Using Features and Their Constraints to Aid Process Planning of Sheet Metal Parts

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Abstract

Process planning is a time-consuming and tedious operation that is necessary to manufacture products. In addition, process plans must be optimized to drive machines most productively. To accomplish this goal, we search for plans that satisfy production feasibility requirements and time constraints. Unfortunately, this search operates in an enormous search-space that is usually impossible to navigate. Therefore, we use features and their corresponding heuristics to guide the search. To make the search more tractable, we convert some features into corresponding constraints as a priori knowledge to prune the space. The applications of these features are presented in this paper. We also discuss the feature interaction problems in the process planning.

In this paper, we focus on the production of bent sheet metal parts and the machine setup. We have designed over forty test parts with our "Parallel Design" system, and the features are automatically generated as the design progresses. After the design is complete, an automatic process planning system uses the features and generates new ones to aid the production of a near-minimum manufacturing cost plan. Finally, these plans are used to produce parts on an automatic bending system.

1 Introduction

The sheet metal industry has focused on the automation of punching, shearing and nesting processes for sheet metal parts [1], and only few researchers have investigated the bending operation: Inui and Kimura [2] related product models with features and processes for bending operation; Bourne [3] developed an automatic bending process planner to generate plans with near-minimum manufacturing costs. This topic includes many challenges: the automatic selection of tools, workpiece grasping, bend sequence determination and 3D part dynamics (such as droop and vibration).

The representation of a sheet metal part should provide sufficient information to make a complete production plan. As a first step, the design must be unambiguous; it should represent one and exactly one part. Secondly, the design must be complete so all the information required to recognize a correct part is present, such as tolerances. Finally, additional information helps identify aspects of the design such as known features. While this last item is not necessary, it can make an extremely difficult planning task relatively easy.

Two approaches have been developed to identify features in a design: feature recognition [4] and design-with-features [5]. The feature recognition approach searches the geometric description of a part for known patterns and then labels the geometry subsets with a feature name. The design-with-features approach allows the designer to directly label the geometry. This has been used in various ways. For example, simulated manufacturing operations have been used to design a part, and then those operation names have been attached to the geometry, so the process planner can relate them to the actual process [6,7]. Cutkosky et al. [8] have observed that the product development cycle can be reduced by awareness of manufacturing processes during the design process and that the features often carry these relationships.

The process planning for bending sheet metal is considered difficult because it is highly geometry-dependent. A small variation in the part geometry can result in completely different bending sequences. Therefore, using the variant approach to generate the bending process plans may not work even though it has already been tried in the industry.

The number of possible bending sequences is large even for a moderately complex part, and it grows exponentially with the number of bends. Thus, enumerating and evaluating all possible sequences is not practical and sometimes not possible. In our approach, we interpret the design as a set of features and use precedence heuristics and constraints associated with these features to help search for feasible bending sequences. To optimize the plan, the precedence heuristics and constraints are applied in our planning as follows:

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1. We use precedence heuristics to adjust the costs of the nodes in the A* search and help guide to the promising paths (lower manufacturing costs or time).
2. We use precedence constraints to eliminate sequences from the search-space (all possible bending sequences) and therefore, substantially reduce the amount of search.

While the use of features looks inviting, because they provide useful encoding of known information, they can also cause new problems. For example, features can interact in negative ways. One feature may suggest process-a; another feature, process-b. This conflict raises questions of how these feature interactions can be detected and resolved. Hayes [9] used production rules to resolve negative interactions between features, and Nau et al. [10] used feature algebras to derive alternative interpretations of features to avoid them. Our approach to deal with feature interaction problems is to use domain-dependent knowledge to detect the interactions, and then assign precedences among the conflicting features (constraints) to resolve the interactions.

2 Background

This section describes the background of sheet metal bending and current sheet metal design and process planning practice.

2.1 Overview of Sheet Metal Bending

Sheet metal bending operation usually involves putting the sheet metal flat on the die of the press brake or bending machine, and then the die will come up (or the punch goes down) and bend the flat. The bending operation can either be done manually or automatically. In Fig. 1, we show the automatic bending system (Amada BM100) used in this research, which has been augmented by our own open architecture controller. This system consists of a CNC press brake, a five-axis robot, a loader/unloader and a 3-axis backgage used to located parts before bending.

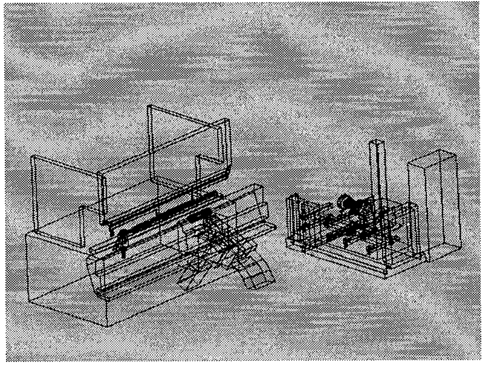


FIGURE 1. Amada BM100 Bending System.

2.2 Conventions of Sheet Metal Part Drawing

The conventions for sheet metal part drawing are as follows: solid lines represent the boundaries of the part and the dotted lines or dashed lines, bend lines. In this paper, all numbers associated with the sheet metal parts in the figures are the names of the corresponding bend lines.

2.3 Current Design and Planning Practice

State-of-the-art sheet metal parts design systems only represent the final 3D part geometry. This geometry describes either the wire-frame or the boundary representation of a part. Unfolding software is then used to discover the topological relationships between the surfaces. With the unfolding result, the 2D flat layout with the bend deductions can be calculated [11]. The disadvantages of the current design approach are the lack of feature information and the correlation between 2D and 3D parts cab be ambiguous.

When the design is complete, manufacturing engineers manually identify features most useful for the process planning task. The plans are produced by human experts and often have to be adjusted several times in a trial-and-error process.

2.4 The Bending Process Planning System

Our process planning system consists of four sub-systems: an operations planner, a tooling system, a grasping system and a motion planner.

Operations Planner: This system generates possible bending sequences and then asks other sub-systems to evaluate the manufacturing costs of the sequences. If possible, the costs are measured in terms of manufacturing time. An A* search algorithm is used to achieve near-minimum manufacturing costs. Precedence heuristics are used to adjust the costs (h and k costs in the A* search) of the nodes and precedence constraints, to limit the breadth of the search tree. The root node of the search is the unbent part (2D flat pattern), and as the search proceeds, it generates the nodes which represent partial bending sequences (intermediate part shape) until all bends are bent (final 3D part shape) or the search fails.

Tooling System: This system selects tools (punches and dies), determines the number of tool stages (segments of punch-die pairs) and stage lengths, and performs interference checking between parts and tools.

Grasping System: This system selects the grippers, determines the best grasping positions for the each bend, and predicts the number of repositions. The reposition operations are necessary whenever the gripper grasps across unbent bend lines. We have to use the repo-gripper to help hold the part and then re-grasp the part to bend the bends grasped previously. Imagine a four-bend box, we can bend three bends all at once but we have to reposition the part and then bend the last bend.

Motion Planner: The system consists of two sub-systems: the "*Gross Motion Planner*" that determines the transfer motion of the robot, and the "*Fine Motion Planner*" that determines the motion of the robot when the part is inside the punch-die space, especially the retraction of the part after it is bent.

Each sub-system is designed to cooperate with operations planner so as to develop a near optimal plan.

3 Representation of Sheet Metal Part and Features

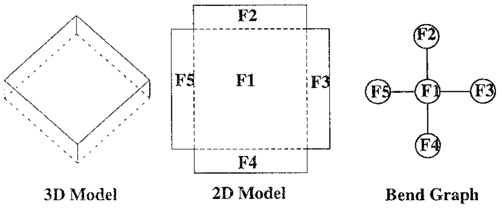
Our system uses multiple representations of the sheet metal part to track the changes of the part during different manufacturing stages. A 1D representation is used for the punching and nesting process, a 2D representation is used for the punching and shearing processes, and a 3D representation is used for the bending process. The final assembly of the sheet metal product is represented as the connectivity relationship between its 3D parts, this relationship effectively adds a fourth dimension.

In our previous work [12], we developed the Parallel Design System which is a design-with-features system that manages the relationships between the multiple representations of sheet metal parts. For example, when a 2D part is bent, it is stretched in the process, which means that the part dimensions are effectively different in these two representations. Therefore, the system handles the correspondence between the models at the level of topology and cannot carelessly introduce or extinguish new faces or edges as the bending operation proceeds.

3.1 Features of Sheet Metal Part

In this paper, we are primary concerned with the features that are directly related to geometry of the parts and can help prepare process plans more efficiently. They are related to the bending sequence determination, grasping strategy, tools selection or fine motion strategy. We label sets of geometric entities as features and classify them as follows:

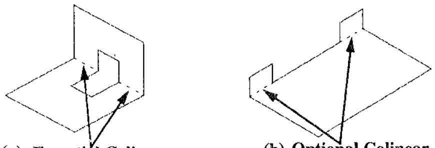
- *Holes, cutouts, slots and notches*: they are primitive shapes to be removed.
- *Bend Graph*: an important feature for determining the bending sequence is the topological relationships between bends and the faces they connect. We call this relationship "bend graph," with the faces as nodes and the bend lines as links. Each link contains bending information such as bend angles, bend radius and bend deduction. The 2D/3D models and bend graph of a four-bend box is shown in Fig. 2
- *Internal Tab*: internal tab is a flange connected to a hole. For most parts, the internal tab bends should be bent first, or interference will occur in the later bends.



3D Model 2D Model Bend Graph

FIGURE 2. Bend graph of a four-bend box.

- *Essential and Optional Colinear Bends*: essential colinear bends (see Fig. 3a) are those bends with distinct bend lines that must be bent simultaneously to prevent distortion. In most cases, optional colinear bends can be considered for efficiency (Fig. 3b). For example, the part in Fig. 3b could be planned as one bend with one stage instead of two bends with two stages. We group the essential and optional colinear bends as one bend in the bend graph to simplify the reasoning during the planning process.



(a) Essential Colinear Bends (b) Optional Colinear Bends

FIGURE 3. (a) Essential colinear bend and (b) Optional colinear bend.

- *Outside/inside bend*: Outside and inside bends are labelled relative to the current grasping position (Fig. 4), since the critical constraint is what the angle of the bend line is relative to the gripping plane. Typically, the plane of the gripper must match the plane of bend line.Because of the severe geometric limitations imposed by the process and machine, usually, outside bends should be bent first to avoid part interference with tools. For instance, in Fig. 4, we apply the "outside bend first" rule and generate the feasible (interference-free) bending sequence. But in Fig. 5a, channels can violate this rule and, therefore, we eliminate this rule in the presence of channels (Fig. 5b).
- *Taller Flange*: some flanges can be labelled as tall

flanges if their heights are tall relative to others. The taller flanges may cause interference with the punch, and make the grasping more difficult if they are bent earlier. Therefore, we prefer to bend the taller flanges later in the plans.

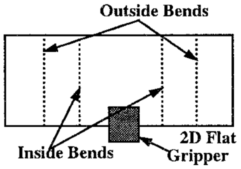


FIGURE 4. Outside/inside bends.

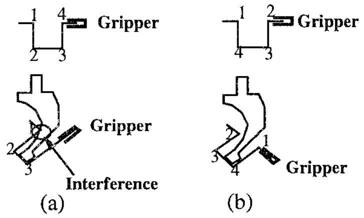


FIGURE 5. (a).Bending sequence with outside-bends-first rule. (b). Bending sequence without outside-bends-first rule. (numbers shown here are bending sequences)

- *Channel:* channel is a special feature for tool selection and bending sequence determination. The rule for recognizing channels is to look at the bend graph along a certain direction (for example, vertical or horizontal directions) and match the patterns. If all the bend angles are 90 degrees then the possible patterns for channels are (-,+,+,-) or (+, -,-,+). The channel feature suggests special tools (see Fig. 6a) or a particular ordering of the bending sequence that violates the "outside bend first" rule.
- *Hemming bend*: a hemming bend is a bend where the material is folded on top of itself or simply a bend with the bend angle of 180 or -180 degrees. The hemming bend suggests special tools (see Fig. 6b), and it is considered as a two-step (for instance, a 120 and 60 degrees combination) bend in the bend graph.
- *Large radius bend*: most V-die bends have bend radii smaller than twice the part thickness; however, large radius bends have larger bend radii and need special tools (see Fig. 6c).
- *Shorter/longer bend*: each bend is classified as either a shorter or longer bend according to the length of bend line. Intuitively, we can bend shorter bends on a longer die stage, but we can't bend longer bends on a shorter die-stage. The idea is to "bend shorter bends before longer bends. Otherwise, we may need additional stages, and possibly run out of die space. This rule can reduce the number of stages and the tool setup time. This is especially important if the part has many bends.

3.2 Applications of the Features in Process Planning

These features discussed in 3.1 can eliminate expensive computation and reasoning, provide precedence heuristics and constraints for bending sequences and suggest special tools. The goal of our system is to quickly generate the complete and near-optimal process plan that consists of four parts: tools selection and setup, workpiece grasping, bending sequence determination, and robot motion plan.

3.3 Tools Selection and Setup

We select certain pairs of punches and dies to meet the bending requirements such as bending angle, bending radius, and material type. For each bend, we need to determine the number of stages and the stage lengths. Special tools should be selected for channel bends, hemming bends, and large radius bends (Fig. 6). We have to treat these features as constraints in selecting the tools during the planning in order to satisfy the part design.

For the given bending sequence, the initial shape begins with 2D flat, and the intermediate shape is simulated before and after the bend in the punch-die space. We then check the collisions between the part and tools.

Dimples and louvers are represented as bounding boxes in the designs, so conservative estimates can be made for detecting collisions between the part and tools, or the part itself.

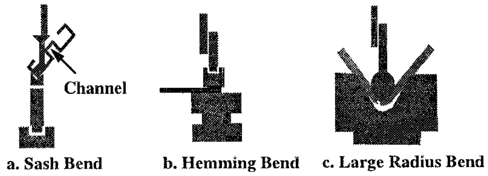


FIGURE 6. Special tools.

3.4 Workpiece Grasping

In our bending system, a five-axis robot is holding and positioning the part. In order to determine better grasping positions for each bend, the grasping module must choose appropriate grippers for parts of different geometry. Usually, holes and cutouts are considered as bad grasping areas if the contact area of the gripper and the part is less than about 80% of the area. The grippers have limited knuckle heights, so they can only grasp across short bent flanges. Grasping dimples or louvers must also be avoided. Special steps are taken dealing with hemming bends and large radius bends, once they are bent.

3.5 Bending Sequence Determination

Most of the features directly or indirectly relate to the bending sequence determination. We convert them into precedence heuristics or constraints to guide the search for a plan.

Several precedence rules are used in selecting bending sequences. For instance, the outside bends should precede inside bends, and internal tab bends and the shorter bends should be bent first. These rules suggest partial ordering of the complete bending sequence. The operations planner searches the sequences incrementally and obtains a near-minimum cost sequence if there is one.

3.6 Robot Motion Planning

For a given bending sequence, the intermediate shape of the part is calculated, and the bounding box approximation of the intermediate shape is used for the gross motion of the robot. Because we have a sparse environment, we can use the bounding box approximation for the robot gross motion planning.

When the workpiece is going into or retracting the punch and die space, this step of the process is referred to as fine motion planning. To plan the path more efficiently, we must identify the position and orientation of dimples, louvers and bent internal tabs. Generally speaking, fine motion planning will couple with tools selection.

4 Converting Features into Heuristics and Constraints

In our system, features either suggests precedence rules or the tool-selection, grasping and motion strategies. The precedence rules can be used as precedence heuristics or precedence constraints depending on the certainty factors of these relations. The certainty factors are determined by past planning expertise and geometry reasoning. For instance, the "outside bend first" rule is a strong heuristic compared with "the shorter bend first" rule. There are default heuristics and constraints in the planner and the users have the flexibility to change or overwrite these settings. Features also suggest special tools, workpiece grasping and fine-motion strategies. These features are converted as constraints which are related to the bending sequences. The relationship between features, precedence heuristics and constraints, and other type of constraints is shown in Fig. 7.

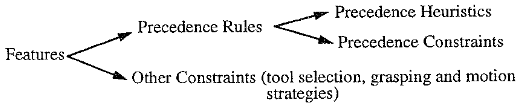


FIGURE 7. Relationships between features, heuristic and constraints.

Due to the combinatorial explosion characteristic of the search, for a part with *N* bends, the complexity of the ordering will be of at least *N!* (if we exclude the re-position operations and optional colinear bends in the ordering). However, if we use the feature information and convert them into precedence constraints, we can potentially avoid the combinatorial explosion and improve production efficiency

We have developed a *precedence language* to represent heuristics and constraints in our planner. The language contains three syntactic forms:

numerical number: representing the bend index.

""*: representing zero or more bend indices.

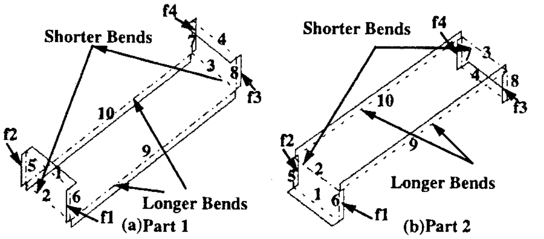
"?": representing one and only one bend index.

For instance, if the constraint is "bend 1 is the first bend," the corresponding representation is (1 *). If the constraint is "bend 1 precedes bend 5," (* 1 * 5 *). The current system also supports conjunctive constraints, such as ((* 1 * 3 *) (* 2 * 4 *)), which means "bend 1 precedes bend 3" *and* "bend 2 precedes bend 4." The heuristics can be written the same way as the constraints except there is a penalty associated with each constraint if the current sequences violate the constraints.

4.1 Feature Interactions

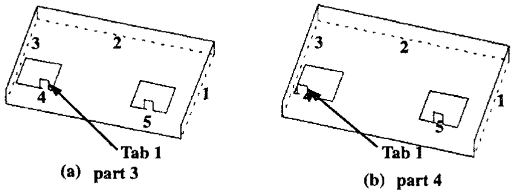
The major problem of using features in process planning is the interaction of features, especially negative interactions, i.e., bending one feature first makes it difficult or impossible to bend subsequent ones. We resolve these interactions by assigning the precedences among them. After having tested many parts, we have verified that the interactions of features are highly geometry-dependent. For instance, the part in Fig. 8a, bends 2 and 3 are shorter bends, and bends 9 and 10, longer bends. The "shorter bends first" rule applies for this part (which are written as: ((* 2 * 9 *) (* 2 * 10 *) (* 3 * 9 *) (* 3 * 10 *))). However, if we look at the part in Fig. 8b, which has the identical features as the previous part except the bend angles of bends 2 and 3 are -90 degrees (bent down operation), according to the "shorter bend first" rule, bends 2 and 3 should precede bends 9 and 10. But, if we put the constraints in the search, we cannot bends 9 or 10 if bends 2 or 3 are already bent, since we cannot place the part on the die (the flanges f1, f2, f3 and f4 will interfere with the tools). In this case, we should bend the longer bends 9 and 10 before bends 2 and 3 to resolve the interaction (((* 9 * 2 *) (* 9 * 3 *) (* 10 * 2 *) (* 10 * 3 *))).

Another example of feature interaction is shown in Fig. 9a and 9b, these two parts have almost identical shape except the positions of the "Tab1" are different (in part 4, "Tab 1" is very close to the bend 3). Each part has two internal tab bends (4 and 5). According to the "internal bends first" rule, bends 4 and 5 should be bent before bend 3. This rule applies for the part in Fig. 9a. However, for the part in Fig. 9b, if we bend 4 first, we can never bend 3 (tab1 will interfere with the tools). Instead, we should bend 5 first and bend 3 before 4, i.e., (* 5 * 3 * 4 *).



(a)Part 1 (b)Part 2

FIGURE 8. (a) and (b): Feature interaction between shorter bends and longer bends.



(a) part 3 (b) part 4

FIGURE 9. (a) and (b): Feature interaction between internal tabs.

Fortunately, the numbers of negative feature interaction is relatively rare and most typical parts have at most one interaction.

We have set up the planning environment for these parts discussed above. The default constraints for all the parts are as follows: never do colinear bends, never do inside bends. The other settings are listed in Table 1. For part family (part 1 and 2) in Fig. 8, one of the assigned heuristics is the "shorter bend first" rule with penalty cost, 3. For part family (part 3 and 4) in Fig. 9, one of the assigned heuristics is the "internal tab bend first" rule with penalty cost, 6. We also give part 4 (Fig. 9b) an assigned constraint to help resolve the interaction problem.

In Table 2, we show the search results with the settings in Table 1. We compare the *number of nodes* visited in the A* search space. Each node represents a partial bending sequence in the search.

In these results, we run the operations planner and the tooling system since these two sub-systems use these features most extensively.The results show that parts with almost identical shapes can result in totally different bending sequences. The feature interactions show a significant improvement in the amount of search space.For part family 1 (part 1 and 2 in Fig.8, 79 vs. 44 nodes), and for part family 2 (part 3 and 4 in Fig. 9, 191 vs. 20 nodes).We should notice that, for parts with bends perpendicular and very close to other bends, such as bend 3 in part 4 (Fig.9b), should be bend first. We convert this rule into constraint ((* 3 * 4 *)) and save almost 90% (191 v.s. 21 nodes) of nodes visited. This shows the power of using constraints to resolve the interactions. There are few rules we are confident enough to use them as constraints. To develop these constraints, we do a case-by-case study of process geometry and limitations, and convert them into precedence constraints either before planning or during the planning.

TABLE 1. Settings for the planning examples.

Part Number	**Part 1 (Fig. 8a)**	**Part 2 (Fig. 8b)**	**Part 3 (Fig. 9a)**	**Part 4 (Fig. 9b)**
No. of Bends	10	10	5	5
Default Precedence Heuristics	Tall bends penalty 6	Internal tab bends penalty 6	Long bends penalty 3	Tall bends penalty 6
Assigned Precedence Constraints	Not Applicable			((* 3 * 4 *))
Assigned Precedence Heuristics	((* 2 * 9 *) 3) ((* 3 * 9 *) 3)	((* 2 * 10 *) 3) ((* 3 * 10 *) 3)	((* 4 * 3 *) 6)	((* 5 * 3 *) 6)

TABLE 2. Search results.

Search Space	**Part 1 (Fig. 8a)**	**Part 2 (Fig. 8b)**	**Part 3 (Fig. 9a)**	**Part 4 (Fig.9b)**
Planned Bending Sequence	(8 7 6 5 4 1 10 9 3 2)	(8 7 6 5 4 3 1 2 10 9)	(5 4 3 2 1)	(5 3 4 2 1)
Using *assigned heuristics*	44	79	20	191
Using *assigned constraints*	Not Applicable			21

We found that even if we convert features into constraints, sometimes, we still cannot avoid combinatorial problems. In Fig. 10, there are interactions between two channels and two possible colinear bends labelled. There are combinations of bending all channels at a time, or one at a time. The possible colinear bends have similar combinations. The problems occur when we try to group the same kind of features as a single feature, for instance, try to bend two channels at a time as a single channel and three colinear bends as a colinear bend.

Grouping features might be favorable because of its efficiency but it will make planning more difficult since we have to consider the all of the subsets of constituent features, which causes a new combinatorial problem.

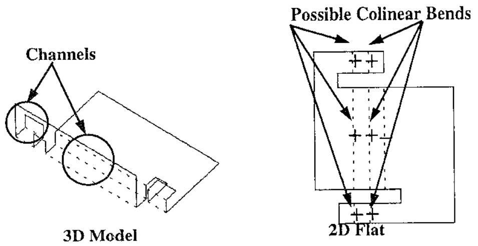


FIGURE 10. Combinatorial problems for grouping features (in 14b, the "+" signs represent bent up operations and the "-" sign, bent down operation).

5 Conclusions and Future Work

In this paper, we identify several important features for bent sheet metal parts and use them in the production of process plans. The features suggest precedence rules, or constraints for tool selection, workpiece grasping and motion strategies. We then convert the features into corresponding precedence heuristics and constraints. We found that if we can convert some of the features into the corresponding constraints and use them as a *priori* knowledge to prune the search space, then the search becomes more tractable.

The interaction of features can mislead the search or sometimes make the search fail. We show two examples and resolve the interactions by assigning precedences among these constraints before performing the search. This is done by using domain-dependent knowledge which are obtained by past planning expertise and part geometry reasoning. Interactions could be detected when the sub-systems begin to return costs of infinity, and the search backtracks too often. We have applied our planning system on many complicated parts, and the results are satisfactory. We have planned a 7-bend part in 22 minutes which used to take the human experts 3 days to prepare the plan which includes the bending sequence, robot motion, grasping position and tools selection.

Our future work will include identifying new features, improving our precedence language, automatically converting the features into corresponding heuristics and constraints before and during the planning stage, reasoning more about the features interactions, and resolving the interactions for bent sheet process.

Acknowledgment

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