed in this paper.



**Fig 2. Layout of the Virtual Sheet metal Bending Setup Planner**

The layout of the virtual sheet metal bending setup planner is as shown in Fig 2. The flat pattern of the sheet metal component along with the bend lines and corresponding bend angles are drawn in Autocad and stored in DXF format. A typical input drawing for a component is shown in Fig 3(a) and the corresponding final 3D component is shown in Fig 3(c). The filename of the flat pattern is given as the input to the system. The face and bend details as shown in Fig 3(b) are extracted from the DXF file and the component is represented as face-adjacency graph [2,3] as shown in Fig 3(d) and the corresponding face-adjacency matrix is shown in Fig 3(e). Detailed text about the DXF format is available in Autocad help. All possible bending sequences are generated and each bending sequence is virtually simulated on the sheet metal and checked for any tool-part interference till all feasible bending sequences are obtained. The number of tool changes required for all the feasible sequences are determined and the sequence which requires minimum number of tool changes is determined as the optimal sequence. Finally the bending setup plan with the optimal bending sequence, part positioning, part reorientation and tool stacking details is automatically generated.



**Fig 3. (a) Flat Pattern of a Component, (b) Face and bend details of the Component, (c) Final Shape of the Component after Bending, (d) Representation of the Component as Face Adjacency Graph, (e) The Face Adjacency Matrix of the Component.**

## SEQUENCE GENERATION

Given a sheet metal component with  $n$  bends, all possible sequences have to be generated first in order to select the feasible bending sequences from among the generated  $n!$  sequences. Consider  $S_{ij}$  is the bend number of the  $j^{\text{th}}$  bend in the  $i^{\text{th}}$  sequence, where  $j$  varies from 1 to  $n$  and  $i$  varies from 1 to  $n!$ . The algorithm for generating  $n!$  sequences is as follows:

- Step 1 : Initialize the first sequence ( $i = 1$ ) as  $S_{ij} = \{1, 2, 3, \dots, n\}$ ;
- Step 2 : Set  $i = i + 1$ ;
- Step 3 : Set  $j = 1$ ;
- Step 4 : IF  $i = (n-j)!$  THEN set  $S_{ij} = S_{(i-1)j} + 1$ ; ELSE  $S_{ij} = S_{(i-1)j}$ ;
- Step 5 : IF  $S_{ij} \neq S_{ik}$ ; where  $k = 1$  to  $(j-1)$  THEN set  $S_{ij} = S_{ij}$ ; ELSE set  $S_{ij} = S_{ij} + 1$ ;
- Step 6 : IF  $S_{ij} = n + 1$  THEN  $S_{ij} = 1$ ; ELSE  $S_{ij} = S_{ij}$ ;
- Step 7 : Set  $j = j + 1$ ; and perform the steps 4, 5 and 6 till  $j = n$ ;
- Step 8 : Repeat steps 2 to 7 till  $i = n!$ ;

A partial list of the sequences generated for  $n = 5$  is shown in Table 1.

**Table 1. Few bend sequences out of 120 sequences for  $n = 5$**

Seq. No.	Bend Sequence	Seq. No.	Bend Sequence	Seq. No.	Bend Sequence
1	1 2 3 4 5	25	2 1 3 5 4	111	5 3 1 4 2
2	1 2 3 5 4	26	2 1 3 4 5	112	5 3 1 2 4
3	1 2 4 3 5	27	2 1 4 5 3	113	5 3 2 4 1
4	1 2 4 5 3	28	2 1 4 3 5	114	5 3 2 1 4
5	1 2 5 3 4	29	2 1 5 3 4	115	5 4 3 2 1
6	1 2 5 4 3	30	2 1 5 4 3	116	5 4 3 1 2
7	1 3 2 5 4	31	2 3 1 4 5	117	5 4 1 2 3
8	1 3 2 4 5	32	2 3 1 5 4	118	5 4 1 3 2
9	1 3 4 5 2	33	2 3 4 1 5	119	5 4 2 1 3
10	1 3 4 2 5	34	2 3 4 5 1	120	5 4 2 3 1

## BENDING

After generating  $n!$  sequences, the first bending sequence is chosen and the bends are made one by one as follows:

- Step 1 : Translate the component such that the start point of the bend line of  $S_{ij}$  lies at the origin.
- Step 2 : Rotate the component about  $Z$  axis such that the bend line lies in the  $XZ$  plane.
- Step 3 : Rotate the component about  $Y$  axis such that the bend line lies in the  $X$  axis.
- Step 4 : Rotate the component about  $X$  axis such that both the immediate faces connected to the bend line lies in the  $XY$  plane.
- Step 5 : Determine both the face chains connected to the bend line.
- Step 6 : Determine the face chain lying in the negative  $Y$  direction and rotate that face chain by  $\theta_r$  in the clockwise direction about the  $X$  axis, where  $\theta_r = (180 - \theta) / 2$ ; and  $\theta$  – the bend angle as given in the input drawing.
- Step 7 : Rotate the other face chain by  $\theta_r$  in the counter-clockwise direction about the  $X$  axis.
- Step 8 : Check for any tool-part collision with the intermediate component geometry. If any collision occurs then go to step 10.
- Step 9 : Repeat the steps 1 to 8 for all  $j$  values.
- Step 10: Set  $i = i + 1$ ; and repeat the steps 1 to 9.
- Step 11: Repeat steps 1 to 10 till all sequences ( i.e.  $i = n!$  ) are analysed.

The above mentioned steps 1 to 10 are explained with the example component shown in Fig 3. The first bending sequence for the component is  $b1, b2, b3, b4, b5$ . For performing the first bending operation ( $b1$ ), the component is translated such that the start point of bend line  $b1$  lies at the origin as shown in Fig 4(a). Translation is done as follows:

$$[P'] = [P][T];$$

where  $[P]$  is the point matrix of all vertices that form the component;  $[T]$  is the translation matrix and  $[P']$  is the translated point matrix.

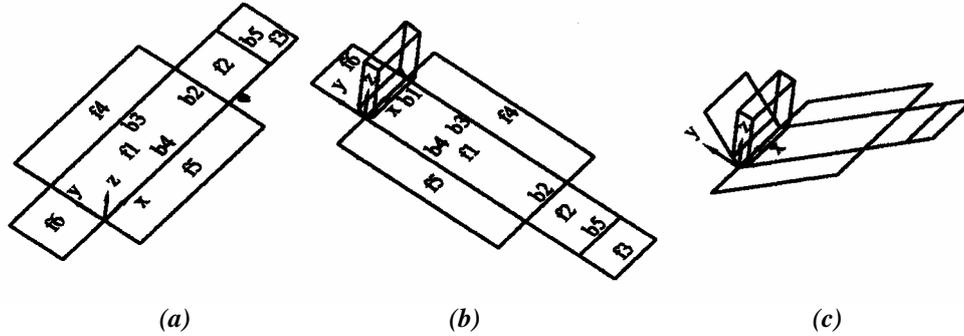


Fig 4. (a) Translation of the component to origin for the first bend, (b) Rotation of the component to make the bend line parallel to XZ plane, (c) Rotation of the Face Chains.

Table 2. All Feasible Bending Sequences for the Component shown in Fig 3.

Seq. No.	Bend Sequence	No. of tool changes	Seq. No.	Bend Sequence	No. of tool changes	Seq. No.	Bend Sequence	No. of tool changes
9	1 3 4 5 2	3	66	3 4 1 5 2	2	95	4 5 3 2 1	4
10	2 3 4 5 2	4	69	3 5 4 1 2	4	96	4 5 3 1 2	4
16	1 4 3 5 2	3	70	3 5 4 2 1	4	98	5 1 4 3 2	3
18	1 4 5 3 2	5	71	3 5 1 4 2	4	101	5 1 3 4 2	3
21	1 5 3 4 2	3	76	4 1 3 5 2	4	109	5 3 4 1 2	3
23	1 5 4 3 2	3	78	4 1 5 3 2	4	110	5 3 4 2 1	3
49	3 1 4 5 2	4	86	4 3 1 5 2	2	111	5 3 1 4 2	5
51	3 1 5 4 2	4	89	4 3 5 1 2	2	115	5 4 3 2 1	3
63	3 4 5 2 1	2	90	4 3 5 2 1	2	116	5 4 3 1 2	3
64	3 4 5 1 2	2	91	4 5 1 3 2	4	118	5 4 1 3 2	5

In the next step, the component is rotated about the  $Z$  axis (using rotation matrices) by  $90^\circ$  to make the bend line lie in the  $XZ$  plane as shown in Fig 4(b). The third step is not needed as the bend line is already lying in the  $X$  axis. Similarly the faces  $f1$  and  $f6$  that are connected to the bend line lies in the  $XY$  plane and hence step 4 is not needed. In step 5, the face chains connected to the bend line are determined from the face-adjacency graph as  $f1, f2, f3, f4, f5$  and  $f6$ . In this case, the second face chain consists only of one face ( $f6$ ). The first face chain i.e.  $f1, f2, f3, f4, f5$  lies in the negative  $Y$  direction and hence these faces are rotated by  $\theta_r$  in the clockwise direction about the  $X$  axis. In this case,  $\theta_r = 45^\circ$ . Similarly the face  $f6$  is rotated by  $\theta_r$  in the counter clockwise direction about the  $X$  axis as shown in Fig 4(c). Then it is checked for any tool-part interference which is explained in the next section. In this case, there is no collision and hence the next bend  $b2$  is performed. Instead if there is any collision, then all other bends in the particular sequence are discarded and the next sequence is chosen to perform the bends one by one. If there is no tool-part collision for any sequence even after completing all the bends, then that particular sequence is a feasible bending sequence for the given component. For the component shown in Fig 3, the first eight sequences are not

feasible sequences (Table 1) whereas the ninth sequence is a feasible sequence. Among 120 possible sequences, thirty sequences turned out to be feasible sequences, which are shown in Table 2.

## COLLISION CHECKING

While bending, after rotating one face chain by  $\theta_r$  in the clockwise direction and the other face chain by  $\theta_r$  in the counter clockwise direction, it should be checked for any tool-part collision. Collision check is done between the tool and the sheet metal component as follows. Since the bend line is aligned with the  $X$  axis before rotating the face chains, the tool cross-section profile lies in the  $YZ$  plane as shown in Fig 4(c). The component edges and the tool profile are projected on to the  $YZ$  plane. Then, it is checked whether there is any intersection between these projected component edges (other than the edges belonging to the immediate faces that are connected to the particular bend line) and the projected tool profile edges. If any component edge intersects with the tool profile edge then it is checked whether the  $X$  values of both the end points of the component edge is lesser than the lowest  $X$  value of the tool geometry or greater than the highest  $X$  value of the tool geometry. If this condition is not satisfied then it is concluded that there is tool-part collision. The tool length (along the  $X$  axis) is taken as the length of the bend line minus 2 mm [4].

## TOOL CHANGE

The number of tool changes required for all feasible sequences are determined in order to find out the optimal sequence. Tool change can be found out by the fact that for a given sequence, if there is any change in bend length between consecutive bends, then it needs a tool change. The steps to be followed for finding out the number of tool changes required for a given sequence is as follows:

Step 1 : Set  $tool\_change = 1$  and  $j = 2$ ;

Step 2 : If  $bend\_length_{(j-1)} \neq bend\_length_j$ , then set  $tool\_change = tool\_change + 1$ ;

Step 3 : Set  $j = j + 1$ ; and repeat step 2 till  $j = n$ ;

The number of tool changes required for all feasible sequences for the part shown in Fig 3 is shown in Table 2. After finding out the number of tool changes for all feasible sequences, the sequence with minimal number of tool changes is determined as the optimal sequence. In this case, six sequences have minimal number of tool changes (3 4 5 2 1, 3 4 5 1 2, 3 4 1 5 2, 4 3 1 5 2, 4 3 5 1 2, 4 3 5 2 1). Among these sequences, the first sequence (3 4 5 2 1) is taken as the optimal sequence.

## GRAPHICAL SIMULATION AND BENDING SETUP PLAN

The system automatically generates an Autocad script file that can be executed in Autocad. On executing the Autocad script file, the graphical bending simulation of the optimal sequence can be viewed. Initially the flat pattern will be displayed in the Autocad screen followed by the display of repositioning of the component such that the first bend line lies in the  $X$  axis. Then the component geometry after bending (rotating both the face chains) along with the tool is displayed. Similarly for all other bends, component repositioning, tool and bending are displayed. For components having bend angles ( $\theta$ ) greater than  $180^\circ$ , the component has to be reoriented upside down. For example, if the bend angle between any two adjacent faces is  $270^\circ$ , then the component has to be reoriented upside down and the component is bent by only  $90^\circ$ .

