Computer Aided Process Planning for Sheet Metal Bending: A State of the Art

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Abstract:

Purpose of this paper is to offer the reader an overview of recently performed and ongoing research related to process planning for sheet metal bending, thus providing a starting point for further exploration of this field. The scope of this review paper is limited to sheet metal bending as performed on numerically controlled press brakes, with special focus on air bending. Automatic process planning requires a good understanding of the material behaviour under process conditions. Therefore some space has been reserved for an overview of bend modelling efforts and, directly linked to this, in-process measurement and adaptive control methods. Part representation and feature classification methods for bent sheet metal parts are also discussed. Sections are dedicated to the core problems of fully automated process planning in sheet metal bending: bend sequencing, collision detection, tolerance verification and tool selection. The state-of-the-art review is completed with an overview of ergonomic analysis methods for process plan evaluation.

Keywords:

Process planning, bending, sheet metal, CAPP, press brake

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1 Introduction

Sheet metal forming is one of the oldest manufacturing processes known to mankind [1], and bending can probably be considered its most basic variant. However, the numerous research contributions dedicated to sheet metal bending that have been published over the past decade, and the constant stream of announcements by R&D departments of machine constructors form strong indications that not all research challenges related to sheet metal bending have been exhausted.

Purpose of this paper is to offer the reader an overview of recently performed and ongoing research related to process planning for sheet metal bending, thus providing a starting point for further exploration of this field.

Sheet metal parts are typically produced by a sequence of bending operations. The bending process starts with a flat workpiece and ends up with a three-dimensional object of interconnected flanges. The bending operations are executed on bending machines -- so-called press brakes -- using various tools and holding devices (see Fig. 1). Tools consist of dies and punches of different shape and length. Usually, a machine can hold several tools at the same time, while a tool can be applied for different bends, too. Tool selection and operation sequencing is based, first of all, on geometrical considerations so as to avoid interferences between the workpiece, the tool and the machine. Furthermore, the planner has to consider a number of issues concerning material properties, tolerances, ergonomics and cost factors.

This state of the art is limited to sheet metal bending as performed on numerically controlled press brakes, with special focus on air bending that involves bending of parts on a V-shaped die with a punch. Swivel bending and wiper bending are explicitly excluded from the scope of this review.

A detailed enumeration of the specific methods or algorithms described by the respective authors would be impractical within the scope of a single article. However, an attempt was made to summarise the most important results and to point out the relevance of the respective contributions. In order not to overload the text, publications are referred to by means of the first author only.

The research efforts, as described in this literature review, can largely be divided into two major categories.

The first group concerns research related to the modelling of material behaviour under bending conditions and related measuring methods (Sections 2 till 4). While the main focus of this review article is on process planning, it was considered useful to also cover these closely related topics, which form the boundary conditions for the actual process planning methods and algorithms. A brief state of the art is sketched for bend modelling (Section 2) and on-line material testing (Section 3). In Section 4 the recent evolution in the field of adaptive control systems for bending are summarized.

The second category contains contributions to the development of specific automatic process planning methods. In order to provide well structured input data for the described procedures, a number of authors have focused their efforts on part representation and classification: a summary is offered in Section 5. Bend sequencing methods are reported in Section 6, while the next three sections are about collision detection, tolerance verification and tool selection. Additionally, a number of research reports related to ergonomic aspects of process planning (Section 10) are mentioned. These publications contain more pragmatic contributions that can also be implemented as stand alone software tools for industrial use.

A schematic overview of the research topics, their interrelationships and the corresponding section numbers are presented in Figures 2 and 3.

2 Bend Modelling

In classical air bending, in order to obtain the required angle, the punch stroke has to be predicted with high precision. This involves two problems

- determining the relationship between angle and punch displacement during bending,
- determining the springback angle.

Complementary, in order to obtain the right dimensions, the position of the back gauge has to be calculated for every bend operation.

Therefore, the development of an analytical model to predict the required machine parameter settings for given material characteristics, sheet thickness and tool geometry, has long been a research objective. Early efforts date back from the start of the 20th century, when Ludwik formulated a number of assumptions that allowed to describe the plastic deformation of sheet metal under bending conditions [2].

Since 1950 the interest in modelling the material behaviour during bending operations has intensified. Gradually a number of Ludwik's assumptions were found not to reflect the reality with an acceptable accuracy. For example, the supposition that the load on a sheet undergoing a bend transformation could be approximated as a pure bending momentum was found to be inaccurate. In consequence the geometry of the resulting bend is not cylindrical, as formerly assumed. For the commonly used ratios of V-die width and sheet thickness, ignoring stresses in directions orthogonal to the sheet surface or parallel to the bend line was also found to lead to significant deviations between predicted bend angles and experimental results. In parallel the analytical functions used to approximate the stress-strain relationship were refined stepwise, from a rigid - ideal plastic model to, eventually, a formulation known as Swift's equation, which allows to represent the material behaviour by means of a single, continuous analytical function:

$$\sigma(\varepsilon) = C(\varepsilon + \varepsilon_0)^n \qquad \text{for C, } \varepsilon_0\text{, n : material constants} \qquad (1)$$

A comprehensive, chronological overview of the important development steps can be found in [3], while more detailed descriptions of the phenomena occurring during bend operations are available in [4] and [5].

Based on the discrepancies identified in earlier research, a number of more refined bend models, that incorporate a more realistic material behaviour, were presented in recent years.

De Vin [4, 6, 7] described a bend model in which three different bend zones are distinguished:

- a zone in direct contact with the punch, characterized by a circular deformation with internal radius equal to the tool tip radius;

- a zone with a variable radius starting from the first zone until the point where only elastic deformation occurs;
- a zone which, after elastic springback, shows no permanent deformation (straight bend legs).

In this model, referred to as the Three Section Model, the calculation of the sheet curvature is based on the assumption that the influence of shear forces can be ignored. A direct relation between the local bending moment and the curvature at the corresponding location could thus be formulated. Starting from the calculated deformation of the sheet and compensating for the elastic springback, this relation allows to define the required punch displacement for a known tool geometry.

The author reports deviations between the predicted punch position and the experimental results ranging from 0.1 to 0.5 mm [4]. The sensitivity of the bend angle for errors in punch displacement values is, however, high: for the tested sheets and a bend angle of 90° the sensitivity of the bend angle for the punch displacement was 8.98 °/mm [6]. Another observation was the systematic prediction of too low springback angle values. Applying the model for the calculation of unfolded lengths (blank sizes) also resulted in systematic errors [3].

Another recent development in bend modelling was reported by Lutters [8]. The described Equilibrium Model is based on the principle that, at any moment during a bend operation, an equilibrium exists between the external forces and the internal stresses in the material. When undergoing an increase of external load, the sheet will deform further until a new equilibrium is achieved. Starting from a flat sheet, the consecutive shapes of a number of elementary sheet segments can thus be calculated iteratively, until springback compensation results in the required bend angle. A plane strain situation is assumed and the influence of shear stress is taken into account. Variable orthogonal reaction forces at the contact points with the punch, and friction forces are incorporated in the model.

The reported deviations between calculated and measured punch displacements, obtained in laboratory conditions, are significantly lower than the errors in the output of the Three Section Model. Deviations of 0.1-0.2 mm are an indication of the accuracy of the model, once the parameters in Swift's stress strain relationship (C, ε_0, n) have been adjusted to the behaviour of the used material.

At the Research Centre of the Belgian Metalworking Industry (WTCM/CRIF), Aerens further developed the Three Section Model [9]. The most important origin of discrepancy between reality and the model predictions was found to be the penetration of the punch tip in the material, causing important stress and strain disturbances. Using FEM computation results this effect was introduced in the bending model. He also introduced the drop of the elasticity modulus consecutive to large prestrain. Experimental validation showed that the error on springback predictions did not exceed 0.3° and the error on the performed angle did not exceed 1°.

Verification of the developed models led to a growing awareness that the process parameters can only be predicted with an acceptable accuracy if the exact material characteristics are known. As a result, efforts were initiated to measure these characteristics during the bending process, as described in the next section.

3 Material Properties Measurement and In-Process Measuring Methods

Crucial for the applicability of the described bend models is the detailed knowledge of the material characteristics. Appropriate test methods are required to measure the material properties under bending conditions. The measurement of the relationship between a local bending moment and the resulting curvature of the sheet received special attention in recent years. Several test set-ups to bend a sheet sample with a pure moment were also developed to measure these relationships as input for bending models [10, 11, 12, 13, 14, 15].

The approach to measure the material behaviour, instead of relying on database information, has the advantage of eliminating imprecisions due to the variations in material properties between different batches of sheets. Also the anisotropy of the material can be taken into account if samples corresponding to the bend direction, with fixed orientation relative to the rolling direction, are prepared.

WTCM/CRIF developed a device that bends sheet samples till 6 mm thickness with a pure bending moment at a preset strain rate [9]. Strain rates similar to production rates can be imposed. Different authors developed a method to measure material characteristics from a bending test and use them in bending models in order to compute the punch stroke [16, 17, 18].

Robroek [16] reported an effort to develop an analytical bend simulation module based on a moment-curvature relation, measured during a bend test performed on the actual sheet material. This approach, referred to as the Inverse Method, allows to eliminate uncertainty related to the deviations between the nominal material characteristics and the actual sheets. Since, in principle, a single bend test performed in a production situation allows to collect the required input data for the model, the practical application of the described system in a workshop environment seems realistic. However, for the tested implementation the author reports deviations between the calculated and the actual bend angles up to 3.2°, leading to the conclusion that further refinement of the method is required.

Stelson [17] developed a method to identify the material characteristics of a sheet being bent from real time force displacement data. However, the author makes some important simplifying assumptions. With the applied model and the measured material characteristics, the bending angle error is claimed not to exceed 1°.

Yang [18] proposed a control system based on the force-punch displacement curves, the obtained bend angle and the corresponding control values measured in process during previous bending operations. Two fuzzy models were developed to steer the selective retrieval of these curves from the experimental database and to correct irregularities in the data. A test implementation resulted in a bend angle accuracy within a range of ±0.3º for 90º bends performed on a number of mild steel sheets from different origin. Although these preliminary results meet industrial expectations, the proposed method still requires collecting a large amount of experimental data before the system becomes operational.

It is obvious that the requirement to perform one or more practical tests before a new batch of sheets can be used for production purposes is in conflict with the objective of predicting process parameters by means of an analytical model only. Practically speaking it means a step back in the direction of making one or more test parts and modifying process parameters until the resulting part geometry complies with the specified tolerance requirements.

Moreover, it is important to realize that, however accurately a model may reflect the real behaviour of sheet metal under bending conditions, a number of factors remain hard to predict: variations in the thickness (DIN1541, for example, allows deviations up to ±0.15 mm for sheets with a nominal thickness of 1.5 mm), anisotropy in the material due to cold rolling, deformation of the machine structure, tool wear, etc. Due to the very sensitive relations between the punch displacement and these factors, the precision with which a required punch displacement can be predicted still results in bend angle errors of an order of magnitude of degrees [19]. Other factors that could be of importance are time related: for example the dwell time at the lower dead point (maximum punch displacement) was, according to Anokye-Siribor [20], found to have a significant influence on the spring-back angles for aluminium and titanium alloys.

Therefore, controlling the motion of the punch, based on in-process measurement of the angle, has been introduced as a way out of this dilemma. This method is referred to as "Adaptive Bending". Recent developments in this direction are reported in the next section.

4 Adaptive Bending

Up-to-date CNC press brakes, as applied for air bending, are normally equipped with measuring gauges to provide the necessary feedback concerning the actual punch displacement to the controller. An important improvement for these commonly applied control systems would be to use the bend angle as the controlled variable, instead of the punch displacement. As already indicated in Section 2, the sensitivity of the bend angle for changes in the punch displacement is very high. A direct measurement of the bend angle, with a feedback connection to the control system, can, however, effectively eliminate the need for a very precise prediction of the required punch displacement.

Over the last few years a number of joint projects between manufacturers of press brakes and research institutes have lead to a variety of hardware solutions and a number of control strategies to implement this idea. In the following paragraphs the main concepts for such systems are summarized (Section 4.1). Complementary work related to springback control is summarized in Section 4.2.

4.1 Angle Measuring Systems

The first category of angle measuring systems is based on a contact sensor for distance measurement [21, 22] (Fig. 4). The bending angle (β) is obtained through trigonometric calculations, with the measured sensor displacement (d), the known reference position (c), and the orientation (γ) of the measuring system as input data.

$$\beta = f(c, d, \gamma) \qquad (2)$$

Where dies with rotatable elements are used, a direct angle measurement is possible by means of incremental shaft encoders registering the rotation of the rollers [21] (Fig. 5).

$$\beta = f(\gamma) \qquad (3)$$

A third category of angle measuring devices uses non-contact optical systems [23, 24, 25]. Different variants exist. A first principle is based on reflecting a single laser spot projected on the sheet metal surface by a swivelling combined projector and sensor system. The orientation of the rotating light source, corresponding to the laser beam direction orthogonal to the bend leg (γ), can be obtained by averaging the measured angles ($\gamma+\Delta\gamma$ and $\gamma-\Delta\gamma$) at which the maximum energy is detected in the sensors (Fig. 6).

$$\beta = f(\gamma + \Delta\gamma, \gamma - \Delta\gamma) \qquad (4)$$

In a second variant the laser light is projected in a planar mode, creating a linear pattern on the sheet metal and, as a reference, a line on the die. A digital camera, placed under an angle in the horizontal plane, allows continuous angle monitoring by analysing the angle between the two projected lines and the original vertical reference line on the unloaded die.

A fourth angle-measuring concept uses special punch tools with integrated gauges. In a first variant the punch is equipped with two gauges that can move freely in the vertical direction [26]. The circular discs at the end of these gauges have different radii, so that they will have a different vertical position (y_1 and y_2) when contact is made with the part. The difference (y_1-y_2) between the two measured positions is unique for every bend angle value (Fig. 7).

A variant with four linear displacement probes mounted close to the punch tip is described in [27]. At each side of the punch, two probes measure the distance to the sheet. The bending angle is obtained through trigonometric calculations, with the measured displacements and the distance between the probes.

$$\beta = f(y_1, y_2) \qquad (5)$$

Kwok [28] reports an effort to support adaptive bending by means of a vision system. Images, captured by means of a conventional CCD camera, are analysed to identify the complete bend profile. This allows not only to measure the bend angle, but also to adjust the bending model to the actual shape of the bent zone.

Several variants of these measurement systems have been implemented in commercially available adaptive control solutions. In fact, most leading manufacturers of CNC press brakes nowadays offer adaptive control systems with a typical accuracy of between ± 0.3 and 0.5° as options on their high end product lines. In these implementations one can observe a trend towards duplicate measurement sensors that allow to monitor the bend angle at both sides of the punch. The requirement for dedicated punches and/or dies for some of these measurement systems forms a constraint that has to be taken into account during process planning.

4.2 Springback Control Strategies

Estimates for springback angle correction can be retrieved from a database [29], computed by means of a bending model or derived from in-process measurements. A straightforward approach for springback measurement is the intermediate, incremental reversal of the ram until no further springback can be traced [21]. A more precise expected springback value, corresponding to the nominal bend angle, can then be calculated based on the obtained data.

In order to avoid losing contact between the punch tip and the workpiece, a number of developers opted for a combined angle and force measurement. This can be implemented through pressure measurement in the hydraulic system or by means of an additional force sensor built into the die [22, 24]. This additional sensor allows to unload the part almost completely without the risk of losing contact between the punch and the workpiece. The sensor also allows to collect relevant information related to sheet thickness.

The introduction of adaptive bending systems to a large extent eliminates the uncertainties linked to the variation in material properties (thickness, tensile strength, strain hardening) that typically limit the accuracy of bend models as described in Section 2.

5 Part Representation and Classification

Process planning for bending operations requires a number of computationally expensive steps. An economic part representation scheme is therefore of great importance for the efficiency of the combined process planning activities. A large number of publications contain proposed representation schemes, often developed in the context of a dedicated modelling system for sheet metal parts.

5.1 Feature Based Modelling

In most generic CAD modelling systems today, rather than describing the parts by means of basic geometric entities, part models are mostly defined as composed of a number of higher level features. A large number of publications contains proposed taxonomies of such design and/or manufacturing features [30, 31, 32, 33, 34, 35].

Belarbia [30] distinguishes the following basic features: walls, bends, form features (obtained as a result of the use of forming punches and dies), cuts (general type of holes), punches and notches (specific user defined shapes corresponding to available cutting tools).

Some authors use a structured hierarchy of features [33, 34]. A class of primary features (also labelled as master, main or parent features) typically includes all entities that define the all-over shape of the part and can be specified without reference to underlying features. This class contains so-called walls, also referred to as flanges or faces, and bends. Secondary features (primitive features or co-features) can be applied with reference to a primary feature only and include different types of cut-outs and form features.

Within the class of main features some authors [33, 34] further subdivide the bend features in simple bends and features such as hemmed or curled edges. Another typical feature classification is based on the distinction between passage (different types of holes) and non-passage features (external edges and form features) [32]. De Vin [31] described the taxonomy of the Part-S system, in which bends are replaced by a feature type referred to as “connections”. A connection is a design feature that can refer to either a bend or a welded seam. From a design perspective, the automatic determination of seams and bend lines, based on a three dimensional functional model, creates a greater degree of freedom by allowing the designer to focus on the functional optimisation of a part, rather than on the manufacturability aspects.

5.2 Feasibility Analysis and Part Layout Optimisation

De Vries [36] suggested a list of criteria to evaluate the feasibility of a design, based on the topology of the different types of connections, and to optimise the choice of bend and weld lines. In this context Shpitalni [37] presented a modelling system for the conceptual design of sheet metal parts based on a sketching interface. A sketched view of the part is interpreted to reconstruct the 3D geometry, followed by a detailed analysis of the connections between faces to define the required seam welds. Where necessary, a design is automatically split into multiple parts.

An evaluation and optimisation system based on different optimisation criteria was developed by Duflou [38] and provides optimised blank layouts that are conform to the layouts generated by expert process planners. Minimizing the contour length of the blank proved to be a dominant optimisation criterion. Note that this corresponds to maximizing the total bend length and thus minimizing the possible seam welding effort.

5.3 Model Representation

Typical for sheet metal parts is the nearly uniform and limited thickness of the composing features. Since a prescribed sheet thickness exceeding 3 mm is rather uncommon in many industrial sectors, a number of authors propose model representation schemes in which this dimension is ignored [32, 39, 40, 41, 42, 43]. Compared to the original volumetric models, the data size of these so-called foil models is only about 20 % of the original model [39], while all relevant information can be preserved in the form of attributes that allow to reconstruct the original volume model. As a result of this increased information density, calculation times for process planning sub-tasks can be expected to be reduced with a factor of approximately 100 [39].

Geißler [40] described a foil model with extended flanges: bend features are replaced by straight edges that coincide with the intersection line of the corresponding bend flanges (Fig. 8C and 9A). Shpitalni [42] reported a foil model in which the nominal dimensions of the bent part and the unfolded pattern are identical: the part is assumed to be formed with a bend radius equal to 0, so that bend allowances can be ignored and the axis of rotation coincides with the bend edge.

Inui [41] described a foil model with additional bend axes: these line segments coincide with the axis of rotation that allows transforming the part from an unfolded to a bent state by means of a single rotation. The determination of the location of the bend axes is based on the knowledge of the respective bend allowances or, equivalent to this, the location of a neutral fibre per bend (R_n in Fig 9B).

Duflou [43] enhanced this model with a flange extension (ΔL) equivalent to half the circumference of the cylindrical bend zone. In this way an unfolded blank can be considered as composed of foil flanges with the bend lines as common edges. After forming these flanges are located in the mid planes of the volumetric model of the part, while the bend zones are more accurately approximated in function of e.g. collision detection (cf. deviation d in Fig 9A and B).

5.4 Part Classification

The enormous variety of possible topological configurations, that are a consequence of the flexibility of sheet metal contouring and forming processes, makes the introduction of an unambiguous classification system for sheet metal parts a hard undertaking. The limited applicability of variant process planning strategies (cf. Section 6) for bending processes also does not support the introduction of a group technology database. Nevertheless, an evaluation of the major topological characteristics of a part can provide a useful indication for the preselection of tools and/or applicable heuristic rules for bend sequencing purposes. Efforts to automatically recognize similarities between sheet metal parts are reported by Cser [44], Geiger [45, 46, 47] and Greska [48]. The applied methods are adjusted to the fuzziness of the part categories that can be distinguished. A label such as “box type”, for example, could cover a range of parts with different numbers of bends, bend angles, and overall scale, but has a meaning that refers to some, hard to quantify, common characteristics among all those parts. A possible definition of a “box” could be: a part containing “one face that is surrounded almost completely by bending edges, with wings that have the same orientation and angles of approximately 90º” [44].

A number of artificial intelligence methods are called upon to identify parts that fit into these vague categories. Part descriptions by means of semantic networks allow to formalize attributes of part features and the relationships that exist between them [44, 49]. Fuzzy sets are used to quantify the semantic variables that need to be evaluated to identify the possible membership of a part category. While angles of 90º would completely match the example category description given above, the occurrence of an angle of, for example, 80 or 100º should not necessarily exclude the part from the box category, but rather decrease the recognized resemblance with this class. Fuzzy logic is applied for the recognition of 2D contour characteristics as well as typical 3D configurations [50, 51].

Once the similarity between parts can be quantified, re-use of the knowledge available for certain categories of parts is aimed for. Neural networks were found to be a valuable tool in this context [44]. Geiger [52] and Hoffmann [53] report the use of a neural network for the selection and ranking of relevant heuristic process planning rules for given part specifications. The effectiveness of these neural networks depends, to a large extent, on the number and the diversity of the parts and the quality of the output variables used for training the network.

6 Bend Sequencing

A crucial problem to be solved when generating a process plan for a bent sheet metal part is the identification of the suitable sequences to perform the different bend operations. The bending operations should be sequenced so as to avoid part-tool, part-machine and part-part collisions. Although bending operations are local, they often result in global changes in the geometry of the part. Hence, all of their effects can hardly be specified in advance. Process planning, and sequencing especially, is very sensitive even to small, local variations of the part geometry. Producing similar parts may require completely different bending sequences. This is the reason why the so-called variant method can barely be applied as a CAPP strategy for sheet metal bending.

A number of hard reject criteria for the evaluation of bend sequences can be formulated. These criteria can be related to the unavailability of proper gauging edges for part positioning, the detection of a collision during a bend simulation, or the expected non-compliance of the part dimensions with the specified tolerances. Some research contributions dedicated to collision detection and tolerance verification are summarized in Sections 7 and 8.

Other criteria for the evaluation of the quality of a proposed bend sequence are the required effort for the machine set-up and the workload due to manipulation requirements in between and during consecutive bend operations. An overview of the publications dedicated to these topics is offered in Sections 9 and 10.

Due to the combinatorial nature of the problem and the computational complexity of detailed sequence evaluations, a number of researchers have opted for rule-based methods to identify interesting potential solutions. De Vin suggests a number of such rules [4, 54]. Examples are as follows:

- *“Shape determining bends should be performed after other bends.”*
- *“Faces connected to the part with a single bend can be bent in an early stage.”*
- *“Workpiece rotations along two axes must be avoided between consecutive bends.”*
- *“Combinable bends are preferably bent in a single operation.”*

- *“After a bend operation has been completed, proceed with the nearest parallel bend to the same side of the central face.”*
- *“The major part of a component should be situated to the operator’s side of the press brake.”*

In the approach chosen by De Vin [4], the solution space is limited by incorporating systematic tolerance verification in the search procedure. Collision detection is postponed until a sequence has been identified. No backtracking mechanism is reported: for identified collisions better adjusted tool selection is suggested as a possible way out.

Geiger [55] describes a more formal system in which information derived from production rules is mapped to a directed graph: bends are represented as nodes and the relationship between individual bends is mapped to corresponding arcs. The arcs allow to represent precedence preferences per pair of bends. Weight factors can be determined for each arc by means of the classification method and the neural network system referred to in Section 5. The rule-based precedences can lead to conflicting constraints that need to be eliminated in the inference module. For this purpose groups of nodes with conflicting relationships between them are isolated and split into smaller clusters by eliminating some of the arcs with lower weight factors. This procedure is repeated until all loops are eliminated from the graph, after which one or more sequences can be identified that comply with the remaining constraints.

Duflou [43, 56, 57] explored a similar scheme, but concluded that for more complex parts this approach is not well suited to support optimisation. Since bend sequences are not systematically constructed according to a folding or unfolding strategy, collision verification cannot be integrated in the search procedure, which prevents efficient backtracking.

Shpitalni [58] developed a heuristic search method. The bending operations are represented in a tree: every node of the tree refers to an intermediate state of the part, while the leaves correspond to the completely unfolded sheet as obtained by different sequences. The proposed solution procedure starts at the root of the tree (the completely formed part) as a search for a feasible unfolding sequence. The author uses the so-called A* algorithm to limit the number of bend evaluations: the procedure requires every node (i) already taken into consideration to be labelled with a calculated cost (g(i)) and an estimated further cost (h(i)). Here g(i) represents the cost to reach an intermediate state (i) starting from the root node, while h(i) forms an estimate for the cost to reach a completely unfolded state (leaf) starting from the same node. The value of g(i) is calculated as a sum of penalties related to various criteria such as the number of required tool changes, manipulation effort, and stability of the part position for every part set-up. A number of heuristic rules help to estimate the value of h(i).

At each step, the node with the lowest estimated total cost (f(i)=g(i)+h(i)) is selected for further expansion of the tree. In order to limit the search space, collision verification is in principle required before expanding a node. If a sufficiently low value is used for h(i), to assure that the estimated cost does not exceed the calculated cost when an end node is reached, this method will finally lead to the identification of the optimal solution. The breadth first character of this search method, however, results in long calculation times and large memory requirements. The author therefore introduced two measures to indicate a preference for a deepening of the search in an earlier stage.

Firstly the penalty function f(i) was modified by means of a weight factor (w):

$$f(i) = w\,g(i) + (1-w)\,h(i) \qquad \text{for } 0 \le w \le 1 \qquad (6)$$

In a second step the author further reduced penalties on deeper nodes by incorporating the depth of the nodes in the graph (d(i)) into the denominator of the penalty function. Several variants of this modified penalty function $f_x(i)$ were tested:

$$f_x(i) = \frac{w\,g(i) + (1-w)\,h(i)}{d^x(i)} \qquad \text{for } x \in \{1,2\} \qquad (7)$$

Shpitalni [58] reports results for sample parts with up to 16 bends. The obtained costs and calculation times depend heavily on the selected parameters for the penalty function (w and x). Radin [59] tested a two-stage branch-and-bound search algorithm for sequence optimisation based on a similar graph representation scheme. In a first stage an initial solution is identified by means of the A* procedure as described above. A penalty function with weight factor (see Formula 6) is used for this purpose. Recognizing the fact that the applied cost estimates h(i) do not unambiguously represent the potential of partial sequences, the author suggests further optimisation based on the calculated costs g(i) only. In a second stage alternative sequences are therefore compared to the best solution already identified (g_{best} = lowest g(i) for an end node). After the identification of a solution with a calculated lower cost, the value of g_{best} is substituted with the cost g(i) of the new solution. All open nodes with a cost function higher than g_{best} are subsequently eliminated from the search space. The order in which nodes are selected for expansion is still based on the value of the penalty function f(i). Radin reports successful identification of optimal solutions (according to the selected cost calculation method) for parts with up to 10 bends. Tests with a part containing 17 bends allowed to identify feasible solutions, but optimal solutions could not be found within reasonable response time.

A distributed CAPP architecture was proposed by Wang & Bourne [60] and Gupta [61]. Heart of the planner is a sequencing module that, departing from the flat sheet, generates bending sequences incrementally. This central operation planner communicates with modules specialized in tool selection, grasping and motion planning. These modules (1) provide constraints to the central sequencer, (2) augment and evaluate partial solutions, and (3) check the feasibility of final solutions. The sequencer proposes various alternative partial sequences, which are evaluated by each of the specialized modules according to their own cost criteria. Aimed at finding plans of minimal overall cost, an A* search is performed in the central module. Values of the the h(i) cost estimates are provided by the sub-modules.

To reduce the search space – hence, to increase the performance of the planner – hard precedence constraints and soft weighed precedence heuristics are applied directly to some pairs of features [60]. For instance, outside bends should be performed first to avoid “rolling up" the part that would prohibit tool access to outside bend lines. Tall flanges most likely interfere with the press brake; hence the corresponding bends should be postponed as long as possible. The precedence constraints and heuristics add much to the efficiency of the planner provided they are consistent. However, almost each rule has its exceptions. Consequently, the constraints occasionally may interact in a way that makes the plan over-constrained. Such conflicts are resolved manually.

In another extension, results of previously solved subproblems are re-used during the search process whenever possible [62]. The method trades computing time with memory. It is applicable only if the notoriously memory-intensive A* search is used with heuristics that very closely predict the actual costs. In fact, the system works with a heuristic function that sometimes overestimates the cost of the remaining work.

Process planning for a robot-manipulated press brake is presented in [63]. The system detects typical bending patterns, like channels, hats, etc., and generates precedence constraints accordingly. Sequencing decisions are driven by a grasping rule that suggests that bends with the nearest grasping position to the centre of gravity of the sheet should be made first. Having determined the actual grasping position, bendable edges are collected and sequenced. Hence, set-ups are generated first, and bending sequences next in a greedy search process. The total deflection error accumulated in bending is calculated and plans with intolerable accuracy are discarded.

Bend sequences are generated and tools are assigned simultaneously in a planner system that applies genetic algorithms [64]. Before running the genetic search module, a pre-processor looks for bends that can be combined into a single operation. Collision checking is built into the fitness function that accounts also for several operator-related criteria, like processing time, safety, accuracy and risk of the plan.

The conflicting nature of bend and set-up sequencing rules is recognized in a set-up sequencing system that uses fuzzy-set theory [65]. This soft representation method allows capturing practical, well-proven part handling and sequencing rules in a common framework.

Constraint-based approaches have been present in sheet metal bending since the late 1980s [58, 66]. Since these works used special-purpose constraint processing modules added to available CAD/CAPP systems, their experience was mostly limited to specific problems. However, they exposed requirements toward constraint-based methods: (1) the need of working with disjunctive and conditional constraints, (2) coping with constraint sets that may be conflicting, and (3) linking constraint satisfaction with optimisation.

A generic constraint-based model for CAPP and its application in sheet metal bending has been proposed by Márkus and Váncza [67, 68]. The authors argue that the planning problem is more readily tractable as satisfying constraints that represent rules taken from experts. The proposed model captures relevant pieces of domain knowledge - let they be related to part geometry, tolerances, manufacturing processes and resources - in the form of constraints. However, in order to balance the expressiveness of the constraint-based model with the efficiency of constraint satisfaction mechanisms, a free, unlimited variety of constraints is not supported. The model represents predefined tooling, precedence and set-up constraints and provides means for describing conditional as well as hard and soft constraints. Hence, inconsistent pieces of domain knowledge can also be handled. The constraints do not refer to the actual geometric data: they contain just the results of engineering reasoning, inter-mixed with some rules of thumb presented above. Soft constrains are used in two different modes: (1) for evaluating solutions when penalties are summed up for violated soft constraints, and (2) for rejecting partial solutions that do not satisfy various subsets of soft constraints. The planner applies standard constraint satisfaction techniques and a customized branch-and-bound search to find cost-optimal solutions at maximal subsets of satisfied soft constraints. In this way complex CAPP problems could be solved, even in the presence of inconsistent bodies of technological knowledge. However, since no explicit geometric part model was used, the constraints had to be hand-coded and the feasibility of plans could not be guaranteed.

To overcome this difficulty, the system was extended in the bending domain with a geometrical modeller, a constraint generator and plan simulator and analyser [69, 70]. The solution process is based on the communication between a general-purpose constraint solver and the domain-specific geometric expert modules. These modules work on an exact spatial representation of the workpiece, machine and tools: they analyse partial solutions and generate new constraints that the solutions must satisfy. The constraint module solves the dynamically evolving constraint models by combining techniques of constraint propagation, branch-and-bound search and multi-criteria optimisation.

Duflou [43, 57, 71] reformulated the bend sequencing problem as a Travelling Salesman Problem (TSP). The described procedure makes use of geometric hard constraints, based on part details pre-identified by means of fuzzy sets, and a heuristic rule based preference system that incorporates tool set-up considerations and ergonomic criteria. A depth-first branch-and-bound search system is used with a dynamically updated penalty system. The implemented penalty system allows anticipation of hard constraint and heuristic rule violation in an early search stage [71, 72]. This significantly reduces the search space without the elimination of potentially feasible solutions, while efficiently steering the search towards well-optimised solutions. Collision verification is integrated in the search procedure as a backtracking mechanism. The system is robust to the extent that, if a geometrically feasible solution exists for the available tools types, its identification is assured. Large series of parts, with up to 32 bend features, were successfully tested [72]. The computational complexity for the complete procedure, including collision verification and backtracking, can be estimated according to Formula 8.

$$t \approx a\, n^{1.42} \qquad \text{for} \qquad \text{t: processing time (in seconds)} \qquad (8)$$

n: number of bend lines

$a \approx 1.6$ for implementation on a Pentium II, 300 MHz
running Windows 98 with 128 MB RAM

7 Collision Detection

Collision detection has been a much investigated research area in recent years due to the demand from robot control applications as one of the major thriving forces. A review of a selection of publications [73, 74, 75, 76, 77, 78, 79, 80] allows to distinguish three categories of generic algorithms.

A first group contains contributions to interference checking in situations where a number of randomly oriented convex polyhedra (or parts that can be decomposed to the union of a number of such polyhedra) need to be verified for possible collision. Interference can be detected based on distance calculation or linear programming solution methods. Where multiple moving objects need to be described, time dependent verification is introduced. A second group of collision detection methods uses a space occupancy approach. In these methods the workspace is divided in elementary volumes (voxels). For every voxel the occupancy by both, possibly colliding bodies is verified. A third category of algorithms, specifically intended for moving objects, is based on sweep volume calculation. Although the generic algorithms of these three categories are, in principle, applicable for the purpose of collision checking in the context of sheet metal bending operations, they do not make use of the specific geometrical characteristics of the (air-) bending process.

A few researchers dedicated their efforts to develop fast verification tools that could be integrated into a process planning environment for sheet metal bending. Franke [81] reported a simplified sweep volume collision verification method for bending operations. The algorithm is based on the projection of the sweep volumes, covered during the bend cycle, on the XY-plane of the machine co-ordinate system (Fig. 10 A). The system traces intersections of the projected tool contours and the edges of the projected sweep volume. Without additional refinement, the described procedure is suitable for the verification of 2D profiles (no bend angle constraints) and 3D parts containing 90º bend angles and bend lines in two orthogonal directions only.

A variant of this sweep volume approach was worked out by Decubber [82]. Rather than generating the sweep volume, covered by the workpiece as a result of the ram displacement, the author opted for the generation of four equivalent volumes corresponding to fictive punch and die rotations. Fig. 10 B shows an example of the projected, swept tool volumes for a straight punch.

The applicability of the algorithms is limited to the same type of workpieces as can be handled by the method described by Franke. Only intersections between the workpiece and tools can be verified.

Duflou [43, 83] described a full 3D collision verification procedure based on a three-step algorithm (Fig. 11). The proposed approach allows tool-flange, machine-flange as well as flange-flange interference detection. For this purpose machine components are modelled as convex prismatic volumes, while tools can be represented as extrusions of convex or concave polygons or intersections of such extrusions. The part is represented as a number of foil flanges, with a contour specification that allows to represent both external and internal flange edges. For tool-flange and machine-flange combinations a quick mini-max test allows elimination of most pairs, while a half-plane test forms a second filter that further reduces the number of 3D planar polygons withheld for detailed interference verification. For flange-flange interference checking, the procedure contains an additional, preliminary step during which all flanges are allocated to two groups, geometrically separated by the bend line corresponding to the bend operation under evaluation. The flanges of both groups are normally located in different half-spaces, defined by the vertical plane through the punch tool tip. Only flanges (partially) situated in the half space corresponding to the other group should be verified for possible interference with the members of the other group.

Due to the cascade architecture of the proposed procedure, the number of computationally expensive polygon intersection tests is significantly reduced. (Fig. 11 B). The collision test is executed for a preset number of intermediate steps, corresponding to the consecutive stages of the bend stroke.

8 Tolerance Verification

Another major rejection criterion for sequence evaluation is the compliance with tolerance specifications. In cases where sheet metal components were designed as part of an assembly, or whenever individual parts need to undergo further location specific operations, such as e.g. seam welding, tolerance problems can indeed form a justified reason for part rejection.

Traditionally, bending is known as a rather inaccurate manufacturing process. The difficulty to guarantee dimensional accuracy of parts undergoing bending operations has, to some extent, found a solution in the partial reversal of the process chain: performing the cutting operations after the forming process allows to reduce some of the tolerances to the positioning and cutting precision of better controllable operations, such as, for example, laser cutting. If this is not an option, proper process control and identification of an appropriate bend sequence are imperative for compliance with tightly toleranced dimensions. It is obvious that, whenever tolerances are used as a hard reject criterion, only a limited number of part dimensions can be tightly toleranced, in order not to eliminate all bend sequences from the solution space.

In practice the flexible nature of sheet metal parts in directions orthogonal to the bend lines often eases dimensional tolerance constraints. Proper jig design for welding set-ups, for example, can allow to anticipate problems related to the inaccuracy of the air bending process. In consequence, the tolerancing practice for sheet metal parts is often an indication of critical dimensions rather than a specification of rigid tolerances. Indeed, a lack of tolerance standards that take the flexible nature of thin sheet metal parts into account obstructs the integration of tolerance considerations as a strict reject criterion into process planning.

An overview of factors influencing the accuracy of the output of a bend operation is given in reference [4, 84]:

- Process related errors on bend angles: due to the difference between the calculated and the correct punch displacements.
- Process related errors on the length of bend legs: due to deviations between the calculated bend allowances and the real sheet deformation.
- Positioning errors: due to inaccurate gauging, or, in the case of robot manipulation of the part, due to inaccurate consecutive regripping actions.

In order to be able to verify the expected part precision for a given bend sequence, experimental data need to be available to estimate the influence of each of these factors.

Inui [41] reports a geometric simulation technique that allows to verify single bend operations: combinations of minimum and maximum values of three parameters, related to positioning and process accuracy, are used to define 2^3 different transformation matrices for each bend operation. Toleranced dimensions are verified after bend simulations with each of these transformation matrices. If any of these tests leads to dimensions exceeding the allowed tolerance range, the sequence under consideration is rejected.

De Vin [4, 85, 86, 87] uses a conservative approach in which the errors induced in consecutive bend operations are accumulated. Using a tolerance tree, the influence of every bend operation on each of the toleranced dimensions is traced. Starting from the allowed tolerance range, deduction of the accumulated errors allows to verify whether a partial sequence still allows compliance with all tolerance requirements (Fig. 12). De Vin's worst-case scenario is likely to lead to unsolvable sequencing problems in cases where tight tolerance requirements are imposed.

Recognizing the non-deterministic nature of the different types of process errors, Hagenah [88, 89] tested a Monte Carlo simulation method to predict the percentage of rejected parts for known statistical distributions of the different error components. The method requires a large number of statistical data to be available and is, due to its calculation intensive approach, intended for an a posteriori verification rather than as a search support tool. Both methods described above were worked out for dimensional tolerances specified in typical 2D sections.

Since gauging of the workpiece against programmable finger stops by a robot system is known to be less accurate than by a human operator, accuracy issues, and especially positioning errors, require special attention when dealing with robot manipulation of sheet metal parts. A deterministic approach, similar to the method proposed by de Vin, was used by Aomura in a process planning system for robot supported bending [63]. The developed system allows to calculate accumulated set-up positioning errors which can then be compared to predefined tolerances.

9 Tool Selection and Rapid Tooling

9.1 Tool Selection and Verification

For typical cold-formed profiles, the aim of the tool selection phase is to identify a single punch and die combination that allows to perform all required operations in a bend sequence on a single machine set-up. While for simple, box-like parts the Vernier punch and die set suggested by Sturges [90] may form a flexible solution, for generic, 3D parts multiple tool stations are often required. These tool stations need to be tailored to the specific constraints imposed by the part geometry in combination with the chosen bend sequence. Selecting a tool station combination that minimizes the total operator effort during tool set-up and the actual bending phase forms an objective for the process planner.

Franke [81] reported an effort to define appropriate data structures for the description of both “single tools” and tools composed of multiple components (adapter, shaft and forming zone elements). The author also describes a fuzzy logic method for the pre-selection of tools based on prescribed bend radii and angles, while taking tolerance specifications into account. From the tool database the die-width, die-radius and allowed immersion depth, as well as the punch angle and radius are used as input parameters to define an “appropriateness value” per tool pair and per bend operation. This value is used to systematically select the most suitable pair, or combination of multiple tool pairs, according to a list of criteria:

- same punch height for all tool sets;
- same die height for all tool sets;
- if possible only one bending technique;
- if possible only one die type for all operations;
- as few different types of punches as possible;
- as few reversed tools as possible.

Tool selection and bend sequencing are strongly interrelated aspects of planning. So as to generate a feasible process plan, the approach reported by Duflou [91, 92] uses a two-phase procedure for automated and optimised tool selection. In the first phase, tools are pre-selected based on hard constraints derived from the technological and geometric characteristics of the envisaged design. The resulting tool sets are optimised by a Set Covering Problem formulation in order to provide a compact input for the bend sequencing step. In the second phase, the initial tool selection can be modified based on the encountered collisions during the bend sequencing search [57, 71]. The proposed system is able to specify tools that result in the identification of feasible bend sequences for complex, full 3D parts. A considerable performance improvement of the integrated tool selection and bend sequencing module has been recorded compared to bend sequencing with an open tool choice.

In order to prevent the need for a large number of punch and die sets to produce a specified part, appropriate selection of tool lengths can allow the use of a single tool set for multiple bend operations. Hoffmann [93] and Franke [81] described a systematic approach for tool length optimisation. For each bend operation a minimum and a maximum allowed tool length and the corresponding position of the tool relative to the workpiece are defined on the basis of a collision verification procedure (Fig. 13).

When an overlap exists between the allowed length ranges for two tool sets, a tool length interval can be identified that complies with all constraints. This procedure can be repeated for additional bend operations to further reduce the number of required tool stations. After the number of tool sets and the respective tool lengths have been defined, combinations of tool segments that can be used for the actual hardware set-up are selected as a last step in the tool planning procedure.

From a production planning perspective consecutive jobs cannot be considered as stand alone problems in this context.

As an extension of their distributed planner, Gupta & Bourne [94] generated shared set-ups for a set of different parts. The resulting set-ups were given as spatial constraints on the sizes and locations of various tooling stages. The approach helped to optimise the set-up time in batch production.

Collin [95] developed a Travelling Purchaser Problem (TPP) formulation for the global optimisation of a series of tasks allocated to a press brake. Required inputs for this optimisation step are one or more feasible tool sets per task. Identification of an optimal tool station layout on the table of the press brake forms part of the optimisation strategy.

9.2 Rapid Tooling

Where collision verification for a proposed sequence leads to the detection of a geometrical conflict between the workpiece and the tools, an adjusted tool set can be identified, rather than starting a new search for a collision free sequence. Recent industrial developments resulted in practical clamping systems that allow fast set-up of standard tools [96], design methods for the automatic generation of new tool specifications [97], and methods for the rapid fabrication of such tools [97, 98]. These design and rapid manufacturing methods are based on the identification of a tool section that does not lead to tool-workpiece interference for a given bend sequence, and can resist the load required for the forming process. The tool geometry identification can either be an interactive process, or it can be automated by means of a geometric reasoning algorithm or a neural network, as described in [97]. For a given bending sequence, Alva [99] determines the optimal shape of a tool by applying geometric constraint processing. The approach is restricted to the parametric model of a gooseneck punch as well as to 2.5D (so-called sash type) parts.

When an appropriate geometry has been identified, elementary tool segments can be cut by means of typical sheet metal processes, such as punching or laser cutting. The resulting lamellas can be joined by laser welding, gluing or clamping. According to Franke the described methods allow manufacturers to produce tailored tools with a precision of 0.02mm [98].

10 Ergonomic Aspects of Sheet Metal Bending

10.1 Operator Workload Evaluation

Most authors focusing on bend sequencing refer to the manipulation effort for the positioning of workpieces between consecutive bend operations as a relevant evaluation criterion [39, 41, 54, 58, 59, 71, 100, 101]. Different strategies are applied to integrate human factors into the solution procedures.

Inui [41] uses the number of orientation changes of the workpiece during the execution of a bend sequence as an indicator for the handling workload.

De Vin [54] suggests the use of a heuristic rule that discourages consecutive part set-ups, which require a “combined rotation” of the workpiece: accordingly, he penalizes part manipulations involving rotations around more than one axis of the machine co-ordinate system. No distinction is made between rotations around the different axes.

In penalty based evaluation systems, ergonomically disadvantageous manipulations can be avoided by assuring that the accumulated penalty reflects the occurrence of such handling requirements. In this context a number of approximative methods for the quantification of the manipulation efforts have been described.

Shpitalni [58] suggests the use of fixed penalties for rotations around the X-, Y- and Z-axis of the machine co-ordinate system. An experienced process planner defines the appropriate penalty values per workpiece, corresponding to the perceived degree of difficulty for each of the three types of main rotations. This approach has already been applied in commercial software solutions for quite some time [102]. Some systems also allow to specify a fixed penalty for part set-ups, which result in an additional load on the operator due to a disadvantageous weight distribution, e.g., set-ups that require the operator to execute a downward force to stabilize the part are penalized. A maximum allowed downward force can also be set as a rejection criterion for the bend sequence evaluation. A number of other penalty values, which can be specified per workpiece, are related to gauging conditions and simultaneously cover ergonomic and accuracy related considerations.

A combined penalty system was proposed by Radin [59]: five attributes, reflecting different aspects of the workpiece manipulation and the stability of the part during positioning, are distinguished: see Table 1.

A weight factor per attribute (c_i) allows to differentiate the importance of the respective penalty contributions in a combined penalty function (g):

$$g = \frac{c_1 g_H + c_2 g_{tr} + c_3 g_M + c_4 g_0 + c_5 g_n}{\sum c_i} \qquad (9)$$

For a detailed ergonomic evaluation of a proposed process plan, the mass properties of the workpiece to be manipulated play an important role. However, between different parts or consecutive set-ups of a single workpiece, the mass, the location of the point of gravity and the momentum of inertia around the axis of rotation can differ considerably. Duflou [101] developed a fast calculation method to determine the momentary mass properties for consecutive steps in a bend sequence. The method uses equivalent masses, calculated in a pre-processing step based on a triangulation of the workpiece flanges and allocated to the vertices defining the respective flanges in a foil model representation (Fig. 14).

Since the total mass of the workpiece is invariant, it can be calculated in the pre-processing phase. The complexity of this calculation is linearly related to the number of vertices defining the flange contours. Per bend set-up the other mass properties can be determined at low computational costs. The complexity of the required calculation is of an order:

$$\text{for point of gravity location } x_g, y_g, z_g \quad \rightarrow \quad O\left(n_f + \sum_{i=1}^{n_f} n_{ci}\right) \qquad (10)$$

$$\text{for moment of inertia } j_{nn} \quad \rightarrow \quad O\left(n_f + \sum_{i=1}^{n_f}\left(n_i + n_{ci} + \sum_{j=1}^{n_{ci}} n_{ij}\right)\right) \qquad (11)$$

for n_f : number of flanges

n_i : number of vertices defining the external contour of flange i

n_{ci} : number of internal contours in flange i

n_{ij} : number of vertices defining internal contour j of flange i

The obtained mass properties can serve as input for a quantification scheme estimating the required time in process [101].

10.2 Robot Supported Workpiece Manipulation

A number of publications reflects considerable interest for the development of robot supported part manipulation systems [63, 103, 104, 105, 106]. The major objective of the reported R&D efforts is to significantly decrease the requirement for continuous human involvement in press brake operations, and to, simultaneously, eliminate ergonomic restrictions.

No clear comparison between the handling capability and the constraints of human operators and robot-supported systems seems to be available for sheet metal part manipulation. Huwiler [100] warns, however, that handling aspects are more decisive for process plan optimisation when robot manipulators are involved: long transport distances, re-gripping and certain turning operations need to be avoided.

A typical problem related to the use of robot manipulators is the identification of appropriate gripping locations. Reference [104] contains a research contribution by Geiger and Vormann dedicated to this subject.

11 Conclusions

As can be concluded from this literature review, the variety of tasks, involved in process planning for sheet metal bending, spans a rather broad and diverse research area. Significant contributions to the solution of a number of specific sheet metal bending related problems have been reported over the last decade. Bend modelling and, complementary to this, the (in-process) measurement of material properties and adaptive control strategies received wide attention from both academic and industrial side. Bend sequencing has been intensively investigated in recent years. Some automatic sequence generators, capable of handling parts with a high complexity, have been reported. Although some of the underlying research projects are still ongoing, the reported results are already indicating a mature state of development in the covered sub-domains. The results of these research efforts are becoming visible in a number of commercially available software solutions. Some of these packages come close to the objective of a fully automated process planning system for bent sheet metal parts. However, the complete integration of statistical tolerance compliance verification and optimised automatic tool selection, with proper attention for production planning considerations, remain challenges for the future.

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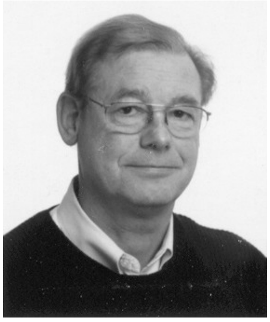
13 Vitae

Dr. Joost Duflou holds master degrees in Architectural Engineering and in Electro-mechanical Engineering. He obtained a PhD in Engineering from K.U.Leuven (Belgium). His principal research activities are situated in the field of design support and automatic process planning methods, specifically oriented towards sheet metal working processes. Since 1999 he is chairholder of the industry sponsored Chair of Sheet Metal Working at the K.U.Leuven, where he also coordinates the Product and Production Management field of study of the Masters in Industrial Management postgraduate program. He is a corresponding member of CIRP.

Dr. József Váncza has been affiliated with the Computer and Automation Research Institute of the Hungarian Academy of Sciences for twenty years. His research centered around artificial intelligence methods – specifically, knowledge-based reasoning, planning methods, constraint programming, evolutionary algorithms, multi-agent technology – and their applications in manufacturing engineering and production management. His current interest is in constraint-based CAPP and scheduling. Dr. Váncza has been lecturing in the above topics for a decade at the Budapest University of Technology and Economics where recently he has been appointed as associate professor. He is corresponding member of CIRP.



Richard Aerens obtained the degree of Technical Engineer in Mechanical Constructions from the Institut Supérieur de l’Etat in Brussels in 1970. After his military service as reserve officer, he joined the Research Centre of the Belgian Metalworking Industry (WTCM-CRIF) as research engineer. From 1972 to 1983 he performed research in the field of grinding (process mechanisms, chatter vibrations, adaptive control). He spent then 2 years on research in robotic industrial applications. From 1985 to 1993 he was Technical Adviser CAD-CAM (general purposes and freeform surface modelling). Since 1993 up to present, he is performing research in the field of CNC-controlled sheet metal working processes (punching and bending).

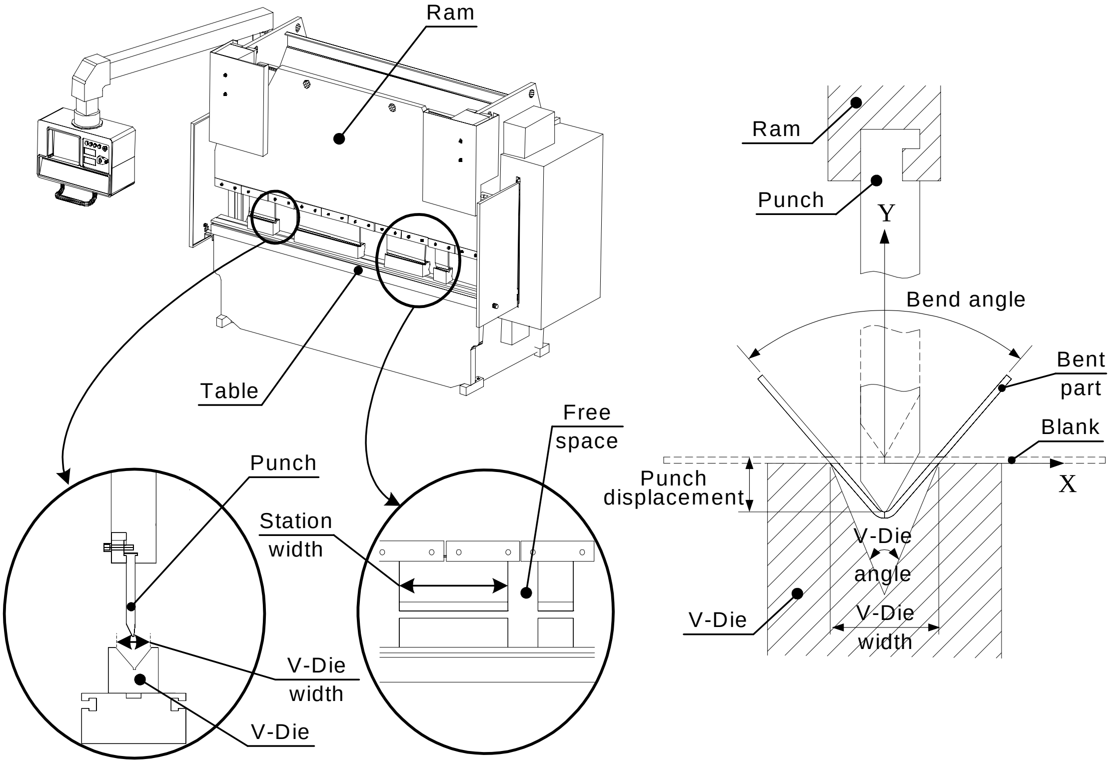


Figure 1: The bending process and its resources.

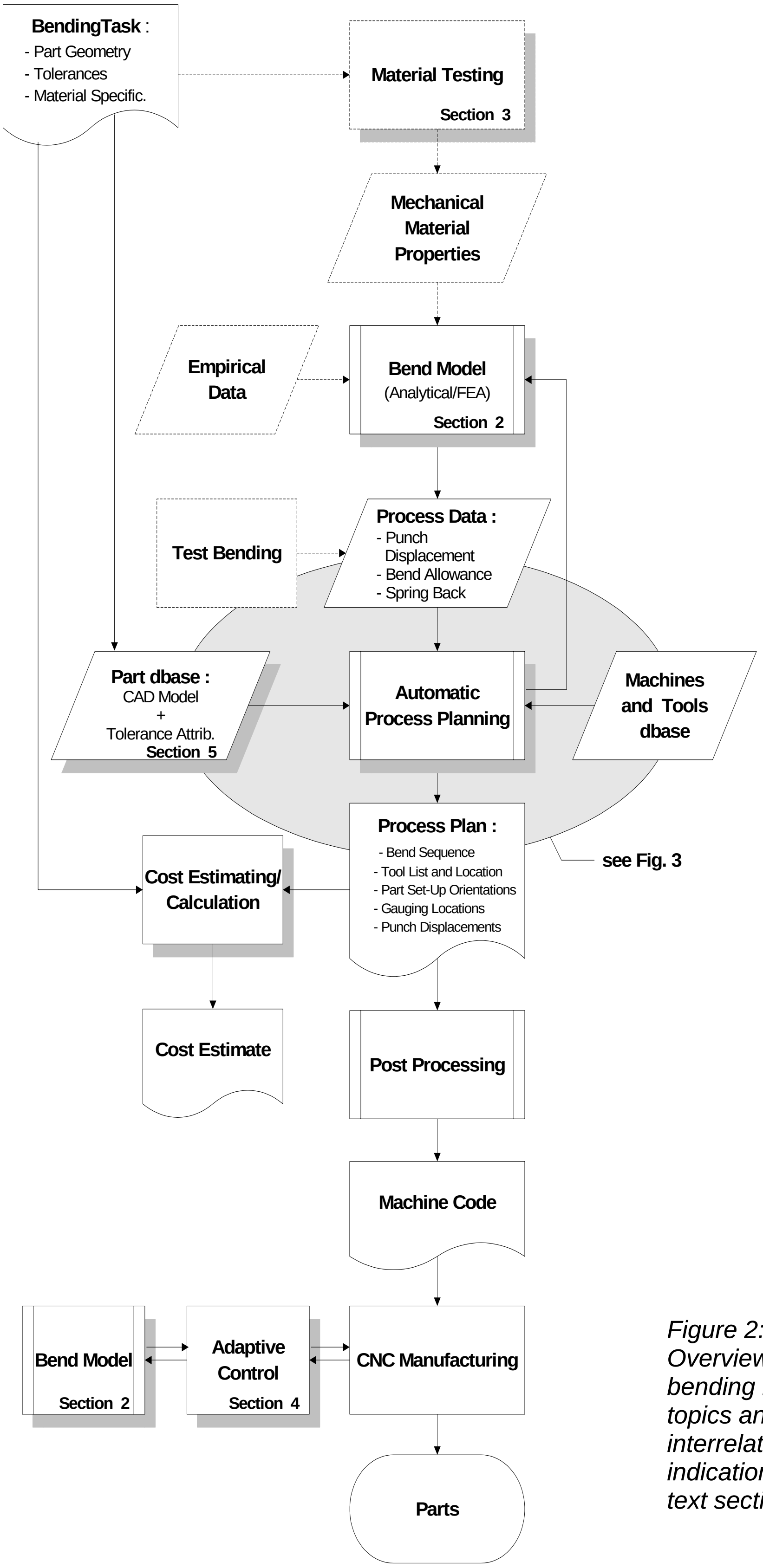


Figure 2:
Overview of sheet metal bending related research topics and their interrelationship, with indication of the corresponding text section numbers

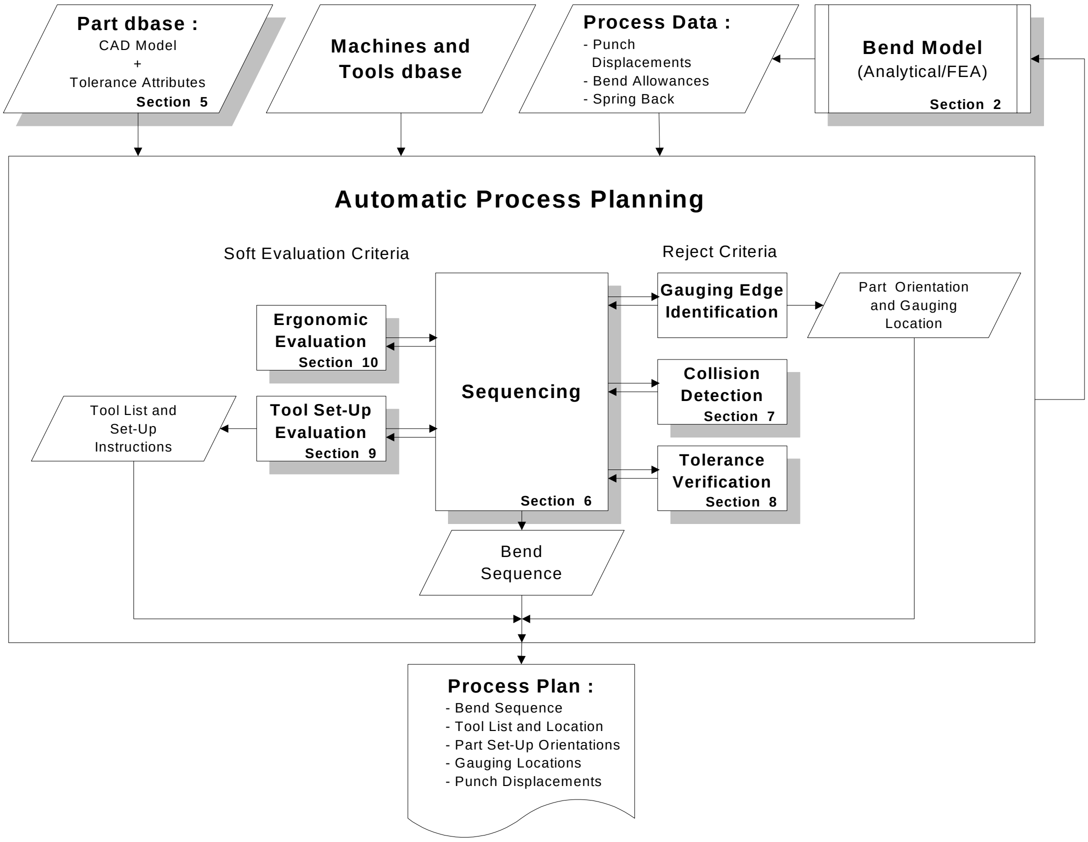


Figure 3: Overview of research topics related to automatic process planning for bending and their interrelationships, with indication of the corresponding section numbers

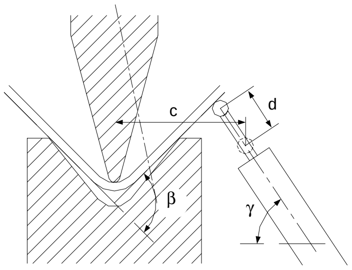


Figure 4:
Indirect angle measurement by means of a contact sensor

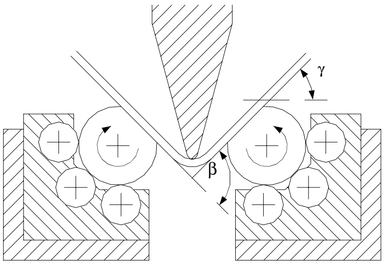


Figure 5:
Angle measurement by means of shaft encoders

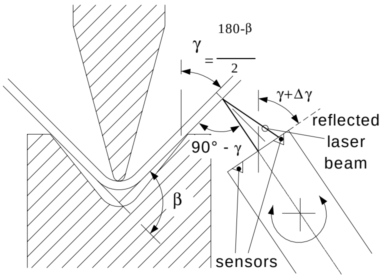


Figure 6:
Non-contact angle measurement by means of a reflected laser
beam

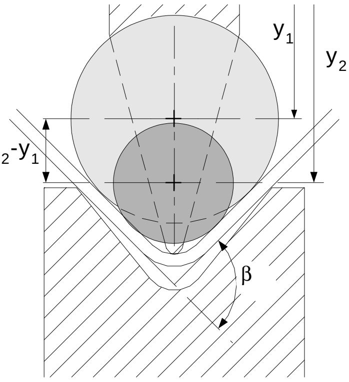


Figure 7: Indirect angle measurement based on four contact points

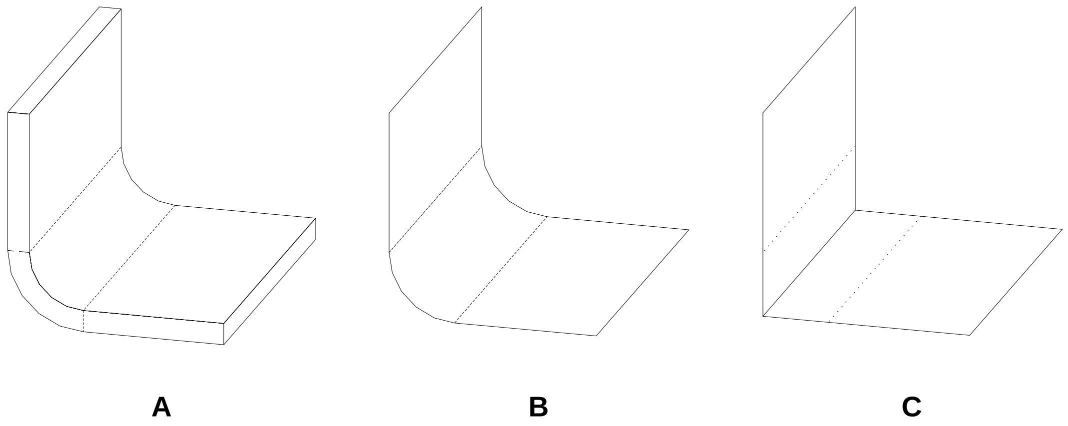


Figure 8: Volumetric model (A), foil model (B) and foil model with extended flanges (C)

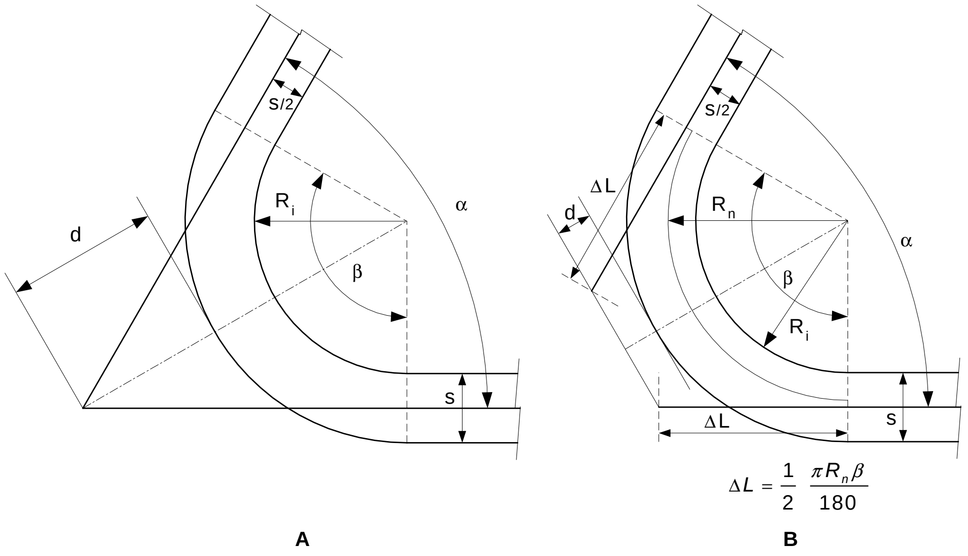


Figure 9: Foil models with flange extension:
A: Model with fully extended flanges according to Geißler [40]
B: Model with limited flange extension according to Duflou [43]

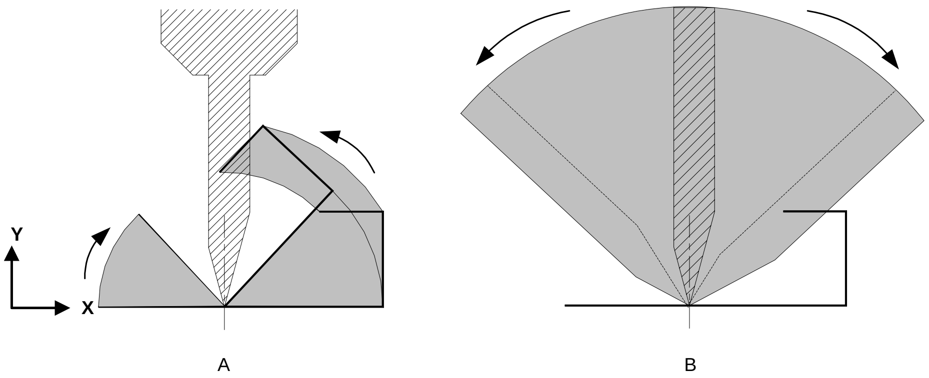


Figure 10: Sweep volume collision detection between punch and workpiece by means of
A: projected swept workpiece volumes [81]
B: projected swept tool volumes [82]

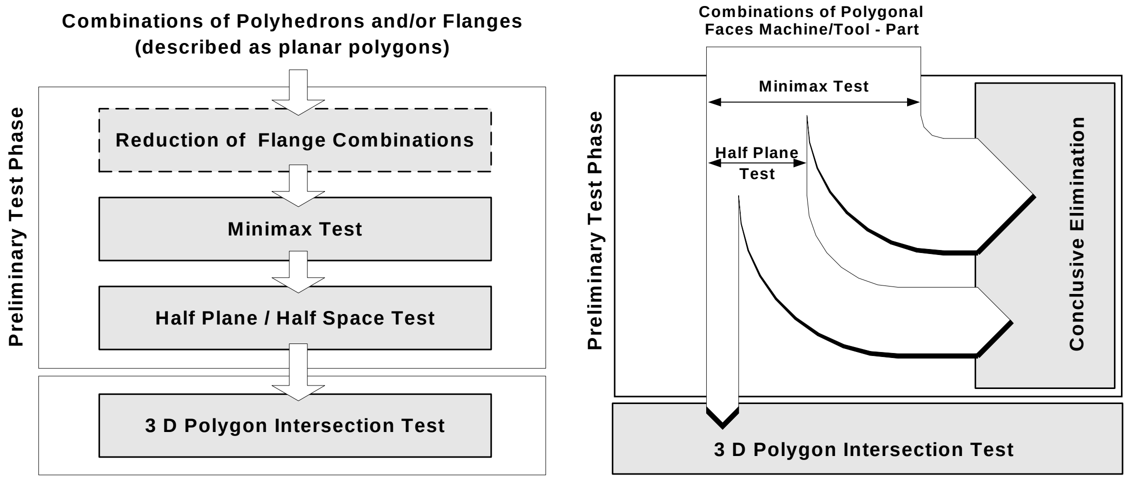


Figure 11: *Cascade architecture of the collision verification algorithm proposed by Duflou [83] (A) and resulting reduction of the number of planar polygonal combinations in consecutive procedure steps (B)*

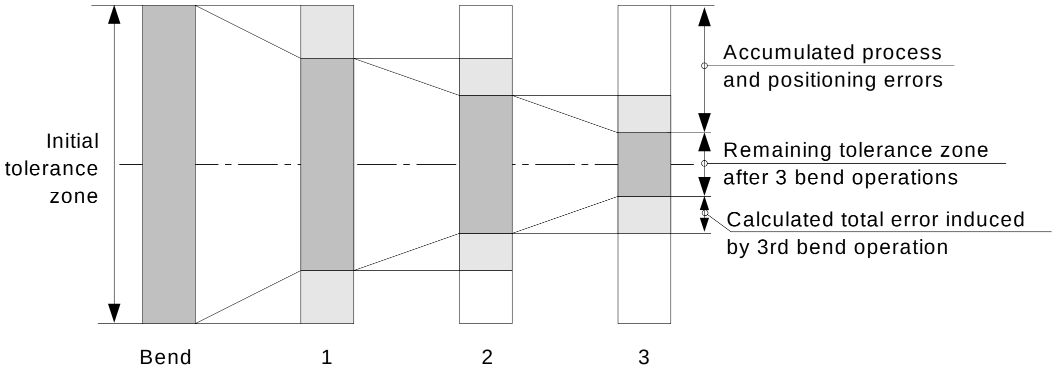


Figure 12: Stepwise reduction of the tolerance zone due to consecutive bend operations according to de Vin [4]

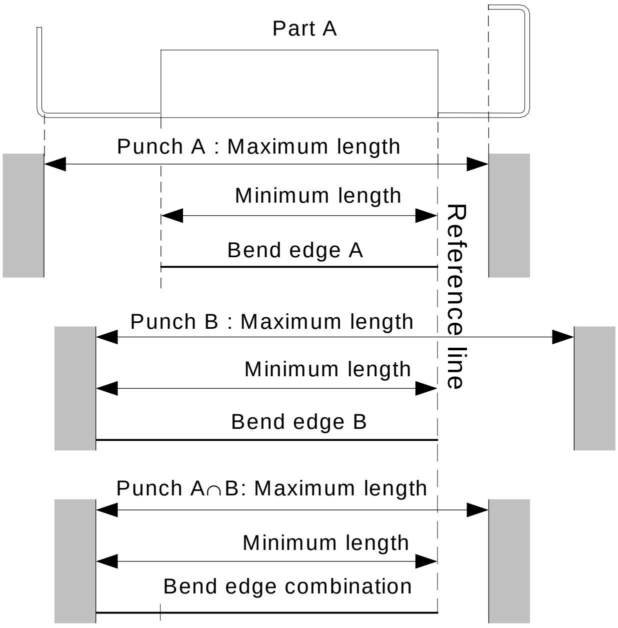


Figure 13: Tool optimisation through the identification of a punch tool suitable for multiple, constrained bend operations according to Franke [81]

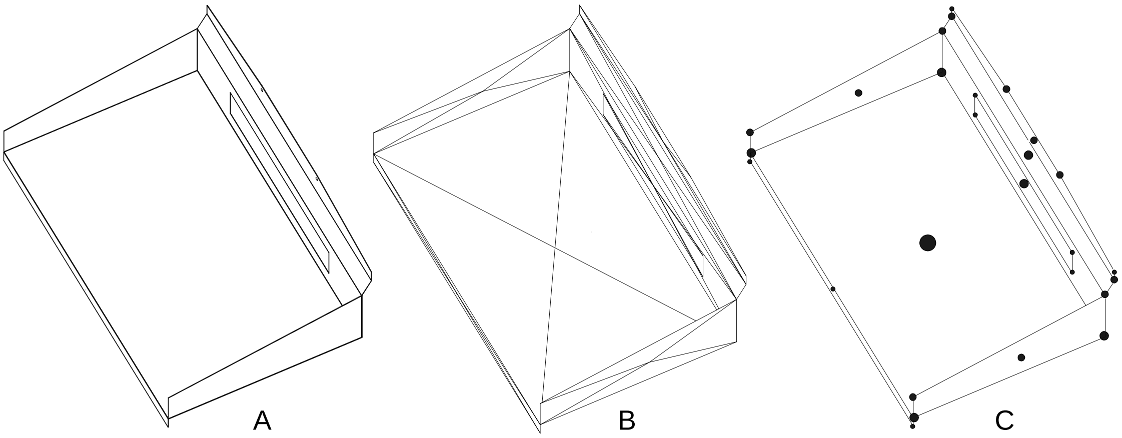


Figure 14: *Consecutive steps in the solid model approximation in function of mass property determination according to Duflou [43, 101]*
A. Reduction to a foil model
B. Triangulation of the flanges
C. Equivalent mass allocation

Attrib.	Definition
g_H	= 0 for centre of gravity to the machine front = 1 for centre of gravity to the machine back
g_{tr}	distance between the centres of two successive bends
g_M	= 1 for sequential bends with different angle signs = 0 for sequential bends with equal angle signs
g_0	= 1 for direction vector (prev. bend) · direction vector (current bend) ≥ 0 = 0 for direction vector (prev. bend) · direction vector (current bend)< 0
g_n	f (normal vector (prev. bend) x normal vector(current bend))

Table 1: Penalty attributes for part handling according to Radin [59]