Constraint-based process planning in sheet metal bending

András Márkus[1] (2), József Váncza[1] and András Kovács[2]

[1] Computer and Automation Research Institute, Hungarian Academy of Sciences

[2] Faculty of Electrical Engineering and Informatics,

Budapest University of Technology and Economics

Abstract

The majority of research dealing with computer-aided process planning of sheet metal bending approaches this problem as heuristic search. Since relevant engineering knowledge mostly consists of declarations that prohibit collisions and just a handful of generative rules, there are no useful means to drive these heuristics. In order to find a new way, we have made experiments with a constraint-based approach: using predefined constraint types and geometric constraint satisfaction, complex bending problems have been solved. By returning not just a single solution but a Pareto-optimal set of solutions (i.e., operation sequences, with appropriate part orientations and tools assigned) we have left the engineers freedom to apply further, not yet modeled parts of their domain knowledge.

Keywords: process planning, constraints, bending

1 INTRODUCTION

Computer aided methods in engineering call for the *efficient use of deficient knowledge* [1]: while the engineer must not try to conceal if his knowledge is not formal enough to be filled into some predefined framework (such as standard optimization methods), the computer expert must not renounce the innovation of problem solving frameworks. One of the promising new research directions in CAX is the integration of optimization and constraint-based techniques for solving complex, loosely defined design, planning and scheduling problems [2].

Earlier we have developed a generic constraint-based model and planning engine for manufacturing process planning [3, 4]. By exploiting the expressive power of constraint programming (CP), the relevant, sometimes conflicting pieces of domain knowledge were represented. The planner applied standard satisfaction techniques and customized search to find cost-optimal solutions in the presence of hard, soft and conditional constraints. The present paper describes our next steps taken from this basis:

- refined modeling in the bending domain, with a new integration of reasoning over geometry and technology,
- refinement of the proposed set of constraint types,
- development of a new solution strategy for balancing multiple evaluation criteria in a user-friendly way,
- evaluation of a mainstream optimization and constraint programming engine.

The paper is organized as follows: Sect. 2 is an overview of related work with constraints in process planning. Sections 3 and 4 outline the problem setting and our planning model for sheet metal bending. Sect. 5 gives details of the geometry module. Sect. 6 outlines branch-and-bound search for Pareto sets. Sect. 7 discusses experiments with the new constraint engine.

2 RELATED WORK

In the production engineering community, constraint based research started with works focused on geometric constraints for assembly and variational product design [5, 6], on the modeling of part families [7] and geometric reasoning in parametric design [8]. Constraint reasoning was applied in [9] to the problem of designing universal sheet metal bending tools for part families.

In the field of process planning, more specifically in operation sequence planning, interest centered around task precedences in assembly [10], and bending of sheet metal parts [11, 12]. Special emphasis was put on dealing with tolerances of bent sheet metals in [13]. Work reported in [3] introduced constraint types that were shown to cover the needs of a wide variety of CAPP problems.

These works explored that (1) the constraint-based methods should be ready to deal with a variety of logical structures and cope with over-constrained problems, and (2) optimization and constraint satisfaction should be seamlessly integrated.

3 PROBLEM SETTING

3.1 Sheet metal bending

Sheet-metal parts are typically produced by a sequence of bending operations. The bending process starts with a flat part and ends up with a three-dimensional object of interconnected planes (see Fig. 1). The bending operations are executed on a bending machine (press brake), using various tool and holding resources. Tools consist of dies and punches of different shape and length. There is also a need of grippers that hold the part during and in-between the operations.

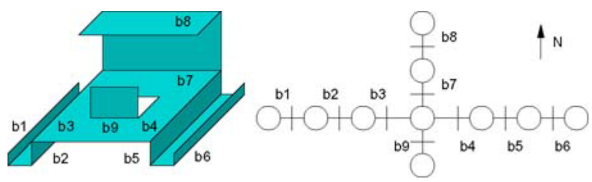

Figure 1: A sample part and its connectivity graph.

The bending operations should be sequenced so as to avoid part-tool, part-machine and part-part collisions (see Fig. 2). Although bending operations are local, they often make global changes in the geometry of the part. Hence, all of their effects can hardly be specified in advance. Process engineers developed various rules of thumb to support the generation of executable sequences [11, 14, 15]. For instance, outside bends should be done first to avoid "rolling up" the part that would prohibit tool access to outside bend lines later. Tall flanges most likely interfere with the bending machine, hence their bends should be postponed as far as possible. It is suggested to make internal bends as early as possible, whereas bends determining the shape of the part should be left to the end of the plan. However, almost each rule has its exception. For instance, on our sample part bends *b1*, *b2* and *b3* form together a so-called channel that should be made from inside toward outside. There are of course some hard rules as well: to compensate for the spring back of the sheet, overbends have to be made. In a corner, to avoid part-part interference, the outside bend must be done strictly before the inside bend. Hence, domain knowledge in bending is unanimously captured by soft knowledge representation methods: by fuzzy rules, preference rules, and/or weighted constraints.

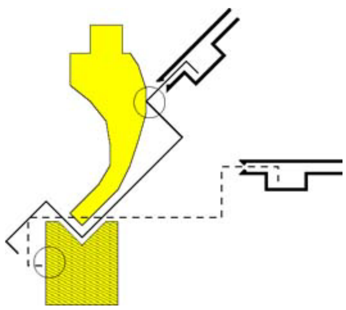

Figure 2: A bending operation on the sample part. Potential places of collisions are encircled.

When selecting (or designing) tools, geometric dimensions, tolerances and bending forces must be taken into consideration. However, the bending operations executed so far determine the intermediate shape of the part and constrain, indirectly, the applicable resource sets of the forthcoming operations. E.g., if bends *b3* and *b4* are performed before *b7*, then *b7* can be made by a tool of exact length only.

The same tool can often make several bends, some of them may be even shorter than the length of the tool. Holdings are also usually appropriate for performing subsequent bending operations. Certain operations may be even merged by using one tool to perform them at the same time. All this gives a chance for optimization. Important optimization criteria are – as in all process planning domains – the minimal tool and holding changeovers. In sheet metal bending a further, specific criteria is that the number of unbalanced operations (when the center of gravity of the part does not fall between the tool and the holding device) should be as small as possible [12]. Note that this criterion is in conflict with that of having the minimal repositioning of the part.

Beyond optimization criteria, realistic CAPP models should provide means to cover and utilize *best practice* by expressing characteristics that the experts anticipate in "good" plans. Such plans are not only feasible but close to optimal – although there might be no proof that good plans must really have these features.

3.2 Our approach to the planning problem

Of course, the basic criterion for the adequacy of a plan is that it must be executable; i.e., it should use the appropriate resources and should be collision-free. In our previous constraint-based experiments in bending, instead of making a complete representation of the geometry of the part and the tools, we have prepared a rich set of constraints over the sequencing and the resource assignments of the operations. However, these constraints did not contain the actual geometric data, just the *results* of such geometrical reasoning, inter-mixed with some rules of thumb presented above. Obviously, such a representation is incomplete, but, in other cases, could easily turn into an over-constrained plan specification. So it happened that we did not succeed in filtering out all illegal plans, or the constraints turned out contradictory even if the problem was well solvable by a human expert. As a matter of fact, the need of using an intricate, carefully tuned system of soft and hard constraints was due to the above mentioned difficulties.

As the next step in our constraint-based bending project, now we have developed a model with much closer integration of geometry and process planning. We extracted crisp knowledge related to the geometry of bent sheet metals from the engineering expertise. With this decision we have lost some of the generality of our earlier model, but, on the other hand, this extension offered a test whether those constraint types are relevant in this setting as well. In a similar way, such a development was a new test against our solution strategies, too.

All in all, our statement of the process planning problem in the bending domain is as follows:

Given are (1) the geometric model of the sheet metal part and the applicable tools, (2) the various optimization criteria, and (3) domain knowledge on some global properties of good plans.

Find a set of solutions that are executable, and optimal in the Pareto sense.

4 CONSTRAINT-BASED PROCESS PLANNING

4.1 Part and tool representation

The frame of the part is described by a connectivity graph, a graph with *pane* and *bend* nodes, where each pane node is connected to nodes corresponding to the adjacent bends. Rectangular plates, each fixed to the corresponding pane node, build up the solid structure of the part. E.g., see Fig. 1, where panes and bends are shown as circles and lines, respectively.

Pairs of dies and punches are referred to as tools. They are characterized by their length, as well as front and back profiles. We do not deal explicitly with grippers and specify each holding with the orientation of the part.

4.2. Operations, resources and plans

There is a set of irreversible operations, one associated to each bend. By executing an operation, the state of the corresponding bend changes from undone to ready. The fabrication process of the workpiece can be modeled as a permutation of these operations, with resources assigned. Tools and orientation the part should be selected from predefined finite sets.

4.3 Constraints and criteria

Our CAPP model represents domain knowledge both by hard and soft constraints. Hard constraints describe characteristics that are required in order to achieve an executable plan, hence, they must be satisfied by the solution. Soft constraints consist of base predicates describing certain pieces of advice, and attached weights that express the importance of the that advice. The constraints belong to the following types:

- operation precedence and neighborhood;
- resource assignment;
- resource sharing (setup formation);
- conditional constraints, where one of the above properties is conditioned by operation precedence and/or resource assignment.