Geometrical tolerance transfer for sheet metal forming processes

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Geometric Tolerance Transfer for Sheet Metal Forming Processes

PhD Thesis

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Abstract

As an essential link between sheet metal design and manufacturing, process planning generates a sequenced set of instructions to manufacture parts. However, according to a literature survey in this thesis, the tolerance transfer issue in sheet metal forming are insufficiently addressed: machining errors and their causes are not presented comprehensively as the sources of final error; only size dimensional tolerances are discussed in detail; computer aided tolerancing for parts formed by a combination of operations such as bending, punching, and blanking, is seldom studied; statistical tolerancing are utilized only for sheet metal assembly issues or size dimensional tolerances, not geometric tolerances.

Therefore, the presented research systematically explores and proposes three dimensional geometrical tolerance transfer approaches for sheet metal part forming. The here proposed models are suitable for worse case or statistical analysis (using the Monte-Carlo methods). First, an integrated CAD/CAPP system based on feature evolvment, associative features, and data association mechanism, is outlined. Then, a mathematical model of geometric tolerance transfer is proposed. Finally, a machining error-correlated cost model is presented and applied to tolerance synthesis for a parallelism tolerance. Angular errors in the estimation of spring back are demonstrated to affect final errors considerably.

The proposed tolerance transfer method is applied to parts formed by bending (parallel and non-parallel) and punching operations jointly. It can, subject to minor modifications, be easily applied to all bending-like and cutting operations and extended to other sheet metal forming operations. Monte-Carlo simulations show that accumulated tolerances may not closely follow a normal distribution. The research work is a solid basis for future work in this area.

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Publications

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Chapter 1

Introduction

1.1 Motivation

Computer Aided Process Planning (CAPP) forms an essential link between Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM). CAPP is the function within a manufacturing facility that establishes the processes and process parameters to be used along with the machines performing those processes [Kang and Park (2002)]. The output of CAPP is a process plan that describes how to convert raw materials from their initial form to the form specified in a detailed (engineering) design.

Process planning is a complex task because it covers aspects of both design and production. A CAPP system has to obtain and synthesize various process information such as geometry and tolerances, material properties of the component, manufacturing processes and tools, holding devices, operation sequencing, and production costs. Then, based on these, it has to create a technically and economically optimal process plan.

Related to part geometry, features are utilized in CAD/CAPP/CAM to integrated all CAx packages. Feature-based process planning has been popular in academia and industry because features allow to integrate design and manufacturing. However, associative relations among engineering features in different stages of product life-cycle are normally ignored, thus consistency of data association and design changes are difficult to be managed.

As an essential part of design and manufacturing, tolerances should be considered in various stages of a product life-cycle. In the design stage, func-

tionality is important and ideal tolerances are small. In manufacturing and inspection process, however, machinability and testability place constraints on the ideal condition; the low tolerance requirements render the production cost more economical. Therefore production and process planners must respect the capability of the defined manufacturing processes as well as the functionality and/or assemblability constraints while making any decision on tolerances. In terms of tolerancing, the primary purpose of process planning is an optimal sequences of set-ups and operations that satisfy the required tolerance specification.

Commonly, two types of tolerances, parametric and geometrical, are used in engineering. A typical example of parametric tolerances are size (or conventional $\pm$) tolerances. Parametric tolerances may cause confusion in process planning and inspection. In order to avoid possible ambiguity, critical dimensions are specified using geometrical dimensions and tolerances (GD&T). The advantage of GD&T representation is that it captures the design intent and shows the functional requirements of the component as well as the method for its inspection [Chiabert et al. (1998)].

Sheet metal components are widely used for consumer and industrial products, especially in the naval, aerospace, and automotive industry, because of their malleability into complex shapes. A typical part from a printer is shown in figure 1.1, formed by bending and punching.

Most of the previous research in CAPP with respect to sheet metal has been devoted to bending operation, although some research work on other operations such as deep-drawing, blanking, or piercing, was presented recently. Different aspects, including machining times, possible collisions with tools or machines, and set-up design, are considered for searching the most suitable process plan. Although tolerancing is a major constituent of process planning, it does not seem that this function has attracted big interest in past research on sheet metal forming. Lots of efforts have been spent on development and optimization of computer-aided process planning system for sheet metal fabrication manufacturing, but the aspect of tolerancing is generally overlooked. however, a few scientists begin to consider tolerance implications in operation and set-up plans, and three dimensional geometrical tolerances are seldom studied for sheet metal part forming process.

Figure 1.1: A typical sheet metal part

1.2 Objective

The main concern of this research work is to study the influence of geometrical tolerancing on process planning for sheet metal fabrication. The main objectives of this project are:

1. To study how to apply associative feature concept and data association on process planning to set up an integrated CAD/CAPP system based on feature evolvement.
2. To develop a method and present corresponding mathematical models for the analysis and synthesis of geometrical tolerances of sheet metal parts forming process.
3. To investigate the effect of tolerance constraints on operation and set-up planning of sheet metal forming.
4. To demonstrate the above by the means of case studies.

Designers and process planners can utilize the methods and results of this project to lower production costs and to evaluate the functionality of designs

and engineering processes. This is significant for sheet metal fabrication manufacturers, as it allows to improve the efficiency of product development life-cycle and to increase manufacturers' competitiveness.

1.3 Research Scope

The scope of this project encompasses the following areas:

- According to ISO 1101:2002 and ISO/TS 17450-1:2005, geometrical tolerances can be divided into four types: form tolerances, orientation tolerances, location tolerances and run-out tolerances. Apart from position tolerances, *orientation tolerances* are most generally used in sheet metal parts, including *perpendicularity tolerance*, *parallelism tolerance* and *angularity tolerance*. These tolerances are the focus of this project.
- Sheet metal parts can be made by various operations. Common sheet metal fabrication techniques include bending, rolling, drawing, punching, welding, hemming, flanging, folding, shearing, and so on. In this project the *bending* and *punching* operations are focused on as for that they are the most typical operations and tolerance stacks that are limited to the above three tolerances' design requirement.
- Only *design and manufacturing processes for sheet metal components* are considered. Production stages such as assembly and inspection are not taken into account.
- Geometrical features are generally called by their type [ISO 14660-1:1999, ISO/TS 17450-1:2005]. They consist of points, lines, planes, cylinders, and other surfaces. For three dimensional sheet metal parts manufactured by bending and punching, *sets of holes*, *planar or inclined surfaces*, and *bend lines* are the leading forming features [Jagirdar et al. (2001)]. Other kinds of surfaces and non-surfaces entities can be modelled in a similar way as parallel and angular surfaces, and perpendicular surfaces can be connected by holes to form a dimension graph.

1.4 Contributions

The main contributions of this research are:

1. A model of an integrated CAD/CAPP system based on associative feature evolvement. Data association and change management mechanisms are emphasized.
2. A mathematical model of geometrical tolerances transfer for sheet metal forming, especially three-dimensional tolerance transfer.
3. Case studies using worse case study and statistical tolerance accumulation (the later uses a Monte Carlo simulation) with typical sheet metal parts.
4. The application of a Monte-Carlo simulation to geometric tolerance chains is evaluated from a statistical as well as a computational point of view. An algorithm is proposed to analyze whether or not processes or assemblies fulfill 4- or 6-sigma requirements. This algorithm is analyzed for number of simulations necessary to ensure these requirements.
5. A machining error-based cost model is proposed based on cost analysis for single sheet metal forming operation. It is applied on tolerance synthesis by a case.

1.5 Organization of the Thesis

This thesis comprises seven chapters. This chapter is the first chapter for introducing from technological background and motivation, research objectives, to research scopes and significance. The following and second chapter presents a systematic review of the research work relevant to the proposed study. Chapter 3 proposes the integration of CAD and CAPP system based on associative features and feature evolvement processes. The fourth chapter proposes a mathematical model for tolerance analysis for process with two case studies for parallelism tolerance and position tolerance. Chapter 5 investigates statistical issues of tolerance analysis by applying Monte Carlo simulation. The sixth chapter studies tolerance synthesis issues. Chapter 7

summarizes the research, presents conclusions, and gives some suggestion for future work.

The organization of the thesis is shown in figure 1.2 (The content of the chapter of tolerance synthesis will be added later).

Figure 1.2: Organization of the thesis

Chapter 2

Literature Review

Sheet metal forming (SMF) is one of the most common manufacturing methods for metal parts and is used widely in industries [Hosford and Duncan (1999)]. Main differences between sheet metal forming and conventional material removal machining are summarized in table 2.1.

Table 2.1: Comparison of SMF & conventional machining methods
[modified from Han (2001)]

	Sheet Metal Forming	Conventional Material Removal Machining Process
1	The initial work-pieces are blank metal sheets or parts fabricated from a sheet	The initial work-pieces are not metal sheets
2	The initial parts or blanks are cut out to form the required shape from a large sheet metal layout	The initial raw work-piece is normally sawed, preformed or prepared by casting or forging process. They have less precision than sheet metal blanks
3	Process is irreversible. Once formed incorrectly, parts are scraps	Work-piece can be machined again. Only if the machined work-piece is undersize, it becomes scrap
4	Finishing of the work-piece does not depend on the forming process	Finishing of the work-piece largely depends on the final machining operation
5	The deformation usually causes significant changes in shape, but not in cross-section (sheet thickness and surface characteristics) of the sheet	The cross-section in all orientations is potentially changed

The technical-economic advantages of SMF are that it is a highly efficient process and it can produce complex parts with a high degree of dimensional accuracy, good mechanical properties, and good surface finishes. At the same time, its complexity causes some disadvantages. For example, each operation

may cause changes of the overall geometry of a sheet metal part.

Great advances have been made in the field of sheet metal forming. New processes and working methods have been developed and improved continuously by computer tools [Shpitalni and Lipson (2000)]. Many tools for design, process simulation and control are available today [Shpitalni (1993); Makinouchi (1996); Wagener (1997); Lipson and Shpitalni (1998); Tekkaya (2000); Guo et al. (2000); Hsu et al. (2002); Alberti and Fratini (2004); Mackerle (2004); Ahmed et al. (2005); Parente et al. (2006); Wang et al. (2006b); Yamashita et al. (2007)]. Since the 1990s, due to the rapidly diminishing number of experienced process planners for SMF, the requirement of shorter product life cycle, and the importance of 3D CAD/CAM, the research on process planning in this area has gained more attention than ever before. The research areas cover from raw material preparation technologies to process selection, tooling design, operation sequencing, fixture definition, collision detection, and so on [Ramana and Rao (2004); Duffou et al. (2005b)].

Problems related to tolerance emerge in several stages of the life-cycle of a sheet metal part. The problems are characterized by the particular viewpoints and objectives of the individual life-cycle stages. For example, a process planner has to find the most economical processes and their sequence as well as to fulfil the tolerance specification in product design. Tolerance constraints play a significant role in process planning, and computer aided tolerancing is a key technology for determining a machining sequence that results into the best accuracy on some special segments of the part [Zhang et al. (1996); Legoff et al. (1999); Huang et al. (2004)]. However, in sheet metal forming, current approaches of computer aided tolerancing still lack of a clear and comprehensive method to integrate design and process planning. This project attempts to discuss such a model by a graphic approach.

In remainder of this chapter, a survey of sheet metal forming operations is presented at first, in which bending and punching operations are discussed primarily. Then computer aided tolerancing is introduced, followed by theories and applications of Monte Carlo simulation in this field. Finally computer aided process planning (CAPP) in sheet metal forming is presented, especially applications of computer aided tolerancing in this area.

2.1 Sheet Metal Forming Processes

Common sheet metal fabrication techniques include a multitude of different operations. These operations can be classified as in table 2.2.

Table 2.2: Common operations on sheet metal parts

Cutting Operations	Bending-like Operations
Punching, Notching, Shearing, Blanking, Drilling, Piercing, Nibbling, Slitting, Trimming, Shaving	Air Bending, Coining, Bottoming, Hemming, Folding, Flanging
Joining Operations	Forming Operations
Welding, Soldering, Bonding, Riveting, Screwing, Seaming	Drawing, Rolling, Stretching, Spinning, Flattening

Bending and punching are the most popular sheet metal forming processes. Some operations such as folding, flanging, and hemming, can be regarded as bending-like operations because they have similar forming principles. Punching is the most commonly used cutting operation. In this chapter, bending and punching are chosen for case studies and tolerance transfer methods of these case studies can be applied to other bending-like and cutting operations easily.

2.1.1 Bending-like Operations

Bending is a prevalent type of forming operation which provides rigidity and shape to sheet metal parts. In this process, usually a plane sheet or a metal strip is moved around a straight axis lying in the neutral flat. Metal flow takes place in the plastic range of the metal, so that the bent part retains permanently set after removal of the applied stress. The cross section of the bend inward from the neutral plane is in compression, and the rest of the bend is in tension [Schuler GmbH (1998)]. The tensile stress decreases toward the center of the sheet thickness and becomes zero at the neutral axis whereas the compressive stress increases from the neutral axis toward the inside of the bend as shown in Figure 2.1.

Figure 2.1: Bending of sheet metal
[modified from Schuler GmbH (1998)]

Sheet metal bending operation involves placing sheet metal on a die against an auto-gauge to locate the part precisely. The punch and mould (die) are mounted on a press machine, which controls relative motion between the punch and die and provides necessary bending pressures. Grippers hold the part during and between operations.

Bending processes fall into several categories: air bending, bottom bending, coining, U-bending, etc. Air bending is a bending process in which the punch touches the work piece and the work piece does not touch the bottom of the die. Bottom bending is a bending process where the punch and the work piece bottom on the die. Coining is a bending process in which the punch and the work piece bottom on the die and compressive stress is applied to the bending region to increase the amount of plastic deformation.

Bend Allowance (BA)

If the bend radius is small relative to the thickness of raw material, the sheet metal tends to stretch during bending. This influences the accuracy of dimensions and tolerances of final part. Thus it is important to reflect this in working dimensions.

The problem is to determine the length of the neutral axis before bending to account for stretching of the bent. This length is called *bend allowance*, and it can be estimated as follows:

$$BA = 2\pi \frac{\alpha}{360} (R + K_{ba}T) \quad (2.1)$$

where BA = bend allowance, mm; α = bend angle, degrees; R = bend radius, mm; T = material thickness, mm; and K_{ba} is factor to estimate stretching, which is t/T , t is distance from the inside face to the neutral axis.

K_{ba} is a ratio that gives the location of neutral sheet with respect to the thickness of the sheet metal part. The value of K_{ba} is usually estimated by adopting some recommended design values in an actual calculation. In order to get more accurate results of calculating, many CAD programs calculate the bend allowance by using K_{ba} (or Y-factor in the case of Pro-E where the Y-factor is $\frac{K_{ba}\pi}{2}$) [Groover (2001)]. For air bending, bottom bending and coining, Diegel (2002) presented a method for calculating the most accurate value of K_{ba} that can be obtained by using reverse engineering.

Springback

When the bending pressure is removed, elastic energy in the bent part causes it to recover partially toward its original shape as illustrated in figure 2.2. This elastic recovery is called *springback* (see figure 2.2), defined as the increase in included angle of the bent part relative to the included angle of the forming tool after the tool is removed. This is expressed as:

$$Springback = \frac{\alpha_f - \alpha_i}{\alpha_i} = \frac{R_f - R_i}{R_i} \quad (2.2)$$

where α_f is the bending angle after springback in degrees; α_i is the bending angle before springback in degrees; R_f is the final bend radius after springback in mm; R_i is the bend radius before springback in mm.

Springback should be predicted in bending operations and the punch position adjusted accordingly. It causes changes in shape and dimensions that can create major problems in the assembly. Hence springback prediction is an important issue in the sheet metal forming industry. It is difficult for design engineers to predict springback, as many variables influence it:

Figure 2.2: Springback
[Altan (2003)]

material variations in mechanical properties, tool geometry (including die radius and the gap between the die and the punch), sheet thickness, punch stroke, lubricant condition, etc. The springback of the bent sheet is often approximated using the expression 2.1.1:

$$\frac{R_i}{R_f} = 4\left(\frac{R_i Y}{ET}\right)^3 - 3\left(\frac{R_i Y}{ET}\right) + 1, \quad (2.3)$$

where R_f is the final bend radius after springback in mm; R_i is the bend radius before springback in mm; Y is the yield strength of the sheet metal in MPa; E is Young's modulus of the sheet metal in GPa; and T is the thickness of the sheet material in mm.

For air bending, the spring back usually ranges from 5 to 10 degrees. Bottom bending makes for a controlled angle with very little spring back by setting the final position of the punch such that the clearance between the punch and die surfaces is less than the thickness of blank sheet. Coining is a bending operation in which compressive pressure is applied to the bending region to increase the amount of plastic deforming. It reduced the amount of springback.

Various investigations show the influence of process parameters such as bend radius, die gap and punching speeds, and material properties such as sheet thickness, flow stress, texture and grain size on springback [Li et al.

(2002b); Chan et al. (2004); Choi and Chin (2006); Kim et al. (2007)].

2.1.2 Punching

Punching is a very efficient, inexpensive and flexible way of producing cutouts from sheet metal. The term punching describes a slitting process, in which a punching machine separates a sheet of metal by striking it. In punching, the cut-out part of sheet is scrap, and remaining material is a desired part. Opposed to it, in blanking the cut-out section of the part is the required part.

Punching is usually utilized to create holes of various shapes in sheet metal material. Traditional punching operations produce a single geometry with the same tool. NC-controlled punching operations with multiple standard tools can produce a wide range of geometries characterized by simple geometrical elements like lines and circles [Schuler GmbH (1998)]. The punching operation of sheet metal part is shown in figure 2.3.

Figure 2.3: Sheet metal punching

2.2 Computer Aided Tolerancing

Tolerances and tolerance-related problems play an ubiquitous role in both the product design and process design. The existing research can be classified into seven distinct categories as in figure 2.4 and of which some are further discussed later. In this figure, the dashed lines means tolerance transfer technique generates from tolerance analysis and tolerance synthesis, as explained later in section 2.2.4.

Figure 2.4: Research on computer aided tolerancing
[Modified from Hong and Chang (2002)]

2.2.1 Geometrical Dimensioning and Tolerancing

Two main types of *tolerancing schemes* are in use: parametric and geometrical. Parametric tolerancing identifies a set of parameters and assigns limits to the parameters that define a range of values, such as size tolerances (conventional $\pm$) [Requicha (1993)] and statistical tolerances. A recently proposed tolerancing scheme called vectorial tolerancing falls into this category [Wirtz (1991)].

Defined by ISO 1101 and ANSI Y14.15M:1982, Geometrical Dimensioning and Tolerancing (GD&T) is a dimensioning system that benefits both design engineering and manufacturing engineering. It allows designers to set tolerance limits not just for the size of an object, but for all of the various critical characteristics of a part.

Geometrical tolerances describe the acceptable range of variation in geometry from a nominal or reference geometry. They designate values to certain characteristics of features, such as forms, orientations, locations, and run-outs. Detailed explanation and examples of current standards on geometrical dimensioning and tolerancing can be found in ANSI Y14.15M:1994 or ISO specifications such as ISO 1101:2002, ISO 14660-1:1999, ISO/TS 17450-1:2005. Figure 2.5 shows major tolerances and symbols in use (redrawn from ISO 1101:2002).

Among geometrical tolerances, orientation and position tolerances are often used in sheet metal parts. Orientation tolerances include perpendicularity, parallelism and angularity tolerances, as shown in figure 2.6. A special view of geometrical error evaluation with lots of related research work has been presented by Shunmugam (1986, 1987, 1988, 1991); Namboothiri and Shunmugam (1998); Samuel and Shunmugam (1999, 2003); Venkaiah and Shunmugam (2007a,b). The methods are mainly based on CMM, computational geometrical techniques or Artificial Intelligence (AI).

2.2.2 Tolerance Analysis

Tolerance analysis is a method to estimate the accumulation of design tolerances on a component's dimensions and features, and to verify the proper functionality of a design. This topic has drawn considerable attention and many papers have been published on 1D, 2D and 3D tolerancing.

The analysis methods can be classified based on the types of analyzed variations:

- Dimensional (lengths and angles).
- Geometrical (flatness, roundness, angularity, etc.).
- Kinematic variations (small adjustments between mating parts in mechanical assemblies) [Chase et al. (1997)].

Geometrical Tolerances		Symbols
Form Tolerances	Straightness
	Flatness
	Circularity
	Cylindricity
	Profile of any line
	Profile of any surface
Location Tolerances	Position
	Concentricity & Coaxiality
	Symmetry
Orientation Tolerances	Parallelism
	Perpendicularity
	Angularity
Run-out Tolerances	Circular run-out
	Total run-out

Figure 2.5: Geometrical dimensions & tolerances
[ISO 1101:2002]

Figure 2.6: Orientation tolerances
[from ISO 1101:2002 and De Vin et al. (1994b)]

Dimensional and geometrical variations are the result of variations in the manufacturing processes or raw materials used in production. Kinematic variations occur at assembly time, whenever small adjustments between mating parts are required to accommodate dimensional or form variations.

Tolerance Analysis Models

Figure 2.7 gives an overview on mathematical models in tolerance analysis:

- *Tolerance Chain Models*, or dimensional tolerance chain models, fall into three categories:
 - Linear/linearized tolerance accumulation models: two most common models for tolerance accumulation are worst case and statistical (Root Sum Square, or RSS) as the equations in table 2.3 [modified from Fortini (1967)].

Here T is the predicted assembly tolerance; T_i are the component tolerances.

Figure 2.7: Main tolerance analysis models

Table 2.3: Linear/linearized tolerance accumulation models

Method	Equation
Worse Case	$T = \sum_{i=1}^n T_i$
RSS	$T = \sqrt{\sum_{i=1}^n T_i^2}$

Following this approach, Greenwood and Chase (1988, 1990) introduced the application of worst case tolerance and simple RSS analysis. The research group in Brigham Young University described similar analysis results for more complex mechanical assemblies or kinematic linkages based on the direct linearization method (DLM) [Chase et al. (1995, 1997); Chase (1999); Gao et al. (1998); Glancy and Chase (1999); Wittwer et al. (2004)]. Gao et al. (1995) compared the results of the direct linearization method with those obtained from the Monte Carlo simulation while Cvetko et al. (1998) presented new metrics for assessing the accuracy of the Monte Carlo analysis method for assemblies. Geometrical feature variations defined in ANSI Y14.5M-1982 tolerance standard are addressed statistically and propagated kinematically in a manner similar to the dimensional variations in assemblies [Chase et al. (1996)]. Downey et al. (2003) discussed the role of tolerance and assembly analysis in smart assembly design, which are applied on nesting forces for exactly constrained mechanical assemblies by Pearce et al. (2004), too.

- Statistical tolerance analysis was developed from the tolerance chain technique. The method aims to determine the probability distribution of system response functions [Seo and Kwak (2002)].
- Monte Carlo simulation circumvents the difficulty in statistical tolerance analysis to determine statistical moments of accumulated tolerances in closed form. Therefore, Monte Carlo simulation methods are frequently used [Chase and Parkinson (1991)]. This method can be readily used for tolerance analysis but rarely for tolerance synthesis, for that it is difficult to get the derivatives of the design function [Singh et al. (2003)].
- *Variational Dimension Model (VDM)*: it was introduced by Shah and Mäntylä (1995) as a special case of variational geometry in which only the dimension (size) can vary. Recent research work focuses on tolerance sensitivity analysis in this area [Dong and Shi (1997)].
- *Variational Solid Models (VSM)*: The variational dimension method is inapplicable to non-polygonal/polyhedral models and certain types of

geometrical tolerances. To overcome this problem, Boyer and Stewart (1991) proposed a set of solid-based variational geometry approaches, named *Variational Solid Models (VSM)*. It was proven to be appropriate for tolerance analysis application, such as the analysis of assembly of toleranced parts [Akella and Mason (2000); Li and Roy (2001)].

Three Dimensional Tolerance Analysis

Dimensional tolerance chain models do not meet the requirements of (three dimensional) geometrical tolerances as used in industry. Three dimensional tolerance propagation methods are necessary. The development of a three dimensional tolerance propagation scheme requires two related issues:

- Representation of tolerance zones.
- Spatial tolerance propagation mechanism.

Categories of three dimensional tolerance analysis methods are shown in figure 2.8:

Figure 2.8: Main three dimensional tolerance analysis methods

Preliminary work motivating the development of the 3D tolerance propagation techniques is regarded as the spatial dimensional chain technique [Portman and Shuster (1987); Portman (1995)]. The other methods are mostly a variation of the spatial dimensional chain technique. For example, in [Portman (1995)] the propagation of position errors are taken into

account in terms of a kinematic chain, where the individual error is represented as four-order matrices with three linear and three angular position errors. Then a kinematic chain model associating a set of six virtual joints, three for small translations and three for small rotations, is proposed to every pair of functional elements in a tolerance chain [Laperrière and ElMaraghy (2000)].

Three dimensional tolerance propagation models based on the concept of a small displacement torsor (SDT) are used to simulate three-dimensional fixturing and machining errors and their impacts on the geometry of the finished part. A SDT is a mathematical object that represents the displacement of a rigid body using three rotations and three translations. This approach models the influence of a process plan on functional tolerances as a chain of torsors. Supposed that the displacements are small enough, linearization is used to derive a torsor T as:

$$T = \begin{pmatrix} \alpha & u \\ \beta & v \\ \gamma & w \end{pmatrix} \quad (2.4)$$

where α , β , and γ are the small rotations of the element; u , v , and w are the small translations [Bourdet et al. (1996)].

The SDT-based three dimensional tolerance propagation overcomes the limitations of the traditional tolerance chain models. Based on them, Villeneuve et al. (2001) presented a detailed model of mechanical parts, part-holders and machining operations. Villeneuve and Vignat (2003) extended this method to tolerance synthesis.

Vectorial tolerancing can be applied for the three dimensional tolerance analysis. For example, Varghese et al. (1996b) proposed a method for geometrical tolerance analysis.

Desrochers and Rivière (1997) modelled tolerance zones to handle the propagation of tolerances in a chain by a usual coordinate transformation. Another method of tolerance zone representation is based on a graphical representation of part features, process plans and functional requirements defined with an ISO standard, to analyze three-dimensional tolerance specifications and to generate manufacturing specifications with ISO standards [Anselmetti and Louati (2005)].

2.2.3 Tolerance Synthesis

Tolerance synthesis, or *tolerance allocation*, is the reverse process of tolerance analysis. It provides a rational basis for assigning tolerances to working dimensions. Tolerance synthesis has enormous impact on cost and quality. It affects the fit and function of the product, which can cause poor performance and dissatisfied customers. With respect to manufacturing, tolerance requirements determine the selection of machines, tools and fixtures; the operator skill level and set-up costs; inspection and gage precision; etc. In conclusion, tolerance synthesis affects almost every aspect of the product life-cycle. Most tolerance synthesis approaches are based on the optimization of a cost-tolerance function. These approaches try to get optimal tolerance values when the tolerance stacks are assumed to be fixed. Nevertheless, the utilization of these models in industry is still limited. One major reason is that these models try to take advantage of the superficial knowledge of processes, which is usually obtained from machinist handbooks or company manuals. Process knowledge at this level cannot provide the designer with sufficiently precise tolerance values.

Commonly used tolerance synthesis methods include [Chase (1999)]:

- *Allocation by proportional scaling*: component tolerances are linearly scaled by a constant proportionality factor.
- *Allocation by constant precision factor*: component tolerances are allocated by means of weight factors. In this way, weight factors are assigned to each component tolerance in the accumulation model and the system distributes a corresponding fraction of the tolerance pool to each component. Larger weight factors and corresponding bigger tolerances can be given to those dimensions that are the more costly or difficult to manufacture, which improves the cost and manufacturability of the design.
- *Allocation by optimization techniques*: the most popular optimization technique of component tolerance allocation is to minimize the cost of production of an assembly. It is accomplished by defining a cost-tolerance mathematical model for each component part in the assembly. An optimization algorithm assigns the tolerance for each compo-

nent and searches systematically for the combination of tolerances that minimize the cost.

Tolerance Synthesis Models

Tolerance synthesis or tolerance allocation can be interpreted as minimizing function $f(X_1, X_2, \dots, X_n)$ with respect to a set of tolerances, X_i . According to the nature of the target function $f(X_i)$, existing tolerance synthesis models can be classified as shown in figure 2.9.

Figure 2.9: Main tolerance synthesis methods

Cost-tolerance models are typical analytical cost estimation techniques [Wang et al. (2007)]. The objective of these models is to estimate product cost considering design tolerances of a product as a function of the product cost. As an example, in the *minimum cost optimization method*, a set of tolerances X_i are initially selected. Then, an optimization algorithm is used to find the minimal cost. However, due to the number of variables, the optimization can be rather involved and a global minimum may often be missed [Chase et al. (1989); Chase (1999)].

Some basic cost-tolerance models are listed in table 2.4, where A is the typical fixed cost (per part) in the manufacturing process, B is the cost of making a single part or component, T is the tolerance, and the coefficient k depends on the manufacturing process.

Table 2.4: Cost-tolerance Models

Cost Model	Function
Exponential	$C(T) = Ae^{BT}$
Reciprocal Squared	$C(T) = A + \frac{B}{T^2}$
Reciprocal	$C(T) = A + \frac{B}{T}$
Reciprocal Power	$C(T) = A + \frac{B}{T^k}$
Exponential	$C(T) = Be^{-mt}$
Expon/Recip Power	$C(T) = \frac{Be^{-mt}}{T^k}$
Piecewise Linear	$C(T) = A_i - B_i T_i$

All methods in table 2.4 for assembly can be applied to the allocation of machining tolerances.

Some recent optimization methods are based on AI techniques such as genetic algorithms, artificial neural networks, simulated annealing, neuro-fuzzy learning, and ant colony algorithm [Prabhakaran et al. (2004, 2005)].

Taguchi et al. (1989) presented quality engineering as an approach to handling tolerancing issues. Quality engineering aims at an integrated production system with an overall quality control, in which every activity is controlled in order to produce the products with minimal deviations from target values. Creveling (1997) detailed the various application methods of quality engineering to tolerance analysis and synthesis. Application of parametric design and quality loss functions has been explored recently [Feng and Kusiak (2000); Choi et al. (2000a); Feng et al. (2001)].

Statistical tolerancing synthesis (and process capability index applications) are also important issues in recent years. For example, Lee and Woo (1987) presented a method to resolve discrete tolerance synthesis issue, assuming dimension variables are independent with each other and follow the normal distribution. It assumes that the final tolerance specifications and the distributions of the process dimensions are known [Varghese et al. (1996a)]. For example:

- Based on the distribution function zone (DFZone) approach, Zhang

et al. (1999) presented an optimized cost-tolerance model to solve the statistical tolerance synthesis problems and the model is illustrated with an assembly example.

- Process capability index applications in tolerance synthesis are another important research area [Shiu et al. (2003)].
- Huang and Shiau (2006) established an optimization model, named as reliability index model, with consideration of the required functional reliability, the minimum machining cost and quality loss in this study.

In summary, tolerance synthesis is mainly used for assembly tolerances. However, tolerance synthesis for parts, especially sheet metal parts, has its own characteristics and needs more research.

2.2.4 Tolerance Transfer

Tolerance transfer, as tolerance analysis and synthesis in process planning, is a method to convert design tolerances into to a manufacturing plan.

Conventional Tolerance Transfer Method

Tolerance charting is the most popular conventional tolerance transfer technique. A tolerance chart is a graphical tool for process planners to determine the manufacturing dimensions and tolerances of each machining operation, based on the design dimensions and tolerances.

The fundamental idea of tolerance charting was presented by Britton and Whybrew (1997); Britton et al. (2001). Two main different fundamental tolerance charting techniques, Wade's and Bourde's model, were compared in detail by Lehtihet et al. (2000). The author concludes that Bourde's model appears more appropriate for the treatment of resultant dimensions obtained under a single set-up.

Hong and Chang (2002) gave an overview important tolerance charting-based approaches. However, since the approaches cited in this literature review were further developed:

- Angular tolerance charting [Ji and Xue (2002); Xue and Ji (2004, 2005); Ji and Xue (2006)].

- Digraphic tolerance chart representation method [Ahluwalia (2002); Oh et al. (2003)].
- Rooted tree model and datum-hierarchy tree method [Britton (2002); Thimm et al. (2004a,b)].

Although tolerance charting is applied widely in tolerance transfer, it has a major shortcomings: it cannot deal with complex spatial tolerance transfer issues or geometrical tolerance transfer. In order to predict how geometrical errors are accumulated in a complex final product, development of a three-dimensional analysis methodology is required.

Three Dimensional Tolerance Transfer

Most tolerance charting techniques can handle only the size dimensional tolerances or a limited set of geometric tolerances. Thus it is necessary to develop new tolerance propagation techniques in process planning for 3D tolerance transfer, especially for geometric tolerances.

Existing approaches to three dimensional tolerance analysis that are suitable for tolerance transfer are shown in figure 2.10.

Table 2.5: Three Dimensional Tolerance Transfer Methods

Name	Reference
Small displacement torsor (SDT) and proportioned assembly clearance volume (PACV)	Teissandier et al. (1998, 1999); Legoff et al. (1999); Villeneuve et al. (2001)
Technologically and topologically related surfaces model (TTRS)	Desrochers and Verheul (1999); Desrochers (2003)
Product Data Translator (PDT) approach	Zhou et al. (2002)

Optimization

Sometimes AI techniques are employed for optimization in this area. For instance, Li et al. (2000) proposed a methodology to optimize machining datums and machining tolerances simultaneously using genetic algorithms.

Figure 2.10: Three dimensional tolerance transfer methods

2.2.5 Monte Carlo Simulation

The Monte-Carlo, or random sampling, method numerically determines approximate solutions in mathematical physics and engineering. This stochastic technique was utilized for centuries, but only from 1940s has it gained the status of a method capable to address complex applications.

Five common types of Monte Carlo methods are presented in Robert and Casella (2004):

- Classical Monte Carlo
- Quantum Monte Carlo
- Path-integral quantum Monte Carlo
- Volumetric Monte Carlo
- Simulation Monte Carlo

Three approaches derived from the dimensional tolerance chain are used: linear/linearized tolerance accumulation, statistical tolerance analysis, as well as the Monte Carlo method. The Monte Carlo method has been used extensively for statistical tolerancing. Derivation of the statistical moments of a function of random variables is usually impossible in closed form, especially when the functional form is complicated or piecewise-defined. The Monte Carlo method has the advantage of simplicity and flexibility. However, this method can be computationally expensive. With the improvement of computational capacity of computers, the Monte Carlo method is adopted by many software packages, for example, Variation Simulation Analysis (VSA), and then applied in some commercial software including CATIA, Pro/Engineer and UG [Roy et al. (1991); Hong and Chang (2002)].

Because of the lack of explicitly derived equations, the usage of Monte Carlo simulations is limited:

- Hong and Chang (2002) stated that the Monte Carlo method could be readily used for tolerance analysis, but it was rarely used in tolerance synthesis because it was not easy to get the derivatives or gradients of the design function. Gao et al. (1996); Shan et al. (1999); Singh et al. (2003) explored the tolerance analysis by Monte Carlo methods.

- However, in recent years, some researchers has also paid attention to tolerance synthesis (or allocation) [Lee and Johnson (1993); Lin et al. (1997); Skowronski and Turner (1997); Laperrière and Kabore (2001); Huang et al. (2004); Lee et al. (2005); Di Stefano (2006)] as tolerance analysis.

Monte Carlo simulation is particularly good to integrate several interacting sources of uncertainty. Therefore, it is suitable for statistical tolerance transfer.

2.3 Computer Aided Process Planning

2.3.1 Current Tendency

The Society of Manufacturing Engineers (SME) defines process planning as the systematic determination of methods by which a product is to be manufactured, economically and competitively.

In other words, process planning is the transposition of engineering design information into process steps and instructions to efficiently and effectively manufacture products. Process planning activities include the following [Wang and Li (1991)]:

• Interpretation of product design data	• Determination of machining conditions
• Determination of production tolerances	• Generation of process route sheets
• Determination of setup requirements	• Selection of machining methods and processes
• Selection of tool sets	• Design of jigs and fixtures
• Selection of machine tools	• Calculation of process times
• Sequencing of operations	• NC program generation
• Tool path planning	• Capacity planning

Although CAPP uses almost the same steps taken in manual process planning, it requires less time compared to manual process planning. Due to the rapid diminishing number of experienced process planners in industry, compressed product life cycles, the broad use of CAD/CAM, the research on CAPP has gained more attention than ever before.

Approaches used in CAPP can be categorized as two types [Marri et al. (1998)]:

- *Variant process planning* follows the principle that similar parts require similar plans. This technology is often used in with Group Technology (GT) coding and classification approach
- *Generative process planning* utilizes decision logic, formulae, manufacturing rules, and geometry based data to develop new plan for each part based on input about the part's features and attributes.

Besides the classification above, research can be categorized on the basis of their geometrical modeling as in figure 2.11.

Figure 2.11: Research on process planning

Most research in this area is focused on optimization of process plans, although some other issues such as knowledge and data management in CAPP are important topics [Denkena et al. (2007)]. Optimization techniques used in CAPP can be categorized as:

- Knowledge-based reasoning [Wong and Siu (1995); Chu and Gadh (1996)]

- Graph theoretic approaches [Irani et al. (1995); Lin and Horng (1998); Thimm et al. (2001); Britton et al. (2002)]
- Heuristic algorithms [Li et al. (2002c); Raman and Marefat (2004); Li (2005)]
- Artificial Intelligence (AI) such as Genetic Algorithms (GA), Artificial Neural Network (ANN), Fuzzy Logic, Expert Systems, etc. [Berenji and Khoshnevis (1986); Reddy et al. (1999); Lee and Kim (2001); Lee et al. (2004); Allen et al. (2005)]

2.3.2 Application of Features in Process Planning

Definitions of Features

The use of features originates in the reasoning processes to associate domain knowledge with object representations by natural means. Numerous feature definitions are used in CAD, CAE, CAPP, and CAM. At first machining features were used to integrate CAPP and CAM packages on a geometrical level. Historical definitions of features are reviewed in table 2.6. More recently, the feature concept was expanded to relations between geometrical and non-geometrical entities. This definition of feature is adopted in this thesis.

Regardless of how features are defined, features can be considered as the smallest elements which possess explicit engineering meaning. Therefore, features are suitable as a link between life cycle stages. According to their applications in different stages, features can be classified as (modified from [Chen (2007)]):

• Conceptual design features	• CAE features
• Embodiment design features	• Manufacturing features
• Detailed design features	• Process planning features
• Assembly design features	• Inspection features

Conceptual design features, embodiment design features, and detailed design features are collectively called design features. The process planning

Table 2.6: Definition of features

Definition of a feature.	Source
A region of interest in a part model.	Wilson and Pratt (1988)
Any geometric form or entity that is used in reasoning in one or more design or manufacturing activities.	Cunningham and Dixon (1988)
Generic shapes associated to certain properties or attributes and knowledge useful in reasoning about the product.	Shah and Rogers (1988); Shah (1991)
A partial form or a product characteristic that is considered as a unit and that has a semantic meaning in design, process planning, manufacture, cost estimation or other engineering discipline.	Wierda (1990)
Regions of an object that are meaningful for a specific activity or application	Vandenbrande and Requicha (1993)
A representation of geometrical shape with a set of engineering attributes.	Chan and Nhieu (1993)
The representation of shape aspects of a physical product that are mappable to a generic shape and that have functional significance.	Shah and Mäntylä (1995)
A set of form elements with a functional meaning in a given application context that allows an association between shapes and functionality.	Martino et al. (1998)
A representation of shape aspects of a product that are mappable to a generic shape and functionally significant for some product life-cycle phase.	Bidarra and Bronsvoort (2000)

features are defined to represent the procedures and results of process planning activities. They can represent a process planner's strategy fully through associations to machine tools, setups, machining sequence, and process planning rules.

Sheet metal feature definitions are as diverse as the general feature definitions discussed above. In order to support design and process planning for sheet metal forming, sheet metal features highlight formability. Thus the following attributes define the sheet metal forming features of the part in design and process planning stage [modified from Tang et al. (2001)]:

- Feature identifier
- Feature form
- Material
- Dimensions associated with the feature
- Geometrical tolerance associated with feature
- Primary working direction or die closure direction
- Positioning datum
- Sheet metal forming method

Figure 2.12 shows a sheet metal part with typical forming features. As the base of the part, basic features are defined as primary features or elemental plates which represent the overall shape of a sheet metal part. Typical basic feature types are plates, walls, L-brackets, U-channels, curves, and boxes. Subsidiary features are defined as subsidiary elements which represent localized characters of a sheet metal part. Subsidiary features are modifications of the basic features. Typical subsidiary features are pierced holes, extruded holes, embosses, lancing forms, hems, beads, slots, bosses, ribs, and set-outs. The s-shaped part in figure 2.12 is a basic feature and the hole is a subsidiary feature.

Figure 2.12: Examples of sheet metal part features

Associative Features

Associative Features are a recently defined type of features. Based on object-oriented technology, these features are difficult to be defined in a traditional feature concept. They are defined as classes to represent relations between different forms of non-geometrical and geometrical entities depending on specific applications [Ma and Tong (2003); Ma et al. (2003); Ma and Tong (2004); Ma et al. (2004, 2007)]. The associative feature concept presented extends the Pro-E or other CAD's features concept into generic multi-application collaborative engineering domain with intelligent and self-contained modeling approach. It then supports scalable applications in a flexible manner in declarative form as well as polymorphism capability.

Associative Features are flexible, self-contained, and consistent to model the evolvement of features in different stages of product life-cycle. For example, some sheet metal forming entities, such as machining tools and fixtures can be explicitly defined in feature class as attributes or constraints. The associations are created by reasoning processes such as sequencing, tool se-

lection, gage selection, and fixture selection.

Based on above theories and applications, Chen et al. (2004, 2005, 2006a); Chen (2007) defined associative concept design features, detailed design features and process planning features using a unified feature model. A prototype system was developed to demonstrate the capability and feasibility of the proposed product modeling scheme.

Feature-based Process Planning

Feature-based process planning plays a crucial role in an integration effort of product life-cycle. In feature-based process planning, machining features are recognized CAD model, and machining processes and their sequences are determined based on the features and other machining information.

With a feature-based hierarchical description of the part design, process planning decisions are made based on individual features or groups of features. A feature-based approach allows to automate or semi-automate the processes from design to manufacturing. A simple feature-based flexible process planning system is laid out in figure 2.13.

Figure 2.13: Examples of a simple feature-based process planning system

Summary of recent research in this field is given in table 2.7.

Table 2.7: Summary of application of feature technique on process planning

Source	Main Topic
Tsang and Brissaud (1989); Regli et al. (1995); Amaitik and Kilic (2005)	Feature modeling and classification
Vancza and Markus (1993)	Roles of manufacturing features in process planning
Herbert et al. (1990); Joshi and Chang (1990); Dong et al. (1993); Chan and Case (1994); Kim and Cho (1994); Subrahmanyam and Wozny (1995); Liu et al. (1996); Kruth et al. (1996); Regli et al. (1997); Aldakhilallah and Ramesh (1997); Han et al. (2001); McCormack and Ibrahim (2002); Patil and Pande (2002); Ando et al. (2005); Woo et al. (2005)	Feature recognition/extraction technique
Gupta et al. (1992); Dong et al. (1992); Liou and Suen (1992); Dong and Parsaei (1994); Cherngm et al. (1998); Khoshnevis et al. (1999); Liu (2000); Yang et al. (2001); Xiang et al. (2002); Patil and Pande (2002); Amaitik and Kilic (2006); Chen et al. (2006b); Wang et al. (2006a)	Feature-based CAPP system
Torvinen et al. (1991); Wong and Wong (1995); Hou and Faddis (2005); Chen (2007)	Integration of CAD/CAE /CAM/CIM and CAPP
Gupta and Nau (1995)	Feature-based analysis of the manufacturability of machined parts
Lee and Daftari (1996, 1997); Lin and Lin (1998); Sun et al. (2001)	Feature composition and decomposition
Srinivasan and Sheng (1999a,b)	Feature-based process planning for environmentally conscious machining

Source	Main Topic
Zhang et al. (2000); Beg and Shunmugam (2003); Wong et al. (2006)	Feature-based inspection process planning
Joo et al. (2001); Shunmugam et al. (2002b); Ding et al. (2005); Singh and Jebaraj (2005); Liu and Wang (2007)	Optimization by AI and KBE techniques

Feature-based process planning was a hot research field in recent years. Although many researchers focus on developing CAPP systems or finding optimal process planning procedures, more and more attention is paid to the details of applying feature technique on process planning. For example, besides feature modeling and recognition, *design by features* approaches are utilized in feature conversion, composition and de-composition. Association and integration of CAD/CAE/CAM/CIM and CAPP are equally important topics. And more and more attentions are paid on optimization methods by AI.

2.3.3 Process Planning in Sheet Metal Forming

Overview

In the 1990s, process planning for small batch part manufacturing of sheet metal parts became a major research area. Some researchers focus on computer aided process planning for sheet metal forming [Uzsoy et al. (1991); Lin and Horng (1998); Ramana and Rao (2004)]. The sheet metal manufacturing process comprises many complex operations which make it difficult to construct a comprehensive CAPP system for all sheet metal parts. Being the most common operation of sheet metal forming, bending is one of the most researched topics in this field [Fleischer (1992)]. Other operations such as punching and drawing, or combined operations begin to gain more attention.

Table 2.8 shows a survey of papers on CAPP of sheet metal forming. Only certain typical operations were selected for review as too many sheet metal forming methods exist to be listed comprehensively.

Table 2.8: Review on CAPP for sheet metal forming

	All Operations	Bending	Punching	Drawing	Blanking	A CAPP System	Operation & Tool Selection	Sequencing	Comments
Sitaraman et al. (1991)	✓					✓		✓	Knowledge-based
De Vin et al. (1992)	✓					✓			
Hoffmann et al. (1992)		✓						✓	
Smith et al. (1992)	✓					✓	△	△	
De Vin et al. (1994a)		✓				✓		✓	
Shpitalni and Saddan (1994)		✓						✓	
Streppel and Kals (1994)	✓					✓			
Franke (1995)		✓					✓		
De Vin et al. (1996)		✓				△	✓		
Ong et al. (1997)		✓					△	✓	
Radin et al. (1997)		✓						✓	
De Vin and Streppel (1998)		✓					✓		
Gupta et al. (1998)		✓				✓	✓	✓	
Lin and Chang (1998)		✓					✓	✓	
Choi et al. (1999)		✓			✓	✓			
Duflo et al. (1999)		✓						✓	
Gupta (1999)		✓					✓		
Gupta and Bourne (1999)		✓					✓	✓	
Shpitalni and Radin (1999)		✓						✓	
Choi et al. (2000b)				✓	✓	✓			
De Vin et al. (2000)		✓				✓		△	
Gao et al. (2000)	✓					✓			

	All Operations	Bending	Punching	Drawing	Blanking	A CAPP System	Operation & Tool Selection	Sequencing	Comments
Lutters et al. (2000); Strep-pel et al. (2000)	✓					✓			Based on information system
Alva and Gupta (2001)	✓						✓		Punch design
Thanapandi et al. (2001)		✓					✓	✓	
Aomura and Koguchi (2002)	✓						✓	✓	
Gupta and Rajagopal (2002)	✓						✓		
Kang and Park (2002)				✓		✓		△	
Kim et al. (2002)		✓	✓			✓	△		
Markus et al. (2002)		✓					△	△	Constraint based process planning
Park et al. (2002)				✓		✓			
Thanapandi et al. (2002)		✓						✓	
Huang and Xu (2003)			✓				✓	✓	
Rico et al. (2003)		✓						✓	
Duflou et al. (2005a)		✓					✓		
Nguyen et al. (2005)		✓					✓		
Singh and Sekhon (2005)	✓					✓			
Vosniakos et al. (2005)	✓					✓	✓	△	Forming with progressive die
Wang and Xie (2005)			✓			△	✓	✓	
Cattrysse et al. (2006)		✓					△	✓	

	All Operations	Bending	Punching	Drawing	Blanking	A CAPP System	Operation & Tool Selection	Sequencing	Comments
Ciurana et al. (2006)	✓			△			✓	✓	
Rao et al. (2007)			✓		✓	✓			
Verlinden et al. (2007)		✓	✓				△	△	

✓: discussed in paper in detail; △: touched on in paper

Feature-based Process Planning in Sheet Metal Forming

An early topic in this field is feature representation and classification. De Vin et al. (1992) presented a CAPP system named Part-S, in which bends are classified by a feature type referred to as *connections*. A connection is a design feature, typically a bend or a welded seam. Trappey and Lai (1995) divided the bend features in simple bends and features such as hemmed or curled edges. Then the basic sheet metal features were classified by Belarbia et al. (1996), e.g. walls, bends, form features, cuts, punches, notches. Wang and Bourne (1997) proposed an integrated system for the design and production of sheet-metal parts, identifying several bend features: bend graph, internal tab, essential and optional collinear bend, outside/inside bend, taller flange, shorter/longer bend, channel, corner, hemming bend, large-radius bend, part overhang, louver and dimple.

Shunmugam et al. (2002a) presented a fully automated experimental feature recognition system for sheet metal forming process planning. This system extracts the sheet metal feature information from 2D orthographic drawing to generate process plan without any user interaction.

Some researchers have focused on development of feature-based process planning systems:

- In the integrated modeling and process planning system developed by

Li et al. (2002a) for planning bending operations of progressive dies, the geometrical bend mapping function for feature elements within individual bends, and the transformation matrix for connected sub-bends, are formulated.

- Xie and Xu (2006) developed a prototype STEP-compliant process planning system for sheet metal product development. It integrates software modules for nesting optimization, path optimization and planning, simulation, and machining parameters set-up and CNC machining.
- Another intelligent CAPP system based on feature technique was presented by Zheng et al. (2007), in which stamping process planning of automobile panels needs to establish a process information model based on a 3D model product and feature technology.

Feature-based sheet metal part stampability evaluation and stamping process planning approaches have been studied and presented in a two-part paper by Tang and Gao (2007a,b). Tasks of stampability include identification of the aims, criteria, and procedure of stampability evaluation, the formalization of the stampability evaluation knowledge, and so on. In the second part, a feature mapping system, between a stamping design feature space and a stamping process feature space, has been presented.

Opposed to traditional machining process planning, feature-based process planning for sheet metal forming was not been studied intensively as shown by the literature. Feature representation, classification, recognition and development of feature-based process planning system are still hot topics, but more fields about the characteristics of sheet metal forming processes need to be traversed.

2.4 Tolerance Transfer in Sheet Metal Part Forming

Tolerance transfer in process planning of sheet metal part forming attracted in the past only little attention in literature, and if, the focus is on only bending operations.

Table 2.9: Review on tolerance transfer in sheet metal part forming

Resource	Size Dimensional Tolerance	GD&T	Tolerance Analysis	Tolerance Synthesis	Worse Case	Statistical Tolerancing	Analytic	Graphical	Remarks
De Vin et al. (1994b, 1996); De Vin and Streppel (1998)	✓	△	✓		✓		✓	△	Bending; tolerance tree; discusses the importance of conversion of size tolerances to geometrical tolerances
Shpitalni and Radin (1999)	✓		✓		✓		✓	△	Bending; critical tolerance oriented
Geiger and Hagenah (1999); Geiger et al. (2000); Hagenah (2003)	✓		✓			✓	✓		Bending
Han (2001)	✓		✓		✓			✓	Bending
Aomura and Koguchi (2002)	✓		✓		✓		✓		Bending; based on Shpitalni and Radin (1999)

✓: discussed in paper in detail; △: touched on in paper

The publications in table 2.9 raise the following issues or leave them unaddressed:

- Computer aided tolerancing does not address processes including several operations of distinct nature, such as bending, punching, blanking, and deep-drawing.

- Machining errors, their causes and inter-dependencies are not characterized comprehensively as the sources of final error accumulation, although some of the errors are discussed in papers above.
- Only size dimensional tolerances (using conventional worst case models) are discussed in detail.
- Statistical tolerancing approaches reflect actual part tolerances better than worst-case tolerancing. However, they are utilized only for sheet metal assembly issues [Singh et al. (2003)] or size dimensions [Geiger and Hagenah (1999); Geiger et al. (2000); Hagenah (2003)].
- Tolerance synthesis/allocation for sheet metal part forming are seldom studied. Currently research works are focused on sheet metal assembly [Shiu et al. (2002); Manarvi and Juster (2004)].

2.5 Summary

Feature based process planning for sheet metal forming, that is, data association and integration of CAD, CAE, CAM, CIM and CAPP is only partly addressed in current feature technology.

As a key constraint in process planning, operational dimensioning and tolerancing ensures that dimensions and tolerances of workpieces do not exceed specified design values, and suitable and economical dimensions and tolerances are allocated to each operation.

Geometrical Dimensioning and Tolerancing (GD&T) is an internationally standardized language used to accurately describe a part, and it is often used to replace parametric tolerances such as size dimensional tolerances, to avoid ambiguity. However, today's knowledge on tolerance analysis and synthesis for sheet metal forming processes is insufficient to allow a comprehensive industrial application.

The Monte Carlo method, spatial dimensional chain techniques, transformation matrices, and graph charting techniques are good base for the development of two dimensional and three geometrical tolerance transfer in sheet metal forming, especially for geometrical dimensioning and tolerance analysis.

Chapter 3

Feature Evolvment and Process Planning

3.1 Introduction

Computer Aided Process Planning (CAPP) bridges the gap between CAD and CAM by interpreting sheet metal designs in terms of features and using them to represent commonalities.

Various feature definitions are used in CAD/CAPP/CAM, including recently proposed grouping schema related to geometrical entities. Based on this schema and the also recently proposed associative feature concepts and applications [Ma and Tong (2003); Ma et al. (2003); Ma and Tong (2004); Ma et al. (2004, 2007)], feature evolvment is presented and performed, and data association and integration among different CAD/CAPP system is explored.

3.2 Feature Evolvment and Sheet Metal Part Feature

3.2.1 Feature Evolvment Progress

Depending on the considered product life-cycle stage a feature can be called as conceptual design feature, embodiment design feature, detailed design feature, process planning feature, etc. *Feature evolvment* described how features evolve along with the product life-cycle, including their association and

change management across product life-cycle stages. The feature evolvement progress is shown in figure 3.1 and an example for forming feature evolvement is shown in figure 3.2 (basic concepts are from [Chen(2007)]):

Figure 3.1: Feature evolvement process

- Conceptual design stage: A working structure composed of two conceptual design features, a s-shaped part feature and a hole feature, results in the specification of principles through abstracting the essential customer requirements, concept generation, establishing function structures, evaluating part configuration, etc. The S-shaped part feature is a basic feature and the hole feature is a subsidiary feature.
- Embodiment design stage: Complete working structure including lots of embodiment design features results in evaluating subsidiary features and basic dimensions, which are from part shape elaboration. In this stage, the S-shaped part feature decompose from a basic feature to a series of subsidiary features such as bend features and plate features. The hole feature is still a subsidiary feature, evolving from conceptual design feature to embodiment design feature.
- Detailed design stage: Through part detail refinement, dimensions and tolerances are generated as constraints to existed features. All existed embodiment design features evolve to detailed design features.

(a) Conceptual Design Stage

(b) Embodiment Design Stage

(c) Detailed Design Stage

(d) Process Planning Stage

Figure 3.2: An example for forming feature evolvment

- Process planning stage: Process planning features are generated as the final step of process planning from detailed design features, determined by process planning rules. For example, as shown in figure 3.2, for the hole feature, the data record in the attributes (forming method, forming tool, forming fixture, forming gage, forming datum) determines its basic shape and orientation. These attributes comes directly from different process planning constraints such as tooling planning constraints, gage planning constraints, setup planning constraints, etc.”

The evolvement progress of figures in different stages in figure 3.2 is summarized in table 3.1.

Table 3.1: Forming feature in different stages

Conceptual Feature	Design	Describe a basic function structure
Embodiment Feature	Design	Decompose basic features to subsidiary features
Detailed Feature	Design	Design elements are labelled as features as shown in figure 3.4
Process Planning Feature	Fea-	Process planning elements are added to generate process planning features

3.2.2 Sheet Metal Forming Features

The sheet metal feature definition and its associated rules can represent a sheet metal part structure with geometrical and technical information. Thus these features can be divided into forming features and non-forming features.

A sheet metal forming feature is a set of geometric entities consisting of edges which are spatially connected such that they can be machined by sheet metal forming operations. One method of characterization and identification of 3D sheet metal component forming features is introduced in Jagirdar et al. (2001).

In this research work, two sheet metal forming features are discussed in detail:

- Hole features include punching features, slot features, etc. A hole feature in a detailed design would typically contain the attributes:

– ID	– Orientation
– Name	– Diameter
– Type	– Tolerance
– Depth	– Forming direction
– Position	– Forming method
- Bend-like features mean the features for sheet metal parts formed by bend-like operations, which include bend graph features, bending line features, internal tab features, outside/inside bend features, channel features, corner features, flange features, hemming features, part overhang features, louver and dimple features [modified from Wang and Bourne (1997)]. These features have similar attributes to hole features.

3.2.3 Geometrical Dimensions & Tolerances Features

In an associative feature evolvement CAD/CAPP system, geometrical dimension and tolerance feature of a sheet metal component would typically include:

- Dimension ID, name, type, and value
- Tolerance ID, name, type, and value
- Datum ID, name, and type
- Boundary element ID, name, and type,

where datums and boundary elements are modelled as features. For example, the parallelism tolerance in figure 3.2 (c) can be presented as a GD&T feature in figure 3.3. For this feature, the datum is surface feature **A7Z**, the boundary element is surface feature **A9Z**, dimension type is basic dimension, and the tolerance type is parallelism tolerance.

3.2.4 Feature Labelling and Design Dimension Graph

In order to illustrate the key role of GD&T in engineering design, feature labelling and design feature graph are used to represent design features of

Figure 3.3: Parallelism feature model

a machined part based on design dimension graphs [Thimm et al. (2004a)]. The graph is formed by mapping subsidiary features (surfaces and holes) in the detailed design onto nodes and the edges in the graph are constraints on the features. A design feature graph is connected and acyclic. For example, figure 3.4 shows the design dimension graph of the example part in figure 3.2. In this graph, each feature of the part is labelled according to the principle described below.

The following conventions are adopted for labels in a design feature graph:

- An edge without an arrow represents a size dimension and tolerance. In contrast, an edge with an arrow represents a geometrical dimension and tolerance.
- The head of a directed edge denotes a feature controlled by a geometrical dimension and tolerance from the datum designated by the tail of the arrow.
- An edge labelled with B corresponds to a basic dimension.
- The edges labelled by position tolerance symbol with P , S or T represent primary, secondary, or tertiary datum correspondingly in a datum system.

Figure 3.4: Design feature graph of the example part

- An edge labelled with t represents the thickness of sheet metal, which is an implicit dimension.
- An edge labelled by SP connects two surfaces located on the same plane, that is, two parallel surface of which the parallelism tolerance is zero.

3.3 Data Association by Associate Features

The significance of CAD/CAPP integration arises from the fact that CAPP relies on the product model data provided by CAD to perform precise and consistent process planning for manufacturing. However, stand-alone CAx systems tend to use incompatible formats. For example, most CAD systems are geometry-based, while CAPP/CAM systems are feature-based and domain-dependent. This results in a common weakness of CAPP systems: they are not integrated with CAD or CAM systems and changes in the CAD model are not automatically reflected in the CAM or CAPP model.

Another difficulty in integration of CAD and CAPP raises from a lack of associations between geometric and non-geometrical relations, such as size/geometrical dimensions and tolerances, surface roughness and hardness

in current CAD models.

3.3.1 Key Characteristics of Associative Features

Associative features are used to support sharing feature data among product life-cycle. For example, if the part geometry is modified after a process plan was established, process planning features such as set up features, fixture features, and gage features should be updated accordingly. Therefore, associative features have to be ([Ma and Tong (2003)]):

- Flexible: the capability of an associative feature data structure to be created, edited, and deleted by the end user dynamically through certain composing methods. The data structure should also provide interfaces to support different applications.
- Self-contained (well-defined): validity and integrity of associative features persists across modifications by integrated applications.
- Consistent integration of different applications: associative features can be presented as declarative knowledge and enable higher level knowledge-oriented processing.

Concurrent engineering and product life cycle support requires certain key characteristics of the proposed model of associative features:

- Associative links between related geometric entities.
- Self-validation for the consistency of entities, attributes, and constraints.
- Methods available for constructing, storing, indexing, editing and destroying its instances.
- Methods that can be expanded to interface with query and execution mechanisms for high level knowledge processes.
- Methods to interface with other engineering application tools.

An associative tool to integrate CAD/CAPP can be developed based on the above concept [Ma and Tong (2004)].

3.3.2 Data Association Mechanisms

In a single application, product data can be associated by using an intra-application associative manager. These associations allow respective CAx sections to maintain a consistent model. However, for independent applications, more complex inter-application data association mechanisms than available in a stand-alone CAx system are necessary. In the proposed mechanisms and corresponding scheme in figure 3.5, major modules and their functionalities are:

- Application associative managers manage intra-application data association.
- A constraint-based expert system represents and handles engineering constraints.
- An associative feature modeler defines the fields and methods of associative features that are applicable for all application features.
- A relation manager maintains independency relations.
- A constraint manager evaluates and solves geometric and algebraic constraints.
- A feature geometry manager is responsible for geometrical modeling and association functions.
- A central associative feature-based database (AFDB) is utilized to share and associate geometrical and feature data. The data associations of the AFDB are established in two levels [Chen (2007)]:
 - Geometry-level associations: establishing and maintaining geometrical data association among different life-cycle stages.
 - Feature-level associations: providing a flexible method for non-geometrical data association.

Figure 3.5: Inter-application data association

3.3.3 Change Management

Another crucial issue of application of above data association mechanisms is change management. The associative change management algorithm is shown in figure 3.6.

For each application's operation, data is stored in different specific tables of the AFDB. For example, when inter-application data association occurs, data are stored into associative tables in the database, including feature association tables and geometry associations tables. After a change is validated and requested by an application to the AFDB, it is announced to all effected applications by the database manager. Then each application checks the validity of the change:

- If one or more application cannot accept the change, feedback is sent to the AFDB, which inform the change-requesting application and requests a revision of the change.
- If all applications approve the change, the change is accepted and the AFDB is updated.

3.4 Associative Feature Evolvment CAD/CAPP system

Based on data association and feature evolvment, the architecture of a CAD/CAPP system using associative features shown in figure 3.7. This system includes some function modules as shown in table 3.2.

Main purposes of the system are:

- Generation of an optimized process plan containing all data required to product the given sheet metal part.
- Integration of CAD with process planning.
- A geometrical tolerance constraint-based CAPP system.

The three design stages in figure 3.7 are [modified from Pahl and Beitz (1996)]:

Figure 3.6: Flowchart of the associative change management algorithm

Figure 3.7: The overall associative feature evolvment CAD/CAPP system

Table 3.2: Modules of the system

Name	Description
An associative feature-based database (AFDB)	A central database for feature and data association, as shown in figure 3.5
An associative feature-based modeling module	Models conceptual design features, detailed design features and process planning features, as shown in figure 3.5
A CAD module	Explains and reformulates CAD information
A CAPP module	Process planning feature modeling and geometrical tolerance constraints generation. It is composed by several sub-modules: <ul style="list-style-type: none">• Fixture Planning• Tooling Planning• Gage Planning• Setup planning• Gripper planning

- The conceptual design stage: it generates the most promising principles through abstracting the essential customer requirements, modeling conceptual design features, establishing function structures, searching for suitable working principles and then combine these principles into a working structure.
- The embodiment design stage: it has a result of the structure of a technical system based on embodiment design features modeling in line with a technical and economical analysis.
- The detailed design stage: it completes detailed product design including the arrangement, shapes, dimensions, and materials of all individual parts on features of detailed design as well as production assessment and cost estimation.

3.5 Tolerance Constraint-based Setup Planning Algorithm

Setup planning is a sub-task of process planning [Wang and Li (1991)]. In this thesis, setup planning is discussed as crucial part of process planning. The optimality of the overall process plan while optimizing the setup plan can be ensured by choosing the cost as the same objective function. The results are instructions for setting up parts for machining. This mainly comprises:

- *Setup formation*: the partitioning of all machined features into a certain number of setups such that features grouped into same setup.
- *Datum selection*: determining the features which serve as datums in each setup.
- *Operation Selection & Sequencing*: selecting operations in a setup in such an order that each operation can be machined.

For each sheet metal forming operation, the intermediate workpiece geometry and the tool geometry impose constraints on the tooling stages that are used to perform the forming operations. Setups in a process plan have to respect these constraints. Among them, the constraints of GD&T are the most important ones.

3.5.1 Definition of Constraints

Constraints, or validity conditions, must be clearly defined to specify relationships among features, geometric or topological entities. Table 3.3 shows classes of constraints used in modern CAD systems [modified from Dohmen (1998)].

Table 3.3: Constraints

Constraint Name	Description
Geometric constraints	Specify the geometric relations between feature elements. In figure 3.2 (c), two surfaces of the hole feature H10YZ in the co-plane with the surface feature A2X and B2X .
Dimension constraints	Specify distances between two feature entities. In figure 3.2 (c), the basic dimension 80mm is used to present the distance between the surface feature A7Z and A9Z .
Algebraic constraints	Define the relations among feature parameters using equations. The diameter of the hole feature H10YZ is a quarter of the distance between the surface feature A7Z and A8Z .
Semantic constraints	Specify topological properties of feature elements. The cylindrical side face of the hole feature H10YZ must at least be partly on the boundary, and the top and bottom surface must be not on the boundary.

Some common attributes of constraints are as described in table 3.4 [modified from Tang (2007)].

Setup Constraints

Common setup constraints are shown in table 3.5.

Geometrical dimensions and tolerances are a subset of geometric constraints. As the essential constraints in setup planning of sheet metal forming, their constraint strength is defined as *required* and their constraint sense is *directed*. For example, the constraint graph of the hole feature **H10YZ** in figure 3.2 (c) is shown in figure 3.8, including two GD&T constraints.

Table 3.4: Common attributes of constraints

Attribute	Description
Constraint ID	Used to identify a constraint uniquely.
Constraint name	Names of a constraint.
Owner ID	Identifies the feature a constraint belongs to.
Constraint expression	Establishes relationships between the constrained elements and reference elements.
Constrained entity ID	Specifies a list of constrained entities with reference to the referenced entities.
Referenced entity ID	Identifies reference entities.
Constraint strength	Represents the degree that the constraints need to be imposed when constraint conflict with each other. Several levels are used such as <i>required</i> , <i>strong</i> , <i>medium</i> , and <i>weak</i> . The highest strength is <i>required</i> , and the lowest is <i>weak</i> .
Constraint sense	Is used to specify the direction between constrained entities and referenced entities. A constraint is <i>directed</i> if all members of a list of constrained entities are constrained with respect to one or more referenced entities. Opposed to it, <i>undirected</i> constraints do not distinguish between constrained and referenced entities.
Constraint solving functions	Are utilized to solve constraint based on constraint types
Other functions	Include attribute access functions, behavior control functions, etc.

Figure 3.8: Constraint graph of the hole feature **H10YZ** of the example part

Table 3.5: Types of common setup constraints

Type Name	Description and Examples
Setup formation constraints	Constraints from setup formation. E.g., all punching operations must be performed in the same punching setup.
Operation sequence constraints	Constraints concerned about operation sequencing. E.g., an operation i must be executed before another.
Datum constraints	Constraints related to datum selection. E.g., the first choice of machining datum of a dimension is design datum.
Resource constraints	Constraints about resource compatibility, e.g., compatible setup sets are specified as resource constraints
Other constraints	Constraints from other sections of process planning and design stage. E.g., tooling constraints and GD&T constraints.

3.5.2 Setup Planning Algorithm based on Tolerance Transfer

Setup planning respecting constraints from tolerance transfer would typically comprise the following steps (as shown in figure 3.9):

Main steps of the setup planning are:

1. Gather design and process planning information from CAD model and database with machine capabilities, and so on.
2. Do prophase work that consists of process planning feature & constraint acquisition, setup planning feature modeling, machining errors, etc.
3. Initialize setup constraints according to CAD and process planning information.
4. Select alternative datum combinations.
5. Select alternative setup formation.
6. Generate feasible operation sequences and corresponding setup plans.

Figure 3.9: Setup planning process for sheet metal forming based on tolerance Analysis

7. Generate tolerance constraints, especially GD&T constraints, and allocate the constraints to machining errors of each operation with respect to setup plans.
8. Check the tolerance synthesis results with tolerance constraints and setup plan information.
9. Is the setup plan feasible?
10. If no, ease some setup constraints such as datum selection to get suitable setup plans and reiterate to check whether they meet tolerance constraints.
11. If yes, report feasible setup plans.

The computation complexity of the setup planning algorithm can be calculated based on that of each step:

- Step 1, 2, 3, 4, 5, 9, and 11 are constant complexity;
- Step 6 is theoretically exponential in number of operations;
- Step 7 depends on the employed algorithm (at least linear in the number of constraints);
- Step 8: for the chosen algorithm, the complexity is essentially that of a matrix inverse;
- Step 10: linear in the number of constraints.

Setup Formation

To reduce the influence of machining errors on the part as much as possible, features linked by a size dimension or geometrical dimension should be machined in the same setup, or at least one of the surfaces should be the datum for the machining operation of the other surfaces. This is achieved during setup formation, which is an important stage in setup planning that groups features of a part into setups.

General rules for sheet metal setup formation are:

- Rule 1. In a setup, the precision, dimensions and tolerances of machining features should match the precision, position, orientation and roughness capability of the manufacturing resources.
- Rule 2. A setup should be designed to produce as many features in the machine tool capability as possible.
- Rule 3. A setup should be selected such that minimal position error can be achieved.
- Rule 4. A feature dimensioned relative to a single datum system should be machined in one setup to avoid machining error stack-up. One example is the punching process of parallel holes.

Datum Selection

In sheet metal forming process planning, the selection of setup and operation datums is critical as they directly affect the selection of setup methods, tooling, fixturing and tolerance allocation.

For a given feature, design datum, setup datum, operational datum, and measuring datum can coincide. In case where one differs from the other datums, tolerance transfer occurs. This may impact on the allowance of both machining and measuring tolerances. For instance, if a design dimension cannot be machined directly, the tolerance on the design dimension must be distributed among corresponding operations involved in creating the design dimension. All contributing machining tolerances must be tighter than the design tolerance because their stack-up equals to the design tolerance. Therefore, it is important to find an optimum combination of setups, operational datums, and sequences to minimize the tolerance stack-up. General rules for datum selection are:

- Rule 1. The operational, design, setup and measuring datum of one referenced feature should coincide in order to avoid tolerance stack-up.
- Rule 2. If the setup datum and operational datum of one feature are not identical to the design datum, datum selection must cause minimum tolerance stack-up caused by datum change.

Rule 3. If a machined feature has a geometrical tolerance relationship with one of the datum features, the referencee feature should be the primary setup datum while the other feature is machined.

In order to find feasible datum combinations for operation sequence, the following algorithm is used:

- Step 1: for design dimensions and tolerances of a part, a feasible datum pool D_f is created for each feature.
- Step 2: extract constraints from the prophase work, setup formation and intermediate part shapes.
- Step 3: Search for feasible datum combinations.

An optimal datum combination is determined with respect to setups and tolerance transfer, which is discussed in the following sections.

In cases, where one or more of the rules above cannot be fulfilled, tolerance transfer occurs. It is one of the targets of this work to quantity this transfer.

Alternative Setups and Datums

If a setup plan is not satisfying, alternative choices for setups or datums must be considered. This could be achieved by the means of GA [Coley (1999)], systematic iteration through alternatives (search algorithm such as A* [Jones (2005)]), or simply human interaction.

Sheet Metal Operation Sequencing

Operations can be sequenced in different ways and yet produce parts of identical quality. In this section, the operation sequence from an example part is presented. Five operations are required to form the example part, which are labelled as bending 1 to 4 and punching hole 5, as shown in figure 3.2 (b) and 3.10.

Tolerance Transfer in Setup Planning

The tolerance transfer issue, including tolerance analysis and synthesis and corresponding case studies such as worse case and statistical case are discussed in chapter 4, 5 and 6.

Figure 3.10: An operation sequence of the example part

3.6 Conclusion

In this chapter, feature evolvment concept and sheet metal feature representation are proposed with an emphasis on GD&T features. After that, data association mechanisms and change management mechanisms are also introduced as the basis of an integration of CAD/CAPP system. The system is outlined, based on feature evolvment, data association and associative feature concept. It resolves the data association problem for the integration of CAD/CAPP, and then extend to other CAx systems. After that, a tolerance constraint-based setup planning algorithm is introduced with the rules for setup formation, datum selection and operation sequencing.

Chapter 4

Tolerance Analysis: Worse Case Study

4.1 Introduction

The objective of this chapter is to study the influence of geometrical tolerancing on process planning for sheet metal parts based on worse case assumption. The chapter proposes an approach to analyze geometrical tolerances, which are the key tolerance constraints for sheet metal process planning. Position tolerances and one typical orientation tolerance, parallelism tolerance, are used as they are commonly used in sheet metal parts.

4.2 Background

4.2.1 Assumptions

In order to reduce the complexity of the tolerance accumulation model, the following assumptions are made:

1. The thickness of metal sheet is unchanged by the forming process.
2. Metal sheets remain rigid in shape throughout the forming process.
That is, the shape of the part is only changed in the of vicinity of a bend line.

3. The blank is already formed and its side surfaces are planar and perpendicular to the top and bottom surfaces of the sheet.
4. Alike, the side surfaces of punched holes are perpendicular to the top and bottom surfaces of the part.

4.2.2 Tolerance Analysis Progress

The tolerance analysis process is shown in figure 4.1. Design and process planning information are required by the model.

During the tolerance analysis process, the following items needs to be considered:

- The *design* includes design features, dimension and tolerance requirements, definition of material characteristics.
- The *process plan* includes tooling constraints, gage constraints, setup constraints, gripper constraints, process planning features, bend allowance, springback, machining error constraints (refer to table 2.2.3), etc.
- *Simulation model* is a mathematical model of the part. It is typically a worse case model, a general statistical model, or a Monte Carlo simulation model.
- *Tolerance analysis result* and *actual part geometry* are the result of the simulation.

4.2.3 Machining Errors

Several types of sheet metal machining errors occur in the bending-like and punching processes listed in table 4.1. Here, the term *error* is used to refer to the distribution of *observed errors*. An observed error is the discrepancy between a measured dimension of a part or a process and its specified value for a single workpiece. Error symbols are preceded with the symbol Δ followed by a letter identifying its source. Observed errors have the same letter, but are preceded by a δ .

Figure 4.1: Simulation progress of tolerance analysis

Table 4.1: Errors in sheet metal forming

Operation	Error	Symbol	Typical value	Standard Deviation σ
General	Blanking error	ΔB	0.05 – 0.1mm	0.015mm
	Positioning error	ΔP	0.05 – 0.1mm	0.015mm
	Thickness error	ΔT	2 – 5% sheet thickness	0.01mm if $t = 2\text{mm}$
Bending	Error in length caused by setup & process	ΔL_b	0.05 – 0.2mm	0.015mm
	Error in length caused by stretching	ΔL_s	see text	
	Angular bending error	$\Delta \alpha$	$0.5^\circ - 2^\circ$	0.1°
Punching	Error in length of position	ΔL_p	0.05 – 0.2mm	0.015mm
	Error in hole shape	ΔD	0.05 – 0.1mm	0.015mm

The worse case assumption means that the extreme of machining errors are used as the upper and lower process tolerances in the simulation.

- The blanking error ΔB is the distribution of the distance between the ideal and the actual outline of a sheet metal blank.
- Error in length is one key source for tolerances during bending or punching. In bending operations, ΔL_b is caused by:
 - The inaccuracy of the machine tool setup, for example, the inaccuracy of the punch position relative to the die or fixture. For one batch blanks, the mean and variance of this error is considered as invariable.
 - The inaccuracy of the machining process is caused by many factors such as the incorrectness of the kinematic scheme of the machine tool, the geometrical inaccuracy of machine tool and cutting tool, the deformation of the machining system under external forces, and the thermal deformation of the machining system [Wang and Li (1991)].
- For punching operations, the error ΔL_p results from the inaccuracy of the machine tool setup and machining process.
- The length error ΔL_s is the difference between the real and estimated stretching of the workpiece incurred by bending. Typical values for the error in bending allowances could not be identified by the authors. ΔL_s is assumed to be zero.
- The positioning error ΔP originates in an inaccurate workpiece setting. Positioning error ΔP describes the distances between individual, idealised datums and the corresponding points on the workpiece. The position of the workpiece with respect to the datums **a**, **b**, and **c** is affected by the observed errors $\delta P_a, \delta P_b, \delta P_c \in \Delta P$. In worse case study in this chapter, the model is simplified to: $\delta P_a = \delta P_b = \delta P$.
- The angular error $\Delta \alpha$ of a bend is the deviation from the predicted spring-back. It has a direct influence on geometrical tolerances. In a

worse case, if all surfaces are labelled adjacently as S_i , ($i = 1, 2, 3, \dots$), the angular error between two surfaces S_k and S_l ($k < l$) is:

$$\delta\alpha_{k,l} = \delta\alpha_{k,k+1} + \delta\alpha_{k+1,k+2} + \dots + \delta\alpha_{l-1,l} \quad (4.1)$$

The angular error is mainly caused by springback. The average error can be controlled by overbending past the angles specified in designs to counteract springback. In this chapter it is supposed that overbending is utilized and the angular error has a zero mean.

- The error ΔT for the thickness of the sheet is assumed to affect a given blank uniformly. Metal sheet usually has a 5% variation in thickness.
- The error ΔD in a punching process is typically caused by profile and dimensional errors of the punch geometry or the deflection between punch and die. This error is assumed not to change the reference centre or the orientation of the punched feature, such as a hole (as in contrast to ΔL_p).

4.2.4 Surface Labelling

For convenience, a surface representation scheme similar to that of the datum-hierarchy graph technique is utilized [Whybrew et al. (1990)]. In this scheme, each surface is labelled uniquely in each operation stage because each operation causes changes to the overall geometry.

A sheet metal example part is labelled as figure 3.2 (c). A reference coordinate system is arbitrarily located at the bottom left hand end of the final part.

The reference coordinate system provides a frame of reference for defining the surfaces of sheet metal in three dimensional space during process planning.

The concept of *surface sets* is used for surface labelling. A *surface set* is a set of surfaces of the sheet metal part. The first surface in the set is a newly created surface or a surface created by a prior pre-forming operation, e.g. blanking. Then the consequent surfaces' relative positions to the origin of the coordinate system are changed by operations such as bending and punching. The last surface in the set is a finished surface.

Each surface in a set is uniquely identified by an alpha-numeric code consisting of three parts:

- A letter code, which is **A**, or **B**, **H** or **S**. **A** is used arbitrarily for one side of blank and **B** for the other. Different from convectional material removal machining process, each sheet metal forming operation may change their relative orientation and their orientation relative to the coordinate system. For side surfaces and for holes, the letter codes **S** and **H** are employed, respectively.
- An integer number that is unique to the surface set a surface belongs to.
- A letter code, which is either of **X**, **Y** or **Z**, for surface perpendicular to the respective axis or a combination of these for inclined surfaces or holes.

For instance, a label **A2X** represents a surface, that belongs to the second surface set, is perpendicular to the **X** axis, and is located on the plane **A** before the first operation.

If the surface referred to in a process plan, the code is established by a number indicating the position of the surface in the surface set. This is "0" for a new surface.

4.3 Tolerance Analysis: Case Study

4.3.1 Parallelism Tolerance

Based on process planning progress in figure 3.10, setup plans have to be verified whether or not they comply with tolerance constraints.

A basic dimension and parallelism tolerance links the surface **A7Z** and **A9Z** of the example sheet metal part is shown in figure 3.2 (c). In order to cope with the machining error stack-up of sequences in figure 3.10 and 4.3, the errors of the bending operations must be constrained. The setup in figure 3.10 comprises a punch, a die, a gage and an intermediate workpiece.

Based on the sequence in figure 3.10, the final machining error E corresponding to parallelism tolerance can be analyzed. It is the sum of the size dimensional error E_d and the length error caused by angular error E_a :

$$E = E_d + E_a \quad (4.2)$$

The size dimensional error and the angular error are regarded as independent. Although the angular error may bring forth additional positioning error, it can be avoided through correct location methods in forming operation. For example, the location way in figure 4.2 is incorrect, comparing with that in figure 3.10.

Figure 4.2: Wrong location method of bending operation

A detailed analysis of the size dimensional error E_d is shown in figure 4.3 (all errors in the classes given in table 1 are assumed to be equivalent). A further constitution to the error to dimension **A7Z0-A9Z3**, resulting from the angular errors, is discussed later. The punching operation is omitted as it does not influence the parallelism. Operational datums are highlighted by

solid triangles.

Tolerance analysis for the design dimension **A7Z-A9Z** is presented as below according to the forward method. The total error corresponding to the parallelism tolerance is the sum of size dimensional and angular errors, including various types of machining errors.

Let $E_{di}(\mathbf{A}, \mathbf{B})$ denote a size dimensional error between the surfaces **A** and **B** for the i th operation ("0" means the pre-forming operation, e.g. blanking operation), then the tolerance analysis process are:

1. Blanking operation: the blanking operation forms the surface **S1X0** and **S4X0** with the error of δB , that is,

$$E_{d0}(\mathbf{S1X0}, \mathbf{S4X0}) = \delta B \quad (4.3)$$

2. Operation 1: the surfaces **A7Z0**, **B7Z0**, **A2X0**, **B2X0**, **A8Z0**, **B8Z0**, **A3X0**, **B3X0**, **A9Z0**, **B9Z0**, and **S4X1** are formed.

$$E_{d1}(\mathbf{S1X0}, \mathbf{B2X0}) = \delta L_b + \delta P \quad (4.4)$$

$$E_{d1}(\mathbf{B7Z0}, \mathbf{S4X1}) = \delta B + \delta L_b + \delta P \quad (4.5)$$

$$E_{d1}(\mathbf{A7Z0}, \mathbf{S4X1}) = \delta B + \delta L_b + \delta P + \delta T \quad (4.6)$$

3. Operation 2: the surfaces **A8Z1**, **B8Z1**, **A3X1**, **B3X1**, **A9Z1**, **B9Z1**, and **S4X2** are formed.

$$E_{d2}(\mathbf{A7Z0}, \mathbf{A8Z1}) = \delta L_b + \delta P + \delta T \quad (4.7)$$

$$E_{d2}(\mathbf{B2X0}, \mathbf{S4X2}) = \delta B + 2\delta L_b + 2\delta P \quad (4.8)$$

4. Operation 3: the surfaces **A3X2**, **B3X2**, **A9Z2**, **B9Z2**, and **S4X3** are formed.

Figure 4.3: A detailed analysis of tolerance stacks for the bending sequence

$$E_{d3}(\mathbf{S4X3}, \mathbf{A8Z1}) = \delta L_b + \delta P \quad (4.9)$$

$$E_{d3}(\mathbf{B2X0}, \mathbf{A9Z2}) = \delta B + 3\delta L_b + 3\delta P \quad (4.10)$$

5. Operation 4: the surfaces **A9Z3**, **B9Z3**, and **S4X4** are formed.

$$E_{d4}(\mathbf{S4X4}, \mathbf{A3X2}) = \delta L_b + \delta P \quad (4.11)$$

$$E_{d4}(\mathbf{A9Z3}, \mathbf{A8Z1}) = 2\delta L_b + 2\delta P \quad (4.12)$$

6. Operation 5: this operation does not influence the parallelism tolerance.

Therefore, a first estimation of the dimensional error between **A7Z0** and **A9Z3** for the final part is $E_d = 3\delta L_b + 3\delta P + \delta T$.

However, angular errors also contribute to the error between **A7Z0** and **A9Z3**. The influence of the angular errors on the size dimensional error is illustrated by the means of an example part.

Figure 4.4: The influence of the angular error on the size dimensional error

Considering the ultimate positions of surface **B7Z**, the error caused by the angular error E_{a1} of operation 1 is in the interval of $L_2[\cos(\delta\alpha_1) - 1]$ to

0, or $L_2[\cos(-\delta\alpha_1) - 1]$ to 0, that is:

$$E_{a1} = L_2[\cos(\delta\alpha_1) - 1] \quad (4.13)$$

The error E_{a2} corresponding to the parallelism by angular error of operation 2 is:

$$E_{a2} = L_3 \sin(\delta\alpha_1 + \delta\alpha_2) \quad (4.14)$$

The total error E_a caused by angular error corresponding to the parallelism is:

$$E_a = E_{a1} + E_{a2} = L_2[\cos(\delta\alpha_1) - 1] + L_3 \sin(\delta\alpha_1 + \delta\alpha_2) \quad (4.15)$$

Let $L_2 = L_3$ and $\delta\alpha_1, \delta\alpha_2$ in $[-2^\circ, 2^\circ]$, then the resulting min/max deviation in % L is shown in figure 4.5. Because E_2 is much smaller than E_1 and E , the two lines standing for E_1 and E almost coincide.

Figure 4.5: The deviation in % L of bend line 1 and 2

According to above calculation method, the example part in figure 3.2 (c) is analyzed, which is formed by four bending operations and a punching operation. The length dimension is replaced by L_1, L_2, L_3, L_4 , and L_5 . For each bending operation, the angular error is in the range of $\pm\delta\alpha_1, \pm\delta\alpha_2$,

$\pm\delta\alpha_3$ and $\pm\delta\alpha_4$ respectively. As the design datum, the surface **A** is used as reference.

The influence of the angular errors on the parallelism tolerance is shown in figure 4.6.

Figure 4.6: The tolerance analysis of the angular errors

Considering the ultimate positions of surface **A9Z**, the error caused by the angular error of operation 1 E_{a1} is:

$$E_{a1} = L_2[\cos(\delta\alpha_1) - 1] \quad (4.16)$$

The error corresponding to the parallelism by angular error of operation 2 is:

$$E_{a2} = L_3 \sin(\delta\alpha_1 + \delta\alpha_2) \quad (4.17)$$

The error corresponding to the parallelism by angular error of operation 3 is:

$$E_{a3} = (L_4 - L_2)[\cos(\delta\alpha_3 - \delta\alpha_1 - \delta\alpha_2) - 1] \quad (4.18)$$

The error corresponding to the parallelism by angular error of operation 4 is:

$$E_{a4} = L_5 \sin(\delta\alpha_4 + \delta\alpha_3 - \delta\alpha_1 - \delta\alpha_2) \quad (4.19)$$

Let $\delta\alpha_1, \delta\alpha_2, \delta\alpha_3$, and $\delta\alpha_4$ in $[-2^\circ, 2^\circ]$, the total error E_a caused by angular error corresponding to the parallelism is:

$$E_a = E_{a1} + E_{a2} + E_{a3} + E_{a4} \quad (4.20)$$

$$\begin{aligned} &= L_2[\cos(\delta\alpha_1) - 1] + L_3 \sin(\delta\alpha_1 + \delta\alpha_2) \\ &\quad + (L_4 - L_2)[\cos(\delta\alpha_3 - \delta\alpha_1 - \delta\alpha_2) - 1] \\ &\quad + L_5 \sin(\delta\alpha_4 + \delta\alpha_3 - \delta\alpha_1 - \delta\alpha_2), \end{aligned} \quad (4.21)$$

where $\delta\alpha_1, \delta\alpha_2, \delta\alpha_3, \delta\alpha_4$ in $[-2^\circ, 2^\circ]$

The extrema of E_a exist while $\alpha_i, (i = 1, 2, 3, 4)$ are at their maxima or minima, that is, -2 or 2.

Let t denotes the thickness of the workpiece, $L_1 = 50\text{mm}$, $L_2 = 40\text{mm}$, $L_3 = L_1 - t = 48\text{mm}$, $L_4 = 80\text{mm}$, and $L_5 = 40\text{mm}$ as the example part in figure 3.2 (c).

$$E_{a_{max}} = 3.2996, \text{ for } \delta\alpha_1 = \delta\alpha_2 = \delta\alpha_3 = \delta\alpha_4 = 2 \quad (4.22)$$

$$E_{a_{min}} = -3.3970, \text{ for } \delta\alpha_1 = \delta\alpha_2 = \delta\alpha_3 = \delta\alpha_4 = -2 \quad (4.23)$$

For a more detailed discussion of the length error caused by angular error, let $L_4 = 2L_2 = 2L_3 = 2L_5 = 2L$, $\delta\alpha_1, \delta\alpha_2, \delta\alpha_3$, and $\delta\alpha_4$ in $[-2^\circ, 2^\circ]$, then according to equation 4.3.1:

$$E_a = E_{a1} + E_{a2} + E_{a3} + E_{a4} \quad (4.24)$$

$$\begin{aligned} &= L[\cos(\delta\alpha_1) + \sin(\delta\alpha_1 + \delta\alpha_2) \\ &\quad + \cos(\delta\alpha_3 - \delta\alpha_1 - \delta\alpha_2) \\ &\quad + \sin(\delta\alpha_4 + \delta\alpha_3 - \delta\alpha_1 - \delta\alpha_2) - 2] \end{aligned} \quad (4.25)$$

and:

$$-0.0006L \leq E_{a1} \leq 0 \quad (4.26)$$

$$-0.0698L \leq E_{a2} \leq 0.0698L \quad (4.27)$$

$$-0.0055L \leq E_{a3} \leq 0 \quad (4.28)$$

$$-0.1392L \leq E_{a4} \leq 0.1392L \quad (4.29)$$

Obviously, E_{a2} and E_{a4} are the errors that contribute most to E_a . If the lengths of all size dimension are different, the lengths of L_3 and L_5 influence the value of E_a more than those of L_2 and L_4 .

4.3.2 Position Tolerance

For another example part in figure 4.7, the tolerance positions the two holes **H18XZ** and **H19XZ**. The axis of the two holes is constrained by a position tolerance for the datum **A**, that is, the surface **A15Z**, which is one of the key tolerance constraints. A coordinate system is set up as shown in figure 4.7 and all design dimension and tolerance are marked with $L_i (i = 1, 2, 3, \dots)$.

Figure 4.7: Labelling and dimensions of the example part

An operation sequence is illustrated in figure 4.8. In the first operation, two holes are punched. Then two bending operations are performed in succession.

For this sequence, the machining error E is analyzed, that is the sum of the size dimensional error E_d and the error caused by angular error E_a .

E_d is analyzed in the cut-away view diagrams of figure 4.8 (all errors are

assumed to follow the same distribution as given in table 4.1), considering the hole **H18XZ** and **H19XZ**. The size dimensional error is in the direction of the **Z** axis. To make the figure easier to understand, the operational datums are highlighted by solid triangles.

Let $E_{di}(\mathbf{A}, \mathbf{B})$ denote a size dimensional error between the surfaces A and B for the i th operation ("0" means the pre-forming operation, e.g. blanking operation), the tolerance analysis process are:

1. Blanking operation: the blanking operation forms the surface **S9Y0** and **S16Z0**, **S14Y0** and **S17Z0**, **S9Y0** and **S14Y0**, with the error of δB .

$$E_{d0}(\mathbf{S9Y0}, \mathbf{S16Z0}) = \delta B \quad (4.30)$$

$$E_{d0}(\mathbf{S14Y0}, \mathbf{S17Z0}) = \delta B \quad (4.31)$$

$$E_{d0}(\mathbf{S9Y0}, \mathbf{S14Y0}) = \delta B \quad (4.32)$$

2. Operation 1 (Punching): the features **H18XZ0** and **H19XZ0** are formed.

$$E_{d1}(\mathbf{S9Y0}, \mathbf{H18XZ0}) = \delta L_p + \delta P \quad (4.33)$$

$$E_{d1}(\mathbf{S14Y0}, \mathbf{H19XZ0}) = \delta L_p + \delta P \quad (4.34)$$

$$E_{d1}(\mathbf{S9Y0}, \mathbf{H19XZ0}) = \delta B + \delta L_p + \delta P \quad (4.35)$$

3. Operation 2 (Bending 1): the features **A11Y2**, **B11Y2**, **S16Z1**, and **H18XZ1** are formed.

$$E_{d2}(\mathbf{A15Z0}, \mathbf{H18XZ1}) = \delta L_p + \delta L_b + 2\delta P + \delta T \quad (4.36)$$

$$E_{d2}(\mathbf{A15Z0}, \mathbf{S16Z1}) = \delta B + \delta L_b + \delta P + \delta T \quad (4.37)$$

4. Operation 3 (Bending 2): the features **A12Y2**, **B12Y2**, **S17Z1**, and **H19XZ1** are formed.

$$E_{d3}(\mathbf{A15Z0}, \mathbf{H19XZ1}) = \delta B + \delta L_p + \delta L_b + 2\delta P + \delta T \quad (4.38)$$

$$E_{d3}(\mathbf{A15Z0}, \mathbf{S17Z1}) = \delta B + \delta L_b + \delta P + \delta T \quad (4.39)$$

Therefore, the size dimensional error between the features **A15Z0** and **H18XZ1** of the final part is $\delta L_p + \delta L_b + 2\delta P + \delta T$, and the error between the features **A15Z0** and **H19XZ1** of the final part is $\delta B + \delta L_p + \delta L_b + 2\delta P + \delta T$. Both errors are in the direction of **Z**-axis.

The angular errors also must be considered for the calculation of the total error. The error between the axes of the hole **H18XZ1** and **H19XZ1** is also affected by the angular error.

The analysis of the angular error is shown in figure 4.9. For each bending operation, the angular error is in the range of $\pm\delta\alpha_1$ and $\pm\delta\alpha_2$, respectively. As the design datum, the surface **A15Z0** is the reference feature.

According to relative ISO specification [ISO:1101], the position tolerance zone is limited by a cylinder of diameter T_1 , with reference to the surface **A15Z0**. The maximum value of the errors in the direction of **X**-, **Y**-, **Z**-axis must be calculated and compared with T_1 to check whether the ultimate positions of the actual axis of the holes are located in the tolerance zone. Therefore, the displacements of four points **A**, **B**, **C** and **D** in the direction of three axes are calculated.

The displacements caused by size dimensional errors are:

$$\begin{pmatrix} \delta X_{A1} & \delta Y_{A1} & \delta Z_{A1} \\ \delta X_{B1} & \delta Y_{B1} & \delta Z_{B1} \\ \delta X_{C1} & \delta Y_{C1} & \delta Z_{C1} \\ \delta X_{D1} & \delta Y_{D1} & \delta Z_{D1} \end{pmatrix} = \begin{pmatrix} \delta L_p + \delta P & 0 & \delta L_p + \delta L_b + 2\delta P + \delta T \\ \delta L_p + \delta P & 0 & \delta L_p + \delta L_b + 2\delta P + \delta T \\ \delta L_p + \delta P & 0 & \delta B + \delta L_p + \delta L_b + 2\delta P + \delta T \\ \delta L_p + \delta P & 0 & \delta B + \delta L_p + \delta L_b + 2\delta P + \delta T \end{pmatrix} \quad (4.40)$$

Figure 4.9: Analysis of the angular error

The displacements caused by the angular errors are:

$$\begin{pmatrix} \delta X_{A2} & \delta Y_{A2} & \delta Z_{A2} \\ \delta X_{B2} & \delta Y_{B2} & \delta Z_{B2} \\ \delta X_{C2} & \delta Y_{C2} & \delta Z_{C2} \\ \delta X_{D2} & \delta Y_{D2} & \delta Z_{D2} \end{pmatrix} = \begin{pmatrix} 0 & L_{11} \sin(\delta\alpha_1) & L_{11}(\cos(\delta\alpha_1) - 1) \\ 0 & (L_{11} + t) \sin(\delta\alpha_1) & (L_{11} + t)(\cos(\delta\alpha_1) - 1) \\ 0 & -(L_{11} + t) \sin(\delta\alpha_2) & (L_{11} + t)(\cos(\delta\alpha_2) - 1) \\ 0 & -L_{11} \sin(\delta\alpha_2) & L_{11}(\cos(\delta\alpha_2) - 1) \end{pmatrix} \quad (4.41)$$

The ultimate position of the axis must be one of **A-C**, **A-D**, **B-C**, **B-D**, and the total displacements are obtained by a summary of two above matrices. As ΔY does not influence the positional error, the maximal error is determined by the δX and δZ , that is, $|2(\delta L_p + \delta P)|$ and $|\delta B + 2(\delta L_p + \delta L_b + 2\delta P + \delta T) + (L_{11} + t)(\cos(\delta\alpha_1 + \delta\alpha_2) - 2)|$. Let $\delta\alpha_1, \delta\alpha_2$ be in $[-2^\circ, 2^\circ]$, $\delta B, \delta L_p, \delta L_b, \delta P, \delta T$ and L_{11} are assigned exact values, the value of the maximum error can be calculated and compared with T_1 , the geometrical tolerance constraint.

4.4 Conclusion

In this chapter, a worse case analysis of critical tolerances with a focus on geometrical dimensions and tolerances is presented. After the role of tolerance constraints in sheet metal process planning and setup planning are presented, the machining errors in sheet metal bending-like and punching progresses are categorized. Two cases, parallelism and position tolerance, are discussed in the context of tolerance transfer and then tolerance constraint check. And the proposed tolerance transfer method can be easily extended to cope with other geometric tolerances.

Several points are worth to be highlighted:

1. Unlike as in conventional material removal machining progresses, sheet metal forming produces angular errors caused by springback.
2. The influence of the angular errors on geometrical dimensions and tolerances are considered.
3. Being the most typical operations in sheet metal manufacturing, bending-like and punching are selected for case studies.

4. Geometrical dimensions and tolerances are key tolerance constraints. Parallelism tolerance is studied as the most typical orientation tolerances in the first case and position tolerance is investigated in the other.

Based on above analysis, in the next chapter, three dimensional tolerance transfer in sheet metal process planning by Monte Carlo simulation will be explored.

Chapter 5

Tolerance Analysis: Monte Carlo Simulation

5.1 Introduction

Tolerance transfer is often studied under a worse case assumption. In a worse case study, error stack-up is conducted based on the extreme values of machining errors.

As dimensional variations of machined parts naturally follow statistical distributions, a manufactured part seldom has the extreme dimensions predicted by a worse case model. Thus, this approach has the advantage of a simple mathematical model but often leads to overly tight tolerances.

Statistical tolerancing is, in this sense, superior and allows to determine the exact distribution of accumulated errors. However, it is usually difficult to find a closed form for the distribution of part errors based on machining errors. Therefore, a numerical solution is required: the Monte Carlo method.

The tolerance analysis process performed by Monte carlo simulation is illustrated in figure 4.1 with the explanation about the modules.

5.2 Background

5.2.1 Monte Carlo Simulations of Geometrical Errors: Confidence & Computational Effort

In the past the accumulation of geometric errors in closed form was addressed with a limited success. Therefore, this work proposes to replace the explicit tolerance accumulation by a simulation of the production process. The later is a simpler task, as it amounts to adding errors to a CAD or comparable model and to observe its deviation from the nominal model:

1. If the machining, setup and similar errors are known, the machining processes can be simulated and instances of (electronically represented) workpieces can be generated.
2. Surfaces, lines or points on these workpieces can be compared with the design specification.
3. The distribution of the workpieces that are within specification can be statistically analyzed.

This amounts to a Monte-Carlo simulation, which has its own problems: a simulation may be computationally too expensive due to the number of samples required for a reliable estimation of the population. This statement was in the past often brought forward against Monte-Carlo simulations, but was never shown to be true to the best knowledge of the authors.

Currently most proposed methods fail to address, postpone to ‘future research’, or conveniently ignore one or more the following problems.

1. The accumulation of geometric errors (in the form of distributions, intervals, small displacement torsors, vector loops, and so on) is usually inexact as the methods use approximations to allow the mathematical manipulation of the errors.
2. Worst case (min/max) models (in particular sheet metal forming or assemblies) overestimate errors and may estimate average part dimensions wrongly.

3. The comparison of the resulting errors (expressed in the respective authors' preferred notation) with the design specifications in ISO standard is often impossible.
4. Certain errors can not be expressed or accumulated in the respective authors choice of representation (*e.g.* errors for free form surfaces or roundness).

Considering that the accumulation of geometric errors was addressed with a limited success by numerous researchers, this work tries to avoid the tolerance accumulation by replacing it with a simulation of the production process. Figure 5.1 illustrates the main difference between the usual and the here taken approaches. By the nature of the transfer functions and the machining errors, intermittently part errors occur typically in angles and distances between surfaces, lines, and points. In order to compare these with a tolerance zone, the angular and size dimensional errors are sampled (the "usual" approach, sometimes replaced by a convolution of machining errors) and then the distributions are compared with the tolerance zone. However, the information that certain deviations are correlated (the relative position of two surfaces may have a high angular deviation or a high size dimensional deviation from the nominal position, but not both) is lost, resulting in an estimated error distribution. The here proposed approach does not suffer from this problem, as the sampling of the error distribution happens much later.

Furthermore, the here proposed approach is technologically simpler and more versatile, as it amounts to "adding" errors to a CAD or comparable model of a part or assembly.

1. If the machining, setup and similar errors are known, the machining processes can be simulated and instances of (electronically represented) workpieces can be generated.
2. Surfaces, lines or points on these workpieces can be compared with the design specification.
3. The distribution of the workpieces that are within specification can be statistically analysed.

Figure 5.1: Comparison of approaches to determine the compliance of a transfer function with a tolerance zone

4. The proportion of work piece within specification estimated by the method is exact within the statistical limits of the Monte Carlo simulation and the accuracy of the machining errors.

Thus, in principle, all problems discussed above are overcome by the means of a Monte-Carlo simulation (compare Huang et al. (2004)). However, Monte-Carlo simulations have their own problems: a simulation may be computationally too expensive due to the number of samples required for a reliable estimation of the population. This statement was in the past often brought forward against Monte-Carlo simulations, but was never shown to the best knowledge of the authors. Furthermore, current computer technology may have toppled this assumption.

This section tries to address this. In order to abstract from processes and geometric dimensions, the following assumes the presence of a, so called, *oracle* in the sense of 'prophecy' (compare figure 5.2). It is a mechanism to produce the predicted outcomes of the program under test. This oracle has as input a design and a process plan. In the case of a machining process, the oracle simulates a physical process that

1. produces workpieces based on a set of process errors and then
2. determines whether or not individual instances of workpieces are within specification with respect to a particular geometric dimension.

Then, the oracle forwards an *answer* (yes/no) for each simulated workpiece to the statistical analysis.

Dashed boxes: in- or output.

Figure 5.2: The data flow in the Monte-Carlo simulation

In other words, the oracle is a black box hiding an error transfer function or physical process, a set of random number generators simulating the

randomness of physical processes, and an evaluation of the (simulated) workpiece with respect to a given design specification. An answer from the oracle is an apparent random boolean value governed by the content of the black box. The oracle can hide rather different objects.

- For a simulated assembly:
 - a model of the “random” joints and arms in the kinematic chain,
 - the transfer function that models the kinematic chain, and
 - a comparison of the specified and observed positions of the parts.
- For a simulated machining process:
 - simulated machining processes, which implicitly determine the shape of a workpiece based on the process,
 - a comparison of the observed shape of a part with the design specification.
- For a physical process line:
 - the finished workpieces,
 - a metrologic analysis of the parts,
 - and analysis of the measurements with respect to the design specification.

The statistical analysis is based on the number of answers from the oracle and the process requirements (*e.g.* 4- or 6-sigma) [NIST/SEMATECH (2006)]. The statistical analysis has those possible outcomes: a (dis-)qualification of the process or the decision that the number of answers from the oracle is insufficient for a conclusion. If no conclusion is possible, more answers are requested from the oracle.

In the following, details of the proposed approach in the simulation *cum* qualification of forming processes of high-precision machined parts or assemblies are given. In order to render the following discussion easier to read, it is formulated for machining processes only. Similar statements are valid for assemblies or production.

A statistical analysis of the Monte-Carlo Simulation

The answers from the oracle introduced earlier are samples from the Boolean domain and follow a binomial distribution. For such a distribution, be $\hat{p}$ the in general unknown population mean, that is the average number of workpieces fulfilling the design specifications. In general, $\hat{p}$ is unknown but can be estimated from any number of samples. However, such an estimation is usually paired with a confidence interval, with its limit depending on

- n the number of samples (here, the answers from the oracle).
- The confidence $\alpha \in (0, 1)$ in whether or not the simulation has correctly assessed the process.
- $z_{\frac{\alpha}{2}}$ parametrising the confidence width of intervals (see Agresti and Coull (1998); NIST/SEMATECH (2006)).

Of particular interest in this context are the two one-sided confidence intervals discussed below. The first interval has the lower limit ℓ given in equation (5.1), which states that, with confidence α , the true process performance $\hat{p}$ is above ℓ [NIST/SEMATECH (2006)].

$$\ell = \frac{\hat{p} + \frac{z_{\frac{\alpha}{2}}^2}{2n} - z_{\frac{\alpha}{2}}^2 \sqrt{\frac{\hat{p}(1-\hat{p})}{n} + \frac{z_{\frac{\alpha}{2}}^2}{4n^2}}}{1 + \frac{z_{\frac{\alpha}{2}}^2}{n}} \quad (5.1)$$

The probability that a process produces parts to specification is $p_0 = \ell \cdot \alpha$ (the product of the probability that the process plan is within specification and the confidence in the simulation). A 4-sigma or a 6-sigma requirement corresponding to p_0 exceeding 0.9772 or 0.9987, respectively. As n is effectively a monotonically increasing function of ℓ for a given $\hat{p}$ and α , the limit ℓ indirectly determines the number of (simulated) workpieces that need to be evaluated in order to achieve 4- or 6-sigma equivalent requirements. Therefore, the choice of $\ell_{\min}$ (the minimal value of ℓ for which a process plan is accepted) and α is a balance between the number of (simulated) workpieces (the closer α is to one, the more answers from the oracle are needed) and an over-specification of the process ($\ell_{\min} > p_0$). Section 5.2.1 addresses this is-

sue. In order to minimize the computational effort, a Monte-Carlo simulation enquires the oracle

- until $\ell \geq \ell_{\min}$,
- it is somehow clear that the process plan is unsatisfying, or
- the computing time allocated for the simulation is exceeded.

Whether the process plan is clearly unsatisfying can be judged by the means of the upper limit u given in equation (5.2) for the confidence interval for the workpieces being outside specifications.

$$u = \frac{\hat{p} + \frac{z_{\frac{\alpha}{2}}^2}{2n} + z_{\frac{\alpha}{2}}^2 \sqrt{\frac{\hat{p}(1-\hat{p})}{n} + \frac{z_{\frac{\alpha}{2}}^2}{4n^2}}}{1 + \frac{z_{\frac{\alpha}{2}}^2}{n}} \quad (5.2)$$

The simulation is aborted with a negative response if u is lower than $u_{\max}$. Here, $u_{\max}$ is chosen as $u_{\max} = \ell_{\min}$.

Unfortunately, a third case needs to be considered: $\hat{p}$ may be very close (or equal) to $\frac{p_0}{\alpha}$, which means that either $u_{\max}$ or $\ell_{\min}$ are only reached for very large values of n . This implies an excessive long simulation time (theoretically infinite if $\frac{p_0}{\alpha} = \hat{p}$, see section 5.2.1). This requires to set a maximal limit $n_{\max}$. If $n_{\max}$ is reached during a simulation, the process plan is rejected. Table 5.1 summarises the algorithm.

Table 5.1: Decision table for the simulation

Observation	Simulation	Estimated $\hat{p}$ is
$u_{\max} \geq u$	Terminate	unacceptable
$\ell_{\min} \leq \ell$	Terminate	acceptable
$n \geq n_{\max}$	Terminate	unacceptable
Otherwise	Ask oracle for next sample	—

Balancing Process Capabilities & Application Of The Oracle

The number of answers from the oracle necessary to ensure that the selected process parameters (at least) fulfil the requirement is a function of α as well as the true, yet unknown, population mean $\hat{p}$. Figure 5.3 illustrates this for a

few values of z and a 4-sigma specification of the part. The upwards sloped curves on the left indicate the expected number answers needed from the oracle for equation (5.2) to state that the process plan is not to specification (note the logarithmic scale of the vertical axis). The downward sloped curves on the right indicate the number of workpieces to be evaluated before a positive confirmation is expected. For a given value of $z_{\frac{\alpha}{2}}$, the left and right curve approach asymptotically the vertical line $\hat{p} = \frac{p_0}{\alpha}$. For $z_{\frac{\alpha}{2}} = 2.0$ or lower, the procedure will never state that the selected process parameters result in an acceptable error. Figure 5.4 gives similar data as figure 5.3, with the exception that a 6-sigma requirement is imposed on the process plan.

Figure 5.3: Expected number of workpieces to be evaluated before a process or assembly is accepted or rejected for $p_0 = 0.9772$ (a 4-sigma requirement). The vertical lines indicate $\frac{p_0}{\alpha}$.

It can be seen in both figures that the lower the value for confidence α for the estimation of the confidence interval is set, the higher the asymptotic limit for acceptance of the process plan becomes. This implies that more potentially acceptable process plans are rejected. In consequence, for the 4-sigma process requirement, $z_{\frac{\alpha}{2}} = 3.5$ or 3.0 seem to be most appropriate, as the shift of $\frac{p_0}{\alpha}$ to lower values is rather marginal as compared to the additional computational load. Similar, for 6-sigma a value of $z_{\frac{\alpha}{2}} = 4.0$ is appropriate. The selected values for $z_{\frac{\alpha}{2}}$ in turn allow to determine how many workpieces

Figure 5.4: Expected number of workpieces to be evaluated before a process or assembly is accepted or rejected for $p_0 = 0.9987$ (a 6-sigma requirement). The vertical lines indicate $\frac{p_0}{\alpha}$

need to be simulated such that a reasonable response can be expected:

- For the 4-sigma requirement, $n_{\max} = 100\,000$ to $1\,000\,000$ is necessary to reduce the cases where the process is rejected without evidence for its insufficiency (approximately $\hat{p} \in [0.975, 0.980]$).
- For 6-sigma, approximately $n_{\max} = 10\,000\,000$ workpieces have to be simulated in order to reduce the interval of a possible wrong rejection to an acceptable size (approximately $\hat{p} \in [0.99855, 0.99895]$).

A detailed tolerance analysis usually is only required for a (small) set of critical dimensions (read: dimensions specified with geometric dimensions). Consequently, if t_0 is the time in seconds needed for the oracle to produce one answer, a tolerance analysis for a part with c critical dimensions requires $10^5 \cdot c \cdot t_0 \text{sec}$ to $10^7 \cdot c \cdot t_0 \text{sec}$ for 4-sigma requirement and $c \cdot 10^7 \cdot t_0 \text{sec}$ for 6-sigma requirements.

Case Studies

The above presented Monte Carlo approach was applied to the two parts depicted in figures 3.2 (b) and 5.12. Table 5.2 summarises the design di-

mensions, processes, and the errors considered in the simulation. Not all of considered errors have an influence on the design dimension. For example, only the 2-point datums (each datum point is modelled individually as a statistical variable) change the position and angle of the bend line relative to the outline of the part.

Table 5.2: Details for the simulated parts

Part	Process	Geometric dimension	Errors considered	Random process parameters
S-shape	4 bending operations.	Parallelism and minimal material condition for top and bottom surface.	For each operation: positional error for datums, distance of the punch to machine zero, bend angle, size of blank.	11
Axis holder	1 punching, 2 bending operations.	Position of holes.	As above.	14

For both parts, a simulation of the tolerance stacks required less than 2 seconds for 100,000 workpieces on a 2.8GHz Pentium4 using MATLAB 7.0¹. This allows to extrapolate that, for a tolerance analysis of a part with c critical dimensions, a 4-sigma requirement test would need $c \cdot 2\text{sec}$ to $c \cdot 20\text{sec}$, whereas $c \cdot 200\text{sec}$ would be needed for 6-sigma requirements.

Summary

In this section, the number of workpieces that need to be simulated to obtain a reliable estimation of whether accumulated tolerances (as for example in an assembly or a process plan) are within specifications were investigated. An algorithm, which takes into consideration the confidence in the simulation as well as a 4- or 6-sigma requirement, is proposed. The algorithm is independent of the actual transfer function used and, if it is possible to model a

¹MATLAB is a registered trademark by The MathWorks, Inc.

single process exactly, allows to state reliably whether or not a process fulfils a 4- or 6-sigma requirement.

It is shown that the required number of simulated workpieces depends on how close the physical manufacturing process is to the 4- or 6-sigma requirement. The results stipulate that for a 4-sigma requirement, a simulation that evaluates at least 100 000 workpieces or assemblies in a time acceptable to the designer or process planner is needed. A simulation of two sheet metal parts shows that this is within the abilities of a conventional PC.

For 6-sigma requirements, the number of required simulated samples is increased to 10,000,000, which represents a computational effort somewhat excessive for a day-to-day use. On the other hand, the computational effort is sufficiently low to allow the use of the described method as a benchmark for other approaches – in an academic setting, for example.

5.2.2 Machine Coordinate System and Workpiece Coordinate System

In the following the use of two coordinate systems simplifies the mathematical model and an algorithm to transfer tolerances: the machine coordinate system (MCS) and the workpiece coordinate system (WCS). Both coordinate systems are Cartesian, right-handed, and three-dimensional. They can be utilized to deal with geometry information transmission of products formed in a single setup or multiple setups.

The MCS used in this thesis is based on the configuration of the considered machine tool and machinists. From the viewpoint of a machinist standing in the front of the tool,

- the Z-axis is parallel to the motion of the punch and points upwards,
- the X-axis runs from right to left, and
- the Y-axis points towards the machinist.

The origin of the MCS is such that it is in the plane defined by the surface (or the plane defined by the datum points) supporting the sheet metal blank or strip. Furthermore, the one- and two-point datums are on the X- and Y-axes. This definition is used to eliminate the need for a separate definition

of a coordinate system describing the fixture. The introduction of errors describing misalignments of the fixture and the machine are straightforward and can be integrated in the proposed model.

The WCS is defined with reference to a given set of datum points and the surface (that is the three-point datum) used to support the workpiece:

- The Z-axis is such that it points from the supported surface into the material.
- The X- and Y-axis traverse the two-point and the one-point datum or *vice-versa*, whichever results in a right-handed coordinate system.

In the following, coordinate systems in two dimensional figures are usually such that the Z-axis is directed out of the page.

5.2.3 Coordinate Transformations

In the MCS and WCS coordinate systems, all surfaces, lines, points can be labelled and represented by vectors. Surfaces are labelled as s_{iA} or s_{iB} , where A or B indicate the side of the blank. Bending lines are labelled as e_i . The coordinates of vertex v_{iA} (that is a point-feature of the part or workpiece) during operation j are labelled as $\mathbf{v}_{iA,j}^{\mathbf{m}}$ or $\mathbf{v}_{iA,j}^{\mathbf{w}}$, where m and w indicate that the coordinates are given with respect to the MCS and WCS, respectively. In the course of a process the coordinates associated with a vertex change and j indicates that the coordinates are associated to the j th operation (for the blank: $j = 0$). Surfaces, curves and lines are considered to be implicitly defined by vertices and therefore transformations are only formulated for vertices (this implies that lines and planes are perfectly straight and plane, and curves pertain their exact shape, respectively). The mathematical principles used below are adopted from Krzysztof (1991).

In order to obtain a uniform notation for points and vectors during coordinate transformation, a forth coordinate with a value of 1 for points and 0 for vectors is added. Thus the point $\mathbf{v}_{iA,j}^{\mathbf{m}}$ is represented as:

$$\mathbf{v}_{iA,j}^{\mathbf{m}} = \begin{pmatrix} v_{iA,j,x}^m & v_{iA,j,y}^m & v_{iA,j,z}^m & 1 \end{pmatrix} \quad (5.3)$$

Translation matrix Ψ as given in equation 5.4 describes a translation with vector $\mathbf{a} = (dx, dy, dz)$. Note that $\Psi^{-1}(\mathbf{a}) = \Psi(-\mathbf{a})$.

$$\Psi(\mathbf{a}) = \Psi(dx, dy, dz) = \begin{pmatrix} 1 & 0 & 0 & dx \\ 0 & 1 & 0 & dy \\ 0 & 0 & 1 & dz \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (5.4)$$

Rotation matrix Φ describes a rotation around an axis through the origin of the coordinate system. In a right-hand coordinate system, Φ can be described as a product of matrices describing rotations around the X-, Y-, and Z-axis with angles α , β , and γ , respectively:

$$\Phi_x(\alpha) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \alpha & -\sin \alpha & 0 \\ 0 & \sin \alpha & \cos \alpha & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (5.5)$$

$$\Phi_y(\beta) = \begin{pmatrix} \cos \beta & 0 & \sin \beta & 0 \\ 0 & 1 & 0 & 0 \\ -\sin \beta & 0 & \cos \beta & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (5.6)$$

$$\Phi_z(\gamma) = \begin{pmatrix} \cos \gamma & -\sin \gamma & 0 & 0 \\ \sin \gamma & \cos \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (5.7)$$

Any displacement of a part can be described as a combination of translations and rotations. For example, a rotation around an axis through two arbitrary points $\mathbf{v}'$ and $\mathbf{v}''$ can be expressed by two translations and a rotation. A rotation with angle ξ of an arbitrary point $\mathbf{v}$ around $\overrightarrow{\mathbf{v}'\mathbf{v}''}$ can be achieved by $\Psi(-\mathbf{v}') \cdot \Phi(\xi) \cdot \Psi(\mathbf{v}')$ with $\Phi(\xi) = \Phi_z(\lambda) \cdot \Phi_y(\varphi) \cdot \Phi_x(\xi) \cdot \Phi_y(-\varphi) \cdot \Phi_z(-\lambda)$ and angles λ and φ as presented in figure 5.5.

Transformation are here mostly used in two ways:

- A datum change is a combination of aligning the part with the machine coordinate system (section 5.3.3) and then mis-aligning it again to represent the setup and machining errors.
- During bending, some vertices of the part (that is those on one side of the bending line) are rotated around the bend line.

Figure 5.5: The general case of rotation (modified from Krzysztof (1991))

5.3 Sheet Metal Forming Operations

A sheet metal process plan is here defined as a sequence of processes consisting of:

- Three datum points **a**, **b**, and **c** (e.g. the names of the vertices at the workpiece or expressions of them) and a flag X or Y indicating whether the two-point datum (datums **a** and **b**) defines the X- or Y-axis of the WCS. The choice of datums **a** and **b** must be such that the construction of a WCS coordinate system as described below results in a right-handed coordinate system (or **a** and **b** must be exchanged).
- An additional datum point **d** which is used to orient the part with respect to the support (thus is a surrogate for the 3 point datum; see section 5.3.3).
- The operation type and specific process parameters
 - For bending operations: the location of the bend line, the bend angle, and an identification of the points to be rotated

- For punching operations: the location of the hole
- Process tolerances
- Setup constraints and tolerances.

A process is merely a sequence of lists of vertices of parts and their coordinates – called post-process coordinates – in the WCS after a process was performed. The first element in this list comprises the vertices at the corners of the blank, intermittent lists includes the vertices of the workpiece after a certain number of processes and the last list in the sequence contains the vertices of the finished part. Typically, each list in this sequence will comprise more vertices than its predecessor as operations add more features to the part.

The transformation of the part during a process is achieved as follows:

- Step 1: Create the MCS_0 and corresponding (post-process) coordinates for the vertices of the blank part (section 5.3.2). Use these coordinates as input for the next step.
- Step 2 (repeat for all processes):
 - For operation j , calculate the so called pre-process coordinates $\mathbf{V}_{i,j}^w$ for this operation from the post-process coordinates of the preceding operation by
 - * Defining WCS_{j-1} as MCS_{j-1} , then calculate MCS_i based on the datums specified for this process (see section 5.3.3), and then
 - * Displacing the part according to some observed setup errors δP_{ia} , δP_{ib} and δP_{ic} (random numbers in the case of a Monte-Carlo simulation).
 - Add an operation constraint on the surface features and calculate the post-process coordinates of all vertices and essential points after this operation, considering relative machining errors such as δL_b , δL_p , or $\delta \alpha$.
- Step 3: determine the position of all surfaces from the post-process coordinates and compare them with the design specification.

These steps, together with the process plan and the details given in the following sections, allow a straightforward implementation of tolerance transfer:

1. The matrices corresponding to all displacements of the part and coordinate transformations are functions of the data given in the process plan and/or the post-process coordinates of the preceding operation.
2. For punching operations, new vertices are added to the corresponding lists in the process plan. These coordinates are given by the definition of the operation.
3. For bending operations, two vertices with coordinates defined by the process giving the location of the bending line are added and some vertices are rotated around the bending line.

Notably, no optimization, approximation or similar mathematical operation is used in this procedure. It means that the calculated positions of the points are exact within the limits of the assumptions of the tolerance model and the computational effort is within the limits allowing a (Monte-Carlo) simulation.

5.3.1 Review on the Procedure

Based on the process plan above, the MCS and WCS coordinates of each points can be calculated step by step as below:

$$\begin{array}{ccccccc}
 & & & & \tilde{\mathbf{V}}_0^{\mathbf{m}} & \xrightarrow{\text{Defines}} & \mathbf{V}_0^{\mathbf{w}} \\
 \mathbf{V}_0^{\mathbf{w}} & \xrightarrow{\mathbf{T}_1, \mathbf{W}_1} & \mathbf{V}_1^{\mathbf{m}} & \xrightarrow[\text{parameters}]{\text{Process}} & \tilde{\mathbf{V}}_1^{\mathbf{m}} & \xrightarrow{\text{Defines}} & \mathbf{V}_1^{\mathbf{w}} \\
 \mathbf{V}_1^{\mathbf{w}} & \xrightarrow{\mathbf{T}_2, \mathbf{W}_2} & \mathbf{V}_2^{\mathbf{m}} & \xrightarrow[\text{parameters}]{\text{Process}} & \tilde{\mathbf{V}}_1^{\mathbf{m}} & \xrightarrow{\text{Defines}} & \mathbf{V}_2^{\mathbf{w}} \\
 & & & \dots & & & \\
 \mathbf{V}_{n-1}^{\mathbf{w}} & \xrightarrow{\mathbf{T}_n, \mathbf{W}_n} & \mathbf{V}_n^{\mathbf{m}} & \xrightarrow[\text{parameters}]{\text{Process}} & \tilde{\mathbf{V}}_n^{\mathbf{m}} & \xrightarrow{\text{Defines}} & \mathbf{V}_n^{\mathbf{w}}
 \end{array}$$

Here $\mathbf{V}_j^{\mathbf{w}}$ stands for the WCS coordinates of all points of the workpiece after the j th operation respectively; $\mathbf{V}_j^{\mathbf{m}}$ and $\tilde{\mathbf{V}}_j^{\mathbf{m}}$ are the MCS coordinates of

all points of the workpiece before and after the j th operation; $\mathbf{W}_j$ and $\mathbf{T}_j$ are corresponding matrices for aligning and mis-aligning the coordinate systems for the j th operation; and $\mathbf{V}_n^w$ describes the coordinates of the vertices of the final part, which then can be compared with the design specification. In this paper $\mathbf{V}_j^w$ is defined as the same as $\tilde{\mathbf{V}}_{j-1}^m$.

5.3.2 Blanking

The post-process coordinates of the blanking operation define the actual shape of the blank. They are based the design dimensions and on the observed blanking errors δB_i (that is a set of random numbers from ΔB in the case of a Monte-Carlo simulation) and assigned to all vertices at the corners of the blank.

For example, after setting up the pre-process WCS_0 , the coordinates of the four vertices of the blank shown in figure 5.6 are the sums of the ideal coordinates and blanking errors δB_i . Equation 5.8 shows the resulting coordinates.

$$\begin{pmatrix} \mathbf{v}_{1A,0}^w & \mathbf{v}_{2A,0}^w & \mathbf{v}_{3A,0}^w & \mathbf{v}_{4A,0}^w \end{pmatrix} = \begin{pmatrix} 0 & L_1 + \delta B_1 & 0 & L_1 + \delta B_1 \\ 0 & 0 & L_2 + \delta B_2 & L_2 + \delta B_2 \\ T + \delta T & T + \delta T & T + \delta T & T + \delta T \\ 1 & 1 & 1 & 1 \end{pmatrix} \quad (5.8)$$

$$\mathbf{v}_{iB,0}^w = \mathbf{v}_{iA,0}^w - \begin{pmatrix} 0 \\ 0 \\ T + \delta T \\ 0 \end{pmatrix} \quad (1 \leq i \leq 4) \quad (5.9)$$

5.3.3 Aligning the WCS with the MCS

Before process j can be performed, the workpiece has to be aligned with the MCS_j . This is done by defining a coordinate system using some selected vertices, and applying an orthogonal transformation that maps MCS_{j-1} onto the MCS_j . For sheet metal processes, commonly only a 2-point and a 1-point datum are defined (the surface of the sheet serves as 3-point datum). Here,

Figure 5.6: The blank with blanking errors

to simplify the discussion, 3 vertices (that is corners of the part) are chosen for these datums: $\mathbf{v}_a$ and $\mathbf{v}_b$ form the 2-point datum and $\mathbf{v}_c$ forms the 1-point datum. As the 1-point datum may refer to the same corner of the part and the orientation of the sheet is then undefined, a forth vertex $\mathbf{v}_d$, which is not collinear with the two-point datum, is needed (if $\mathbf{v}_a, \mathbf{v}_b \neq \mathbf{v}_c, \mathbf{v}_c = \mathbf{v}_d$ is allowed). All four vertices must be chosen from the surface of the part used as supporting surface (the 3-point datum).

Two situations need to be considered: either the two-point datum defines the X-axis or the Y-axis of the WCS. The earlier case is discussed first. Be $\mathbf{u}_a = \mathbf{v}_a$ and $\mathbf{u}_b = \mathbf{v}_b$ or *vice versa* if the following construction results in a left-handed coordinate system. The X-, Y-, and Z-axis of the WCS_j are then²

²The cross product of vectors is defined as the cross product of the un-augmented vectors to which a zero is added.

$$\begin{aligned}\mathbf{w}_1 &= \frac{\mathbf{u}_a - \mathbf{u}_b}{\|\mathbf{u}_a - \mathbf{u}_b\|} \\ \mathbf{w}_3 &= \frac{\mathbf{w}_1 \times (\mathbf{u}_a - \mathbf{v}_d)}{\|\mathbf{w}_1 \times (\mathbf{u}_a - \mathbf{v}_d)\|} \\ \mathbf{w}_2 &= \mathbf{w}_1 \times \mathbf{w}_3.\end{aligned}$$

The orthogonal transformation for mapping WCS_{j-1} onto the new MCS_j is given by the matrix $\mathbf{W} = \begin{pmatrix} \mathbf{w}_1 & \mathbf{w}_2 & \mathbf{w}_3 & \mathbf{o} \end{pmatrix}$, with $\mathbf{o}$ the chosen origin of the WCS_{j-1} (e.g. $\mathbf{o} = -\mathbf{v}_a$).

In the case that the two-point datum defines the Y-axis of the WCS, the definitions if $\mathbf{w}_1$ and $\mathbf{w}_2$ have to be exchanged.

5.3.4 Locating the Part

Usually, a part is not perfectly aligned with the datum points as section 5.3.3 suggests. This positioning error is represented by a transformation matrix $\mathbf{T}$ which is directly determined from the positioning errors committed at individual datum points.

For example, figure 5.6 and 5.7 show the datum points $\mathbf{a}$, $\mathbf{b}$ and $\mathbf{c}$, that are located on the surface s_{1B} . Then, if L is the distance between datums $\mathbf{a}$ and $\mathbf{b}$, the workpiece is rotated by angle

$$\beta = \arctan \frac{\delta P_b - \delta P_a}{L}. \quad (5.10)$$

The transformation matrix $\mathbf{T}$ (see equation 5.11) changes the WCS coordinates to include the misalignment with the MCS coordinates. As the angle β resulting from the distance is small, $\mathbf{T}$ is the result of a rotation of the workpiece around datum $\mathbf{a}$ followed by a displacement of the part along the X-axis by δP_c and along the Y-axis by δP_a . Here $\mathbf{v}_1$ is the theoretical origin of the MCS and WCS.

$$\mathbf{T} = \mathbf{\Psi}(\delta P_c, \delta P_a, 0) \cdot \mathbf{\Phi}_z(-\beta) = \begin{pmatrix} \cos(\beta) & \sin(\beta) & 0 & \delta P_c \\ -\sin(\beta) & \cos(\beta) & 0 & \delta P_a \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (5.11)$$

Consequently, if $\tilde{\mathbf{V}}_{j-1}^{\mathbf{m}}$ are the post-process MCS coordinates of a previous

process and $\mathbf{V}_{j-1}^w$ is defined as $\tilde{\mathbf{V}}_{j-1}^m$, then $\mathbf{T} \cdot \mathbf{W} \cdot \tilde{\mathbf{V}}_{j-1}^m$ are the pre-process MCS coordinates of the current process.

5.3.5 Punching

Figure 5.7: The punching operation

As punching operations do not change the coordinates of existed features, their pre-and post-process coordinates are identical. The coordinates of vertices defining newly created holes are the sum of the operational parameters (*i.e.* the distance to the origin of the WCS) and the machining errors ΔL_p . The coordinates describing the new features are simply appended to the pre-process coordinates, becoming the post-process coordinates.

A punching operation is sketched in figure 5.7. The center line of the hole is defined by two points $\mathbf{v}_{5A}^m$ and $\mathbf{v}_{5B}^m$. Their MCS coordinates are:

$$\tilde{\mathbf{v}}_{5A}^{\mathbf{m}} = \begin{pmatrix} L_3 + \delta L_{p1} \\ L_4 + \delta L_{p2} \\ T + \delta T \\ 1 \end{pmatrix} \quad (5.12)$$

$$\tilde{\mathbf{v}}_{5B}^{\mathbf{m}} = \tilde{\mathbf{v}}_{5A}^{\mathbf{m}} - \begin{pmatrix} 0 \\ 0 \\ T + \delta T \\ 0 \end{pmatrix} \quad (5.13)$$

where the δL_{pk} are the machining errors of the punching operation and k identifies the error in length for the k th basic dimension.

5.3.6 Bending

During bending operations, a blank can be regarded as a combination of three sections: the fixed, bent (bend allowance), and transformed section, as shown in figure 5.8. Vertices of the fixed section do not change their position with respect to the WCS. The bent section is plastically deformed, of which the bending line e is the centerline. The transformed section is the reminder of the part, rotating around the bending line (relative positions of vertices in this part is invariable).

Correspondingly the process plan divides the pre-process coordinates into three sets, depending in which they are situated. Pre- and post-process coordinates are identical of vertices in the fixed section. Those in the transformed section are rotated around an axis defined by the bending line using a rotation matrix $\mathbf{R}$ and a translation $\mathbf{B}$: if $\mathbf{v}$ are the pre-process coordinates of a vertex, the post-process coordinates are $\mathbf{B} \cdot \mathbf{R} \cdot \mathbf{v}$. The bending line e is defined by the bending axis through points $p_{1,1}$ and $p_{1,2}$ and parallel to X-axis of the MCS. It is the intersection of the neutral plane of the sheet metal and the perpendicular plane the bending line locates (parallel to XZ plane). $\mathbf{R}$ is obtained by adding the machining error ΔL_b to the operational parameters of the bending operation (the bending line is assumed to be parallel to the X-axis of the MCS). After rotation, the position of the transformed vertices must be corrected to accommodate the error caused by bending allowances modelled by matrix $\mathbf{B}$.

The coordinates associated with the vertices $\mathbf{v}'$ and $\mathbf{v}''$ describing the

bend are obtained by an intersection of the bend line with the outline of the part. The coordinates $\mathbf{v}'$ and the sum of the bend angle α and the error $\Delta\alpha$ allow to define $\mathbf{R} = \Psi(-\mathbf{v}')\Phi(180^\circ - \alpha - \delta\alpha)\Psi(\mathbf{v}')$. The vertices $\mathbf{v}'$ and $\mathbf{v}''$ are appended to the list of post-process coordinates.

Figure 5.8 illustrates the bending of a rectangular blank. The dimension of the blank is determined through unfolding with the dimensions of the final part and corresponding bend allowances.

Figure 5.8: Transforming of bending operation

The length of the blank L_2 is:

$$L_2 = (L_3 - R) + BA + (L_4 - R - T) \quad (5.14)$$

The bending length (the distance between the nominal position of the two-point datum and the punch) is $L_b = L_3 - R + \frac{BA}{2}$.

The straight lines l_1 (between v_{1A} and v_{3A}) and l_2 (between v_{2A} and v_{4A}) is expressed as the equations of the coordinates of these vertices.

The bending operation creates line e and the round corner with vertices v_{5A} , v_{6A} , v_{5B} and v_{6B} . In MCS, as the distance between e and X-axis of

the MCS is $L_b + \delta L_b$, the coordinates of the intersection vertices v_{5A} and v_{6A} can be calculated using $Y = L_b + \frac{BA}{2} + \delta L_b$, and v_{7A} and v_{8A} with $Y = L_b - \frac{BA}{2} + \delta L_b$.

For the bending operation illustrated in figure 5.8, the MCS coordinates are:

$$\mathbf{v}_{5A}^{\mathbf{m}} = \begin{pmatrix} \delta P_c + (L_b + \frac{BA}{2} + \delta L_b - \delta P_a) \tan(\beta) \\ L_b + \frac{BA}{2} + \delta L_b \\ T + \delta T \\ 1 \end{pmatrix} \quad (5.15)$$

$$\mathbf{v}_{6A}^{\mathbf{m}} = \mathbf{v}_{5A}^{\mathbf{m}} + \begin{pmatrix} \frac{L_1 + \delta B_1}{\cos(\beta)} \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad (5.16)$$

$$\mathbf{v}_{5B}^{\mathbf{m}} = \mathbf{v}_{5A}^{\mathbf{m}} - \begin{pmatrix} 0 \\ 0 \\ T + \delta T \\ 0 \end{pmatrix} \quad (5.17)$$

$$\mathbf{v}_{6B}^{\mathbf{m}} = \mathbf{v}_{6A}^{\mathbf{m}} - \begin{pmatrix} 0 \\ 0 \\ T + \delta T \\ 0 \end{pmatrix} \quad (5.18)$$

$$\tilde{\mathbf{v}}_{7A}^{\mathbf{m}} = \mathbf{v}_{7A}^{\mathbf{m}} = \begin{pmatrix} \delta P_c + (L_b - \frac{BA}{2} + \delta L_b - \delta P_a) \tan(\beta) \\ L_b - \frac{BA}{2} + \delta L_b \\ T + \delta T \\ 1 \end{pmatrix} \quad (5.19)$$

$$\tilde{\mathbf{v}}_{8A}^{\mathbf{m}} = \mathbf{v}_{8A}^{\mathbf{m}} = \mathbf{v}_{7A}^{\mathbf{m}} + \begin{pmatrix} \frac{L_1 + \delta B_1}{\cos(\beta)} \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad (5.20)$$

$$\tilde{\mathbf{v}}_{7B}^{\mathbf{m}} = \mathbf{v}_{7B}^{\mathbf{m}} = \mathbf{v}_{7A}^{\mathbf{m}} - \begin{pmatrix} 0 \\ 0 \\ T + \delta T \\ 0 \end{pmatrix} \quad (5.21)$$

$$\tilde{\mathbf{v}}_{8B}^{\mathbf{m}} = \mathbf{v}_{8B}^{\mathbf{m}} = \mathbf{v}_{8A}^{\mathbf{m}} - \begin{pmatrix} 0 \\ 0 \\ T + \delta T \\ 0 \end{pmatrix} \quad (5.22)$$

The two points $p_{1,1}$ and $p_{1,2}$ situating the bending axis have the coordinates:

$$\mathbf{p}_{1,1}^{\mathbf{m}} = \begin{pmatrix} \delta P_c + (L_b + \delta L_b - \delta P_a) \tan(\beta) \\ L_b + \delta L_b \\ \frac{1}{2} \cdot (T + \delta T) \\ 1 \end{pmatrix} \quad (5.23)$$

$$\mathbf{p}_{1,2}^{\mathbf{m}} = \mathbf{p}_{1,1}^{\mathbf{m}} + \begin{pmatrix} \frac{L_1 + \delta B_1}{\cos(\beta)} \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad (5.24)$$

The rotation matrices $\mathbf{R}$ is:

$$\begin{aligned} \mathbf{R} &= \Psi(\mathbf{p}_{1,1}^{\mathbf{m}}) \cdot \Phi_x(90 - \delta\alpha) \cdot \Psi(-\mathbf{p}_{1,1}^{\mathbf{m}}) \\ &= \begin{pmatrix} 1 & 0 & 0 & \delta P_c + (L_b - \frac{B_1}{2} + \delta L_b - \delta P_a) \tan(\beta) \\ 0 & \sin(\delta\alpha) & -\cos(\delta\alpha) & (L_b - \frac{B_1}{2} + \delta L_b)(1 - \sin(\delta\alpha)) + K(T + \delta T) \cos(\delta\alpha) \\ 0 & \cos(\delta\alpha) & \sin(\delta\alpha) & -(L_b - \frac{B_1}{2} + \delta L_b) \cos(\delta\alpha) + K(T + \delta T)(1 - \sin(\delta\alpha)) \\ 0 & 0 & 0 & 1 \end{pmatrix} \end{aligned} \quad (5.25)$$

$$\mathbf{B} = \begin{pmatrix} 1 & 0 & 0 & a \\ 0 & 1 & 0 & b \\ 0 & 0 & 1 & c \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (5.26)$$

The parameters a, b, c in the translation matrix $\mathbf{B}$ can be calculated from the pre- and post-process coordinates of $\mathbf{v}_{5A}, \mathbf{v}_{6A}, \mathbf{v}_{5B}, \mathbf{v}_{6B}$ based on the equations 5.27 and 5.28 below. For example, for the vertex $\mathbf{v}_{5A}$, the coordinates before bending are known; after translation, the X coordinate is assumed unchanged, the Y coordinate is L_3 , the Z coordinate is $R + T + dT$. In consequence, the post-process coordinates of all vertices are:

$$\tilde{\mathbf{V}}_A^m = (\mathbf{v}_{1A}^m \quad \mathbf{v}_{2A}^m \quad \mathbf{B} \cdot \mathbf{R} \cdot \mathbf{v}_{3A}^m \quad \mathbf{B} \cdot \mathbf{R} \cdot \mathbf{v}_{4A}^m \\ \mathbf{B} \cdot \mathbf{R} \cdot \mathbf{v}_{5A}^m \quad \mathbf{B} \cdot \mathbf{R} \cdot \mathbf{v}_{6A}^m \quad \mathbf{v}_{7A}^m \quad \mathbf{v}_{8A}^m) \quad (5.27)$$

$$\tilde{\mathbf{V}}_B^m = (\mathbf{v}_{1B}^m \quad \mathbf{v}_{2B}^m \quad \mathbf{B} \cdot \mathbf{R} \cdot \mathbf{v}_{3B}^m \quad \mathbf{B} \cdot \mathbf{R} \cdot \mathbf{v}_{4B}^m \\ \mathbf{B} \cdot \mathbf{R} \cdot \mathbf{v}_{5B}^m \quad \mathbf{B} \cdot \mathbf{R} \cdot \mathbf{v}_{6B}^m \quad \mathbf{v}_{7B}^m \quad \mathbf{v}_{8B}^m) \quad (5.28)$$

As the points $\tilde{\mathbf{v}}_{iA,1}^m, \tilde{\mathbf{v}}_{iB,1}^m (1 \leq i \leq 8)$ are in the same coordinate system, they define the shape of the part.

The generalized procedure of the MCS post-process coordinates is summarized in table 5.3. The label i indicates the number of a vertex, and j that the coordinates are associated to the j th operation (for the blank: $j = 0$).

Table 5.3: Post-process coordinates

	Created Vertices	Existing Vertices
Transformed Section	$\tilde{\mathbf{v}}_{iA,j}^m = \mathbf{B}_j \cdot \mathbf{R}_j \cdot \mathbf{v}_{iA,j}^m$ $\tilde{\mathbf{v}}_{iB,j}^m = \mathbf{B}_j \cdot \mathbf{R}_j \cdot \mathbf{v}_{iB,j}^m$	$\tilde{\mathbf{v}}_{iA,j}^m = \mathbf{B}_j \cdot \mathbf{R}_j \cdot \mathbf{v}_{iA,j}^m$ $= \mathbf{B}_j \cdot \mathbf{R}_j \cdot \mathbf{T}_j \cdot \mathbf{W}_j \cdot \mathbf{v}_{iA,j-1}^w$ $\tilde{\mathbf{v}}_{iB,j}^m = \mathbf{B}_j \cdot \mathbf{R}_j \cdot \mathbf{v}_{iB,j}^m$ $= \mathbf{B}_j \cdot \mathbf{R}_j \cdot \mathbf{T}_j \cdot \mathbf{W}_j \cdot \mathbf{v}_{iB,j-1}^w$
Fixed Section	$\tilde{\mathbf{v}}_{iA,j}^m = \mathbf{v}_{iA,j}^m$ $\tilde{\mathbf{v}}_{iB,j}^m = \mathbf{v}_{iB,j}^m$	$\tilde{\mathbf{v}}_{iA,j}^m = \mathbf{v}_{iA,j}^m$ $= \mathbf{T}_j \cdot \mathbf{W}_j \cdot \mathbf{v}_{iA,j-1}^w$ $\tilde{\mathbf{v}}_{iB,j}^m = \mathbf{v}_{iB,j}^m$ $= \mathbf{T}_j \cdot \mathbf{W}_j \cdot \mathbf{v}_{iB,j-1}^w$
Bent Section	Shared with transformed and fixed section	None

5.4 Example Parts

The procedure outlined in section 5.3 is exemplified for a U-shaped part and a part with three non-parallel bends and punched holes.

5.4.1 Case Study: U-shaped Part

The process plan for the part in figure 5.9 and 5.10 is summarized in table 5.4.

Figure 5.9: The flattened design of a U-shape part with blanking errors

Bending Operation 1

For the given choice of datum points, an alignment of the WCS and the MCS of the first operation is achieved by $\mathbf{W}_1$ (an identity matrix). The misalignment of the WCS and the MCS results in the pre-process coordinates $\mathbf{v}_{iA,1}^m = \mathbf{T}_1 \cdot \mathbf{W}_1 \cdot \mathbf{v}_{iA,0}^w$ and $\mathbf{v}_{iB,1}^m = \mathbf{T}_1 \cdot \mathbf{W}_1 \cdot \mathbf{v}_{iB,0}^w$, with the coordinates of the blank as given in equation (5.8) and (5.9), and $\mathbf{T}_1 = \Psi(\delta P_{1c}, \delta P_{1a}, 0) \cdot \Phi_z(-\beta_1)$.

The length of the blank L_2 is:

$$L_2 = (L_3 - R) + BA + (L_4 - R - R - 2T) + BA + (L_5 - R) \quad (5.29)$$

Figure 5.10: Prototype of a U-shape part

Here bend allowance BA is calculated as in equation 2.1.1, R and α are fixed values for each operation in this chapter.

As the bending line e_1 is defined as $Y = L_{b1} + \delta L_{b1}$, the coordinates of the intersection vertices v_{5A} and v_{6A} are determined by the equation $Y = L_{b1} + \frac{BA}{2} + \delta L_{b1}$, and v_{7A} and v_{8A} by $Y = L_{b1} - \frac{BA}{2} + \delta L_{b1}$.

The bending length L_{b1} is:

$$L_{b1} = L_3 - R + \frac{BA}{2} \quad (5.30)$$

Then the MCS coordinates of all vertices, including $\mathbf{v}_{5A,1}^m, \mathbf{v}_{5B,1}^m, \mathbf{v}_{6A,1}^m, \mathbf{v}_{6B,1}^m, \mathbf{v}_{7A,1}^m, \mathbf{v}_{7B,1}^m, \mathbf{v}_{8A,1}^m$ and $\mathbf{v}_{8B,1}^m$, are calculated as the equations in section 5.3.6.

The two points $p_{1,1}$ and $p_{1,2}$ describing the bending axis have the coordinates:

Table 5.4: The process plan of a U-shaped Part (two-point datum on X-axis)

Operation	Datum				Created vertices	Transformed vertices
	a	b	c	d		
Bending 1	v_{1B}	v_{2B}	v_{1B}	v_{3B}	$v_{5A}, v_{5B}, v_{6A}, v_{6B}, v_{7A}, v_{7B}, v_{8A}, v_{8B}$	$v_{3A}, v_{3B}, v_{4A}, v_{4B}, v_{5A}, v_{5B}, v_{6A}, v_{6B}$
Bending 2	v_{7B}	v_{8B}	v_{7B}	v_{3B}	$v_{9A}, v_{9B}, v_{10A}, v_{10B}, v_{11A}, v_{11B}, v_{12A}, v_{12B}$	$v_{3A}, v_{3B}, v_{4A}, v_{4B}, v_{9A}, v_{9B}, v_{10A}, v_{10B}$

$$\mathbf{p}_{1,1}^{\mathbf{m}} = \begin{pmatrix} \delta P_{1c} + (L_{b1} + \delta L_{b1} - \delta P_{1a}) \tan(\beta_1) \\ L_{b1} + \delta L_{b1} \\ \frac{1}{2} \cdot (T + \delta T) \\ 1 \end{pmatrix} \quad (5.31)$$

$$\mathbf{p}_{1,2}^{\mathbf{m}} = \mathbf{p}_{1,1}^{\mathbf{m}} + \begin{pmatrix} \frac{L_1 + \delta B_1}{\cos(\beta_1)} \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad (5.32)$$

The rotation around the bending axis is described by $\mathbf{R}_1 = \Psi(\mathbf{p}_{1,1}^{\mathbf{m}}) \cdot \Phi_x(90 - \delta\alpha) \cdot \Psi(-\mathbf{p}_{1,1}^{\mathbf{m}})$.

The translation matrix $\mathbf{B}_1$ can be calculated from the pre- and post-process coordinates of $\mathbf{v}_{5A}, \mathbf{v}_{6A}, \mathbf{v}_{5B}, \mathbf{v}_{6B}$. The post-process coordinates of all vertices are in table 5.5.

Bending Operation 2

The datum change matrix $\mathbf{W}_2$ is based on the MCS coordinates of three points on the part: $\mathbf{v}_{7B,1}^{\mathbf{m}}, \mathbf{v}_{8B,1}^{\mathbf{m}}$ and $\mathbf{v}_{7A,1}^{\mathbf{m}}$ (see table 5.4).

The bending length L_{b2} is:

$$L_{b2} = L_4 - T - R + \frac{BA}{2} \quad (5.33)$$

Matrix $\mathbf{T}_2$ models the misalignment of the workpiece with the datum points.

Table 5.5: Post-process coordinates of operation 1

	Created Vertices	Existing Vertices
Transformed Section	For $i \in \{5, 6\}$ $\tilde{\mathbf{v}}_{iA,1}^{\mathbf{m}} = \mathbf{B}_1 \cdot \mathbf{R}_1 \cdot \mathbf{v}_{iA,1}^{\mathbf{m}}$ $\tilde{\mathbf{v}}_{iB,1}^{\mathbf{m}} = \mathbf{B}_1 \cdot \mathbf{R}_1 \cdot \mathbf{v}_{iB,1}^{\mathbf{m}}$	For $i \in \{3, 4\}$ $\tilde{\mathbf{v}}_{iA,1}^{\mathbf{m}} = \mathbf{B}_1 \cdot \mathbf{R}_1 \cdot \mathbf{v}_{iA,1}^{\mathbf{m}}$ $= \mathbf{B}_1 \cdot \mathbf{R}_1 \cdot \mathbf{T}_1 \cdot \mathbf{W}_1 \cdot \mathbf{v}_{iA,0}^{\mathbf{w}}$ $\tilde{\mathbf{v}}_{iB,1}^{\mathbf{m}} = \mathbf{B}_1 \cdot \mathbf{R}_1 \cdot \mathbf{v}_{iB,1}^{\mathbf{m}}$ $= \mathbf{B}_1 \cdot \mathbf{R}_1 \cdot \mathbf{T}_1 \cdot \mathbf{W}_1 \cdot \mathbf{v}_{iB,0}^{\mathbf{w}}$
Fixed Section	For $i \in \{7, 8\}$ $\tilde{\mathbf{v}}_{iA,1}^{\mathbf{m}} = \mathbf{v}_{iA,1}^{\mathbf{m}}$ $\tilde{\mathbf{v}}_{iB,1}^{\mathbf{m}} = \mathbf{v}_{iB,1}^{\mathbf{m}}$	For $i \in \{1, 2\}$ $\tilde{\mathbf{v}}_{iA,1}^{\mathbf{m}} = \mathbf{v}_{iA,1}^{\mathbf{m}}$ $= \mathbf{T}_1 \cdot \mathbf{W}_1 \cdot \mathbf{v}_{iA,0}^{\mathbf{w}}$ $\tilde{\mathbf{v}}_{iB,1}^{\mathbf{m}} = \mathbf{v}_{iB,1}^{\mathbf{m}}$ $= \mathbf{T}_1 \cdot \mathbf{W}_1 \cdot \mathbf{v}_{iB,0}^{\mathbf{w}}$
Bent Section	Shared with transformed and fixed section	None

$$\mathbf{T}_2 = \Psi(\delta P_{2c}, \delta P_{2a}, 0) \cdot \Phi_z(-\beta_2) = \begin{pmatrix} \cos(\beta_2) & \sin(\beta_2) & 0 & \delta P_{2c} \\ -\sin(\beta_2) & \cos(\beta_2) & 0 & \delta P_{2a} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (5.34)$$

The rotation matrix $\mathbf{R}_2 = \Psi(\mathbf{p}_{2,1}^{\mathbf{m}}) \cdot \Phi_x(90 - \delta\alpha) \cdot \Psi(-\mathbf{p}_{2,1}^{\mathbf{m}})$ describes the rotation around bending axis through $\mathbf{p}_{2,1}$ and $\mathbf{p}_{2,2}$.

The translation matrix $\mathbf{B}_2$ is determined by the pre- and post-process coordinates of $\mathbf{v}_{9A}$, $\mathbf{v}_{10A}$, $\mathbf{v}_{9B}$, $\mathbf{v}_{10B}$. The post-process coordinates of all vertices are in table 5.6.

Tolerance Transfer and Monte-Carlo Simulation

The errors for the finished part are calculated using Monte Carlo simulation. This simulation uses relative position of vertices and surfaces, which allows to calculate their deviation from the specified geometrical tolerances caused by machining errors .

For this example: v_{1B} , v_{2B} , v_{7B} , v_{8B} are on the same surface s_{2B} , and v_{3B} , v_{4B} , v_{9B} , v_{10B} are all on the surface s_{5B} . The distances d_1, d_2, d_3 and d_4 between v_{3B} , v_{4B} , v_{9B} , v_{10B} and s_{2B} , respectively, are:

Table 5.6: Post-process coordinates of operation 2

	Created Vertices	Existing Vertices
Transformed Section	For $i \in \{9, 10\}$ $\tilde{\mathbf{v}}_{iA,2}^m = \mathbf{B}_2 \cdot \mathbf{R}_2 \cdot \mathbf{v}_{iA,2}^m$ $\tilde{\mathbf{v}}_{iB,2}^m = \mathbf{B}_2 \cdot \mathbf{R}_2 \cdot \mathbf{v}_{iB,2}^m$	For $i \in \{3, 4\}$ $\tilde{\mathbf{v}}_{iA,2}^m = \mathbf{B}_2 \cdot \mathbf{R}_2 \cdot \mathbf{v}_{iA,2}^m$ $= \mathbf{B}_2 \cdot \mathbf{R}_2 \cdot \mathbf{T}_2 \cdot \mathbf{W}_2 \cdot \mathbf{v}_{iA,1}^w$ $\tilde{\mathbf{v}}_{iB,2}^m = \mathbf{B}_2 \cdot \mathbf{R}_2 \cdot \mathbf{v}_{iB,2}^m$ $= \mathbf{B}_2 \cdot \mathbf{R}_2 \cdot \mathbf{T}_2 \cdot \mathbf{W}_2 \cdot \mathbf{v}_{iB,1}^w$
Fixed Section	For $i \in \{11, 12\}$ $\tilde{\mathbf{v}}_{iA,2}^m = \mathbf{v}_{iA,2}^m$ $\tilde{\mathbf{v}}_{iB,2}^m = \mathbf{v}_{iB,2}^m$	For $i \in \{1, 2, 5, 6, 7, 8\}$ $\tilde{\mathbf{v}}_{iA,2}^m = \mathbf{v}_{iA,2}^m$ $= \mathbf{T}_2 \cdot \mathbf{W}_2 \cdot \mathbf{v}_{iA,1}^w$ $\tilde{\mathbf{v}}_{iB,2}^m = \mathbf{v}_{iB,2}^m$ $= \mathbf{T}_2 \cdot \mathbf{W}_2 \cdot \mathbf{v}_{iB,1}^w$
Bent Section	Shared with transformed and fixed section	None

$$d_1 = \left| \frac{\tilde{v}_{3B,2,y}^m - \frac{\tilde{v}_{1B,2,y}^m}{\tilde{v}_{1B,2,z}^m} \cdot \tilde{v}_{3B,2,z}^m}{\sqrt{1 + \left(\frac{\tilde{v}_{1B,2,y}^m}{\tilde{v}_{1B,2,z}^m}\right)^2}} \right| \quad (5.35)$$

$$d_2 = \left| \frac{\tilde{v}_{4B,2,y}^m - \frac{\tilde{v}_{1B,2,y}^m}{\tilde{v}_{1B,2,z}^m} \cdot \tilde{v}_{4B,2,z}^m}{\sqrt{1 + \left(\frac{\tilde{v}_{1B,2,y}^m}{\tilde{v}_{1B,2,z}^m}\right)^2}} \right| \quad (5.36)$$

$$d_3 = \left| \frac{\tilde{v}_{9B,2,y}^m - \frac{\tilde{v}_{1B,2,y}^m}{\tilde{v}_{1B,2,z}^m} \cdot \tilde{v}_{9B,2,z}^m}{\sqrt{1 + \left(\frac{\tilde{v}_{1B,2,y}^m}{\tilde{v}_{1B,2,z}^m}\right)^2}} \right| \quad (5.37)$$

$$d_4 = \left| \frac{\tilde{v}_{10B,2,y}^m - \frac{\tilde{v}_{1B,2,y}^m}{\tilde{v}_{1B,2,z}^m} \cdot \tilde{v}_{10B,2,z}^m}{\sqrt{1 + \left(\frac{\tilde{v}_{1B,2,y}^m}{\tilde{v}_{1B,2,z}^m}\right)^2}} \right|. \quad (5.38)$$

Let $E = \max_{1 \leq k \leq 4} |d_k - L_4|$; then the tolerance constraint on the position of the two holes is equivalent to $E \leq T_1$. The distribution of error E was simulated using a Monte-Carlo simulation method over one hundred thousand random samples ($L_1 = 25\text{mm}$, $L_3 = 15\text{mm}$, $L_4 = 15\text{mm}$, $L_5 = 10\text{mm}$, $t = 2\text{mm}$, $K = 0.42$ (AL 1050), $\alpha = 90^\circ$, and the machining errors given in table 4.1). Figure 5.11 shows both a frequency histogram of E based on 0.01mm wide intervals and a normal distribution with the sample median (0.015mm) and standard deviation (0.013mm) as the data. The distribution of E is obviously not a normal distribution.

Figure 5.11: Histogram of E

The $\pm 2\sigma$ and $\pm 3\sigma$ limits of the deviation of the samples are displayed in figure 5.11. For a normal distribution and 4σ or a 6σ requirements, at most 4.55% or 0.227%, respectively, of the samples can be outside of the range of $\hat{p} \pm 2\sigma$ or $\hat{p} \pm 3\sigma$ (with $\hat{p}$ the mean value and σ is the standard deviation of the distribution). In this case, 4.517% and 0.916% of the samples, respectively, are outside this range. It can be concluded an approximation

by a normal distribution may lead to a grossly incorrect estimation for 4σ or 6σ requirement: in this example and for a 6σ requirement, 4 times defect parts would be produced as compared to the estimation based on a normal distribution.

5.4.2 Case Study: An Axle Holder

Figure 5.12: The example part

A complex sheet metal part is specified as shown in figure 5.12, that is made from a blank shown in figure 5.13 by four operations: a concurrent punching of holes h_1 and h_2 , and three successive bending operations. For the punching and the first two bending operations the workpiece is located as indicated in figure 5.13. Bending allowances are as in equation 2.1.1, and for $i = 1, 2$, the machining errors $\delta L_{pi,k}$ for hole i are errors in length with respect to the k th basic dimension.

The process plan is outlined in table 5.7. Note that all bending operations have individual errors as the part has to be replaced on the machine (air bending lifts the part of the machine).

Figure 5.13: The flattened design of the example part with blanking and process errors after the punching operation.

The simulation of the process allows to determine the final coordinates of vertices v_{9A}, v_{9B}, v_{10A} and v_{10B} . These vertices determine the position of the centerlines through hole h_1 and h_2 . The transformation steps are similar to those of the U-shape part above, yet the bend lines in this process are not parallel.

Operation 1: Punching Holes 1 and 2

The first operation punches holes h_1 and h_2 concurrently.

The coordinate system transformation matrix $\mathbf{T}_1$ is similar to $\mathbf{T}$ in equation 5.11 with the exception that β_1 is:

$$\beta_1 = \arctan \frac{\delta P_{1b} - \delta P_{1a}}{L_1 - R + L_2 - R + BA}. \quad (5.39)$$

Matrices $\mathbf{W}_1$ and $\mathbf{B}_1$ are identity matrices.

The MCS coordinates of new vertices (the location of the hole centers)

Table 5.7: The process plan of the example complex part (two-point datum on X-axis)

Operation	Datum				Created vertices	Transformed vertices
	a	b	c	d		
1. Punching	v_{1B}	v_{2B}	v_{1B}	v_{8B}	$v_{9A}, v_{9B}, v_{10A}, v_{10B}$	-
2. Bending e_1	v_{1B}	v_{2B}	v_{1B}	v_{8B}	$v_{11A}, v_{11B}, v_{12A}, v_{12B}, v_{13A}, v_{13B}, v_{14A}, v_{14B}$	$v_{7A}, v_{7B}, v_{8A}, v_{8B}, v_{9A}, v_{9B}$
3. Bending e_2	v_{1B}	v_{2B}	v_{1B}	v_{8B}	$v_{15A}, v_{15B}, v_{16A}, v_{16B}, v_{17A}, v_{17B}, v_{18A}, v_{18B}$	$v_{3A}, v_{3B}, v_{4A}, v_{4B}, v_{10A}, v_{10B}$
4. Bending e_3	v_{2B}	v_{16B}	v_{2B}	v_{1B}	$v_{19A}, v_{19B}, v_{20A}, v_{20B}, v_{21A}, v_{21B}, v_{22A}, v_{22B}$	$v_{1A}, v_{1B}, v_{6A}, v_{6B}, v_{7A}, v_{7B}, v_{8A}, v_{8B}, v_{9A}, v_{9B}, v_{11A}, v_{11B}, v_{12A}, v_{12B}, v_{13A}, v_{13B}, v_{14A}, v_{14B}$

are:

$$\tilde{\mathbf{v}}_{9A,1}^{\mathbf{m}} = \begin{pmatrix} L_1 - L_5 + \delta L_{p1,1} \\ L_2 - R + L_9 - R - L_6 + \delta L_{p1,2} \\ T + \delta T \\ 1 \end{pmatrix} \quad (5.40)$$

$$\tilde{\mathbf{v}}_{9B,1}^{\mathbf{m}} = \tilde{\mathbf{v}}_{9A,1}^{\mathbf{m}} - \begin{pmatrix} 0 \\ 0 \\ T + \delta T \\ 0 \end{pmatrix} \quad (5.41)$$

$$\tilde{\mathbf{v}}_{10A,1}^{\mathbf{m}} = \begin{pmatrix} L_2 - R + L_1 - R - L_6 + BA + \delta L_{p2,1} \\ L_4 - R + L_5 - R + BA + \delta L_{p2,2} \\ T + \delta T \\ 1 \end{pmatrix} \quad (5.42)$$

$$\tilde{\mathbf{v}}_{10B,1}^{\mathbf{m}} = \tilde{\mathbf{v}}_{10A,1}^{\mathbf{m}} - \begin{pmatrix} 0 \\ 0 \\ T + \delta T \\ 0 \end{pmatrix} \quad (5.43)$$

Operation 2: Bending at Line e_1

During the second operation the workpiece is bent at line e_1 .

The bending length is $L_{b1} = L_9 - R + \frac{BA}{2}$.

The transformation matrix $\mathbf{T}_2$ is:

$$\mathbf{T}_2 = \Psi(\delta P_{2c}, \delta P_{2a}, 0) \cdot \Phi_z(-\arctan \frac{\delta P_{2b} - \delta P_{2a}}{L_1 - R + L_2 - R + BA}) \quad (5.44)$$

Matrix $\mathbf{B}_2$ is calculated based on the pre- and post-process coordinates of $\mathbf{v}_{13A}, \mathbf{v}_{14A}, \mathbf{v}_{13B}, \mathbf{v}_{14B}$. The post-process coordinates of all vertices for operation 2 are in table 5.8.

Table 5.8: Post-process coordinates of the complex part of operation 2

	Created Vertices	Existing Vertices
Transformed Section	For $i \in \{13, 14\}$ $\tilde{\mathbf{v}}_{iA,2}^m = \mathbf{B}_2 \cdot \mathbf{R}_2 \cdot \mathbf{v}_{iA,2}^m$ $\tilde{\mathbf{v}}_{iB,2}^m = \mathbf{B}_2 \cdot \mathbf{R}_2 \cdot \mathbf{v}_{iB,2}^m$	For $i \in \{7, 8, 9\}$ $\tilde{\mathbf{v}}_{iA,2}^m = \mathbf{B}_2 \cdot \mathbf{R}_2 \cdot \mathbf{v}_{iA,2}^m$ $= \mathbf{B}_2 \cdot \mathbf{R}_2 \cdot \mathbf{T}_2 \cdot \mathbf{W}_2 \cdot \mathbf{v}_{iA,1}^w$ $\tilde{\mathbf{v}}_{iB,2}^m = \mathbf{B}_2 \cdot \mathbf{R}_2 \cdot \mathbf{v}_{iB,2}^m$ $= \mathbf{B}_2 \cdot \mathbf{R}_2 \cdot \mathbf{T}_2 \cdot \mathbf{W}_2 \cdot \mathbf{v}_{iB,1}^w$
Fixed Section	For $i \in \{11, 12\}$ $\tilde{\mathbf{v}}_{iA,2}^m = \mathbf{v}_{iA,2}^m$ $\tilde{\mathbf{v}}_{iB,2}^m = \mathbf{v}_{iB,2}^m$	For $i \in \{1, 2, 3, 4, 5, 6, 10\}$ $\tilde{\mathbf{v}}_{iA,2}^m = \mathbf{v}_{iA,2}^m$ $= \mathbf{T}_2 \cdot \mathbf{W}_2 \cdot \mathbf{v}_{iA,1}^w$ $\tilde{\mathbf{v}}_{iB,2}^m = \mathbf{v}_{iB,2}^m$ $= \mathbf{T}_2 \cdot \mathbf{W}_2 \cdot \mathbf{v}_{iB,1}^w$
Bent Section	Shared with transformed and fixed section	None

Operation 3: Bending at Line e_2

The third operation is the bending operation to form the bending line e_2 in figure 5.13.

The bending length is $L_{b2} = L_4 - R + \frac{BA}{2}$.

The transformation matrix $\mathbf{T}_3$ is:

$$\mathbf{T}_3 = \Psi(\delta P_{3c}, \delta P_{3a}, 0) \cdot \Phi_z(-\arctan \frac{\delta P_{3b} - \delta P_{3a}}{L_1 - R + L_2 - R + BA}) \quad (5.45)$$

Matrix $\mathbf{B}_3$ is obtained based on the pre- and post-process coordinates of $\mathbf{v}_{17A}, \mathbf{v}_{18A}, \mathbf{v}_{17B}, \mathbf{v}_{18B}$.

The post-process coordinates of all vertices of the third operation are in table 5.9.

Table 5.9: Post-process coordinates of the complex part of operation 3

	Created Vertices	Existing Vertices
Transformed Section	For $i \in \{17, 18\}$ $\tilde{\mathbf{v}}_{iA,3}^{\mathbf{m}} = \mathbf{B}_3 \cdot \mathbf{R}_3 \cdot \mathbf{v}_{iA,3}^{\mathbf{m}}$ $\tilde{\mathbf{v}}_{iB,3}^{\mathbf{m}} = \mathbf{B}_3 \cdot \mathbf{R}_3 \cdot \mathbf{v}_{iB,3}^{\mathbf{m}}$	For $i \in \{3, 4, 10\}$ $\tilde{\mathbf{v}}_{iA,3}^{\mathbf{m}} = \mathbf{B}_3 \cdot \mathbf{R}_3 \cdot \mathbf{v}_{iA,3}^{\mathbf{m}}$ $= \mathbf{B}_3 \cdot \mathbf{R}_3 \cdot \mathbf{T}_3 \cdot \mathbf{W}_3 \cdot \mathbf{v}_{iA,2}^{\mathbf{w}}$ $\tilde{\mathbf{v}}_{iB,3}^{\mathbf{m}} = \mathbf{B}_3 \cdot \mathbf{R}_3 \cdot \mathbf{v}_{iB,3}^{\mathbf{m}}$ $= \mathbf{B}_3 \cdot \mathbf{R}_3 \cdot \mathbf{T}_3 \cdot \mathbf{W}_3 \cdot \mathbf{v}_{iB,2}^{\mathbf{w}}$
Fixed Section	For $i \in \{15, 16\}$ $\tilde{\mathbf{v}}_{iA,3}^{\mathbf{m}} = \mathbf{v}_{iA,3}^{\mathbf{m}}$ $\tilde{\mathbf{v}}_{iB,3}^{\mathbf{m}} = \mathbf{v}_{iB,3}^{\mathbf{m}}$	For $i \in \{1, 2, 5, 6, 7, 8, 9, 11, 12, 13, 14\}$ $\tilde{\mathbf{v}}_{iA,3}^{\mathbf{m}} = \mathbf{v}_{iA,3}^{\mathbf{m}}$ $= \mathbf{T}_3 \cdot \mathbf{W}_3 \cdot \mathbf{v}_{iA,2}^{\mathbf{w}}$ $\tilde{\mathbf{v}}_{iB,3}^{\mathbf{m}} = \mathbf{v}_{iB,3}^{\mathbf{m}}$ $= \mathbf{T}_3 \cdot \mathbf{W}_3 \cdot \mathbf{v}_{iB,2}^{\mathbf{w}}$
Bent Section	Shared with transformed and fixed section	None

Operation 4: Bending at Line e_3

The final operation is the fourth operation to bend the line e_3 in figure 5.13. Unlike for earlier bending operations, $\mathbf{W}_4$ has to be calculated from the coordinates of the datums given in table 5.7 and illustrated in figure 5.14.

The bending length is $L_{b3} = L_2 - R + \frac{BA}{2}$.

As the workpiece is repositioned, the definition of transformation matrix $\mathbf{T}_4$ follows the same scheme as for earlier operations with:

$$\beta_4 = \arctan \frac{\delta P_{4b} - \delta P_{4a}}{L_4 - R} \quad (5.46)$$

Matrix $\mathbf{B}_4$ is obtained based on the pre- and post-process coordinates of $\mathbf{v}_{21A}$, $\mathbf{v}_{22A}$, $\mathbf{v}_{21B}$, $\mathbf{v}_{22B}$. The post-process coordinates of all vertices of the final operation are in table 5.10.

Monte-Carlo Simulation

The analysis above positions the vertices v_{9A} , v_{9B} , v_{10A} and v_{10B} as given in equations (5.47), (5.48), (5.49) and (5.50). These coordinates must comply with geometrical tolerance requirement T_1 .

Figure 5.14: Positioning datums for operation 4: projection along Z-axis

$$\mathbf{v}_{9A,4}^w = \mathbf{B}_4 \cdot \mathbf{R}_4 \cdot \mathbf{T}_4 \cdot \mathbf{W}_4 \cdot \mathbf{T}_3 \cdot \mathbf{W}_3 \cdot \mathbf{B}_2 \cdot \mathbf{R}_2 \cdot \mathbf{T}_2 \cdot \mathbf{W}_2 \cdot \mathbf{v}_{9A,1}^w \quad (5.47)$$

$$\mathbf{v}_{9B,4}^w = \mathbf{B}_4 \cdot \mathbf{R}_4 \cdot \mathbf{T}_4 \cdot \mathbf{W}_4 \cdot \mathbf{T}_3 \cdot \mathbf{W}_3 \cdot \mathbf{B}_2 \cdot \mathbf{R}_2 \cdot \mathbf{T}_2 \cdot \mathbf{W}_2 \cdot \mathbf{v}_{9B,1}^w \quad (5.48)$$

$$\mathbf{v}_{10A,4}^w = \mathbf{T}_4 \cdot \mathbf{W}_4 \cdot \mathbf{B}_3 \cdot \mathbf{R}_3 \cdot \mathbf{T}_3 \cdot \mathbf{W}_3 \cdot \mathbf{T}_2 \cdot \mathbf{W}_2 \cdot \mathbf{v}_{10A,1}^w \quad (5.49)$$

$$\mathbf{v}_{10B,4}^w = \mathbf{T}_4 \cdot \mathbf{W}_4 \cdot \mathbf{B}_3 \cdot \mathbf{R}_3 \cdot \mathbf{T}_3 \cdot \mathbf{W}_3 \cdot \mathbf{T}_2 \cdot \mathbf{W}_2 \cdot \mathbf{v}_{10B,1}^w \quad (5.50)$$

In figure 5.15, point **O** indicates the nominal position of the center of the holes, which is decided by basic size dimensions L_5 and L_6 . According to ISO:5458, the geometrical tolerance T_1 is described by the circular tolerance zone with specified diameter T_1 . The four vertices $\mathbf{v}_{9A,4}$, $\mathbf{v}_{9B,4}$, $\mathbf{v}_{10A,4}$, and $\mathbf{v}_{10B,4}$ must be positioned in this tolerance zone.

The axis of the hole must be located within the tolerance zone. Be r_A , r_B , r_C , and r_D the Euclidean distances between **O** and the four vertices $\mathbf{v}_{9A,4}$, $\mathbf{v}_{9B,4}$, $\mathbf{v}_{10A,4}$, or $\mathbf{v}_{10B,4}$ respectively, then the part is within specification if:

Table 5.10: Post-process coordinates of the complex part of operation 4

	Created Vertices	Existing Vertices
Transformed Section	For $i \in \{21, 22\}$ $\tilde{\mathbf{v}}_{iA,4}^{\mathbf{m}} = \mathbf{B}_4 \cdot \mathbf{R}_4 \cdot \mathbf{v}_{iA,4}^{\mathbf{m}}$ $\tilde{\mathbf{v}}_{iB,4}^{\mathbf{m}} = \mathbf{B}_4 \cdot \mathbf{R}_4 \cdot \mathbf{v}_{iB,4}^{\mathbf{m}}$	For $i \in \{1, 6, 7, 8, 9, 11, 12, 13, 14\}$ $\tilde{\mathbf{v}}_{iA,4}^{\mathbf{m}} = \mathbf{B}_4 \cdot \mathbf{R}_4 \cdot \mathbf{v}_{iA,4}^{\mathbf{m}}$ $= \mathbf{B}_4 \cdot \mathbf{R}_4 \cdot \mathbf{T}_4 \cdot \mathbf{W}_4 \cdot \mathbf{v}_{iA,3}^{\mathbf{w}}$ $\tilde{\mathbf{v}}_{iB,4}^{\mathbf{m}} = \mathbf{B}_4 \cdot \mathbf{R}_4 \cdot \mathbf{v}_{iB,4}^{\mathbf{m}}$ $= \mathbf{B}_4 \cdot \mathbf{R}_4 \cdot \mathbf{T}_4 \cdot \mathbf{W}_4 \cdot \mathbf{v}_{iB,3}^{\mathbf{w}}$
Fixed Section	For $i \in \{19, 20\}$ $\tilde{\mathbf{v}}_{iA,4}^{\mathbf{m}} = \mathbf{v}_{iA,4}^{\mathbf{m}}$ $\tilde{\mathbf{v}}_{iB,4}^{\mathbf{m}} = \mathbf{v}_{iB,4}^{\mathbf{m}}$	For $i \in \{2, 3, 4, 5, 10, 15, 16, 17, 18\}$ $\tilde{\mathbf{v}}_{iA,4}^{\mathbf{m}} = \mathbf{v}_{iA,4}^{\mathbf{m}}$ $= \mathbf{T}_4 \cdot \mathbf{W}_4 \cdot \mathbf{v}_{iA,3}^{\mathbf{w}}$ $\tilde{\mathbf{v}}_{iB,4}^{\mathbf{m}} = \mathbf{v}_{iB,4}^{\mathbf{m}}$ $= \mathbf{T}_4 \cdot \mathbf{W}_4 \cdot \mathbf{v}_{iB,3}^{\mathbf{w}}$
Bent Section	Shared with transformed and fixed section	None

$$E_p := 2 \cdot \max\{r_A, r_B, r_C, r_D\} \leq T_1$$

The distribution of E_p was estimated using a Monte Carlo simulation over one hundred thousand random samples ($L_1 = L_2 = 35\text{mm}$, $L_3 = L_7 = L_8 = 20\text{mm}$, $L_4 = 60\text{mm}$, $L_5 = 25\text{mm}$, $L_6 = 10\text{mm}$, $L_9 = 30\text{mm}$, $R = 2\text{mm}$, $t = 2\text{mm}$, $K = 0.42$ (AL 1050), $\alpha = 90^\circ$, and the machining errors as given in table 4.1).

Figure 5.16 displays both a frequency histogram of E_p based on 0.01mm wide intervals and a normal distribution with the sample median (0.161mm) and standard deviation (0.073mm). The plot of the distribution of E_p shows that it is close to a normal distribution, yet somewhat skewed in comparison.

The $\pm 2\sigma$ and $\pm 3\sigma$ limits of the approximated distribution are showed in figure 5.16. In this case, 3.967% of the samples are outside the 4σ limit and 0.808% of the 100,000 samples beyond the 6σ limits.

5.5 Conclusion

In this chapter, a method of tolerance transfer for 3D sheet metal part based on Monte-Carlo simulation and transformation is proposed. It is compatible

Figure 5.15: Position Tolerance Zone

with both the actual sheet metal forming process and ISO *GD&T* specifications. Considering differential machining errors, the final error stack-up can be represented and calculated by this method step by step. Machining errors are assumed in normal distribution here but other distributions such as poisson distribution and exponential distribution can be also adopted to describe observed dimension variations. For each operation, the mathematical models of example parts are presented in detail, showing the coordinates of each vertex of the part. The transformation concept is used to model the work-pieces of the manufacturing process. Finally the mathematical models are applied to two case studies involving parallelism tolerances and position tolerances. The proposed tolerance transfer method based on transformation can be easily utilized to handle other geometric tolerances.

Results of a Monte-Carlo simulation are compared with 4σ and 6σ limits. It can be seen that the distribution of resulting part dimensions may not closely follow the normal distributions. If these distributions are approxi-

Figure 5.16: Histogram of E_p

mated by normal distributions, the overall process capabilities (that is the tolerance stacks) may be wrongly estimated. For example, for the second case, the distribution of E_p is close to normal distribution. However, in the first case study, because of the characteristics of the simulation mathematical model, for any distribution with negative values for machining errors, the resulting distribution of final errors are only positive values. In this given case, a Poisson or similarly shaped function could be fit the data of E . In both cases, approximatively four times more parts out of specification were encountered then stipulated by the approximation.

Chapter 6

Tolerance Synthesis

6.1 Tolerance Synthesis Process

The data flow of the tolerance synthesis process is outlined in figure 6.1. Information such as the design, process data, cost, and international standards are used to generate tolerance constraints. A cost-tolerance model is used in combination with a worse case model or Monte Carlo simulation in order to ensure the compliance with the design specification.

During the tolerance synthesis process, the following needs to be considered:

- The *design* includes design features, dimension and tolerance requirements, definition of material characteristics.
- The *process plan* includes tooling constraints, gage constraints, setup constraints, gripper constraints, process planning features, process capability, and machining error constraints (refer to table 4.1).
- *Experience and rules*: the past tolerance synthesis experience and related tolerancing rules as reference.
- *Standard* may be one of British standards, ISO standards, ANSI standards, DIN standards, or own standards of the manufacturer. This thesis follows ISO standards.
- *Cost constraints*: product cost, management cost, cost functions and

Figure 6.1: Tolerance synthesis process

models, and so on. These constraints are utilized to generate an optimized cost-tolerance model.

- The *initial tolerances* are a "starting point" for later optimizations of the tolerances. Values originate from standards, experience, and costumer requirements.
- A *Cost-tolerance model* defines the relationship between process tolerances and cost for (sheet metal) parts (see section 2.2.3).
- *Simulation model* is typically a worse case model or a statistical model (implemented as a Monte Carlo simulation).
- *Tolerance allocations* and *cost* are the output of the simulation.

6.2 Cost-error Model for Sheet Metal

Commonly the manufacturing cost C of a sheet metal part comprises [modified from Chen and Liu (1999); Tang et al. (2004)]:

- Material cost C_m .
- Manufacturing processing cost C_p .
- Tooling cost C_t .

These costs can be further detailed for sheet metal part cost as shown in figure 6.2.

Figure 6.2: Sheet metal part cost

Most commonly, the cost of a sheet metal part is broken down into a sum of the costs of individual operations (cost reductions due to process sequences are ignored; see section 2.2.3). The cost of a single operation j with machining errors $\mathbf{e}$ is therefore:

$$C(\mathbf{e}, j) = C_m(\mathbf{e}, j) + C_p(\mathbf{e}, j) + C_t(\mathbf{e}, j) \quad (6.1)$$

where $C(\mathbf{e}, j)$ is the cost per part with errors $\mathbf{e}$ ($\mathbf{e}$ is a vector composed of the machining errors committed on the workpiece which impact on the final part's compliance with the design specification.), $C_m(\mathbf{e}, j)$ the raw material cost per part, $C_p(\mathbf{e}, j)$ the processing cost per part, $C_t(\mathbf{e}, j)$ the tooling cost for j th process per part.

The elements of vector $\mathbf{e}$ are machining errors, each individually describing a deviation of a part dimension or datum point from its ideal value. Each operation has a certain number of elements in this vector associated to it:

$$\mathbf{e} = \{e_t | t = 1, 2, \dots\} = \underbrace{\{e_1, e_2, \dots\}}_{\text{operation 1}}, \dots, \underbrace{\{e_m, e_{m+1}, \dots, e_n, \dots\}}_{\text{operation } j}. \quad (6.2)$$

According to Chase et al. (1989), the cost for the j th operation to produce dimensions and tolerances can be further split:

$$C_p(\mathbf{e}, j) = C_{mc}(\mathbf{e}, j) + C_{oc}(\mathbf{e}, j) \quad (6.3)$$

$$= C_{mc}(\mathbf{e}, j) + \sum_{t=m}^n \frac{a_t}{(e_t)^k}, \quad (6.4)$$

where $C_{mc}(\mathbf{e}, j)$ is the machine cost, $C_{oc}(\mathbf{e}, j)$ is the operation cost, t enumerates machining errors for operation j (see equation 6.2), k is the exponent describing how sensitive the process cost is to changes in error distributions, a_t is the constant determining the cost of performing operations.

Therefore, for a sheet metal part formed by n operations, the cost is:

$$C(\mathbf{e}) = \sum_{j=1}^n C(\mathbf{e}, j) \quad (6.5)$$

$$= \sum_{j=1}^n [C_m(\mathbf{e}, j) + C_t(\mathbf{e}, j) + C_{mc}(\mathbf{e}, j)] + \sum_{t=1}^l \frac{a_t}{(e_t)^k}. \quad (6.6)$$

where l is the number of machining errors (the size of vector $\mathbf{e}$).

6.2.1 Cost Optimization Problem

Based on above machining error-correlated cost model, the optimization procedure is outlined in this section. The objective of the optimization is to minimize the total cost of manufacturing while obeying design specification. In other words, it is minimizing $C(\mathbf{e})$ subject to the part tolerances are within design specifications.

As $C_m(e, j)$, $C_t(e, j)$, and $C_{mc}(e, j)$ are very much independent of machining errors, the cost optimization simplifies to the minimization of $\sum_{t=1}^l \frac{a_t}{(e_t)^k}$. Furthermore, if all a_t are equal to a_1 , the cost function is minimal if $a_1 \sum_{t=1}^l (e_t)^{-k}$ is minimal.

In a worse case, the minimization is:

Subject to:

$$E_i \leq T_i \text{ for all design tolerances } T_i \quad (6.7)$$

$$|e_t| \leq b_t, \quad (6.8)$$

where E_i are the accumulated machining errors corresponding to T_i , b_t are the positive limits of machining errors e_t .

The objective function and the constraint equations can be reduced to a single equation by the Lagrange multiplier method [Chase et al. (1989)]. The Lagrange function is represented as:

$$L = \text{objective function} - \sum_{s=1}^n \lambda_s (\text{constraint equation})_s \quad (6.9)$$

where λ_s is the Lagrange multiplier for constraint equation s . For m machining errors and n constraints from design and process, $m + n$ number of simultaneous equations are generated. Solution of these equations represent the optimal tolerance allocation, as shown in section 6.3.

6.3 Case Study

For the sheet metal part shown in figure 3.2 (c) and its process plan in figure 3.10, an optimal tolerance allocation has to be performed. All process tolerances are accumulated as the tolerance analysis process in section 4.3.1.

For this case, $a_t, t = 1, 2, 3, 4$ can be regared as the same, because the four bending operations are similar. However, for other cases, a_t may be different and should be assigned exact values for calculation.

Let $k = 2$ in equation 6.2, minimizing then as minimizing $-(e_t)^2$. The optimization problem of cost minimization can be stated as:

$$\text{Minimize } -\sum_{t=1}^l (e_t)^2 \quad (6.10)$$

$$\text{that is, Minimize } \frac{3}{(\delta L_b)^2} + \frac{3}{(\delta P)^2} + \frac{1}{(\delta T)^2} \quad (6.11)$$

$$+ \frac{4}{(\delta \alpha_1)^2} + \frac{3}{(\delta \alpha_2)^2} + \frac{2}{(\delta \alpha_3)^2} + \frac{1}{(\delta \alpha_4)^2} \quad (6.12)$$

Subject to:

$$\begin{aligned}
 E = E_d + E_a &\leq T_1 \\
 -b_1 &\leq \delta\alpha_1 \leq b_1 \\
 -b_2 &\leq \delta\alpha_2 \leq b_2 \\
 -b_3 &\leq \delta\alpha_3 \leq b_3 \\
 -b_4 &\leq \delta\alpha_4 \leq b_4 \\
 -b_5 &\leq \delta B \leq b_5 \\
 -b_6 &\leq \delta P \leq b_6 \\
 -b_7 &\leq \delta L_b \leq b_7 \\
 -b_8 &\leq \delta L_p \leq b_8 \\
 -b_9 &\leq \delta T \leq b_9.
 \end{aligned}$$

The constraint equations are:

$$\begin{aligned}
 T_1 &\geq 3\delta L_b + 3\delta P + \delta T + \\
 &\quad L_2[\cos(\delta\alpha_1) - 1] + L_3 \sin(\delta\alpha_1 + \delta\alpha_2) \\
 &\quad + (L_4 - L_2)[\cos(\delta\alpha_3 - \delta\alpha_1 - \delta\alpha_2) - 1] \\
 &\quad + L_5 \sin(\delta\alpha_4 + \delta\alpha_3 - \delta\alpha_1 - \delta\alpha_2)
 \end{aligned} \tag{6.13}$$

$$b_t \geq |e_t|. \tag{6.14}$$

The constraint equation 6.13 of T_1 can be simplified as for small angle $\sin \delta\alpha_i$: $\cos \delta\alpha - 1 \leq 0$, and $\sin \delta\alpha_i = \delta\alpha_i$. The Lagrange function for the above problem can be stated as:

$$\begin{aligned}
 L = & \frac{3}{(b_7)^2} + \frac{3}{(b_6)^2} + \frac{1}{(b_9)^2} + \frac{4}{(b_1)^2} + \frac{3}{(b_2)^2} + \frac{2}{(b_3)^2} + \frac{1}{(b_4)^2} \\
 & - \lambda_1[3b_7 + 3b_6 + b_9 + L_3(b_1 + b_2) + L_5(b_4 + b_3 - b_1 - b_2) \\
 & - T_1]
 \end{aligned} \tag{6.15}$$

Following the usual procedure of the Lagrange multiplier method, the partial derivatives of the Lagrange function with respect to all e_t 's and λ_i 's

are equated to zero. If $T_1 = 4\text{mm}$, $L_3 = 48\text{mm}$, $L_5 = 40\text{mm}$, the following is obtained:

$$\begin{aligned} b_1 &= 0.070 \\ b_2 &= 0.063 \\ b_3 &= 0.026 \\ b_4 &= 0.032 \\ b_6 &= 0.088 \\ b_7 &= 0.088 \\ b_9 &= 0.088 \\ \lambda_1 &= -2954.92 \end{aligned}$$

According to the above tolerance synthesis, it is obvious that among all machining errors, $\delta\alpha_3$ contributes the most to the part's tolerance so it is assigned the smallest value; δP , δL_b , and δT , which contribute the least to the part's tolerance, are allocated the biggest values. Values for b_5 and b_8 cannot be obtained from equation 6.15 because δB and δL_p have no influence on the part's tolerance corresponding to parallelism tolerance requirement T_1 .

For this case, a_t is assumed as the same for all machining errors. However, for other cases, a_t may be different and causes different should be assigned exact values for calculation. For example, let $\sum_{j=1}^n [C_m(\mathbf{e}, j) + C_t(\mathbf{e}, j) + C_{mc}(\mathbf{e}, j)] = 2.54$, $a_1 = a_2 = a_3 = a_4 = 0.0002$, $a_5 = 0.0007$, $a_6 = a_7 = a_8 = a_9 = 0.0004$, the analysis result is:

$$\begin{aligned}b_1 &= 0.067 \\b_2 &= 0.061 \\b_3 &= 0.025 \\b_4 &= 0.031 \\b_6 &= 0.106 \\b_7 &= 0.106 \\b_9 &= 0.106 \\\lambda_1 &= -3358.48\end{aligned}$$

The change of coefficient a_t cannot influence the contributions of different errors, so $\delta\alpha_3$ is still assigned the smallest value and δP , δL_b , and δT are allocated the biggest value. However, because a_6 , a_7 , a_9 are bigger than a_1 , a_2 , a_3 , and a_4 , δP , δL_b , and δT are assigned with relatively bigger limitations than last time to control the total cost. And at the same time, the limitations of $\delta\alpha_1$, $\delta\alpha_2$, $\delta\alpha_3$, and $\delta\alpha_4$ are become smaller.

6.4 Conclusion

In this chapter, the problems of allocating tolerances to the manufacturing errors are formulated. The purpose is to minimize the accumulated costs of the selected sets of manufacturing operations. Machining errors are redesigned to fit the geometrical tolerance requirements. A machining error-base model is presented based on cost analysis for single sheet metal forming operation and reciprocal power method for assembly tolerance synthesis. A case concerned with a parallelism tolerance is utilized to demonstrate the approach, which can be easily transposed to deal with other geometric tolerances. However, in this case this mathematical model is simplified and is only suitable for the condition that constraint equations can be linearized. For instance, the angular error values $\delta\alpha_i$ are regarded so small enough that $\sin(\delta\alpha_i)$ is regarded as equal to $\delta\alpha_i$. If the constraints can not be converted to linear equations, or a higher level of accuracy is needed, other mathematical methods, such as Newton's iteration methods, can be utilized. For more complex equations

AI techniques such as genetic algorithms are useful.

Chapter 7

Conclusion and Future Work

7.1 Summary

This dissertation presents an in-depth review of CAPP technologies and tolerance transfer approaches in sheet metal forming. Currently most researchers focus on developing efficient CAPP systems while only little considered in is given to the tolerance transfer issue in sheet metal part process planning. The publications in this field leave these issues unaddressed with few exception:

- Only bending operation are addressed. More sheet metal forming processes including bending, punching, blanking, deep-drawing and so on, should be studied for tolerance transfer.
- Machining errors and their causes are not considered comprehensively.
- Only size dimensional tolerances are discussed in detail.
- Statistical tolerancing methods are utilized only for sheet metal assembly issues or size dimensions.
- Three dimensional, geometrical tolerance synthesis for sheet metal part forming is an unresolved issue.

In this thesis, all above issues are resolved in a systematic way. The handling of tolerance transfer in sheet metal forming in several aspects such as application of associative feature concept and data association permits the integration of CAD/CAPP systems, tolerance transfer in three dimensions, geometrical tolerance transfer, are concluded:

- A method for the analysis of critical tolerances with a focus on geometrical tolerances and a process planning algorithm considering data association by feature evolvement is presented. Geometrical tolerances as defined in ISO:1101 are the focus of this project. Being the most typical operations in sheet metal manufacturing, bending and punching are selected for case studies.
- Based on associative feature concept and feature evolvement, the integration of CAD/CAPP is presented. An integrated system comprises four modules: an associative feature-based database, an associative feature-based modeling module, a CAD module and a CAPP module. Data association and change management mechanisms by associate features are highlighted as the key mechanisms of the system. A tolerance constraint-based process planning algorithm is introduced with the rules for setup formation generation, datum selection and operation sequencing. Process plans have to be validated against tolerance constraints based on three dimensional geometrical tolerance transfer.
- For tolerance transfer, this thesis covers the issues presented above that few researcher addressed. Three dimensional geometrical tolerance transfer are discussed. In tolerance analysis, all types of machining errors in sheet metal bending and punching processes are analyzed comprehensively for total error accumulation by worse case study and Monte Carlo simulation. Especially the error caused by angular errors are considered in detail. An algorithm relaying on a Monte Carlo simulation is proposed to analyze whether or not processes or assemblies fulfill 4- or 6-sigma requirements. The algorithm analyzed for the number of simulations is necessary to ensure these requirements. Parallelism and position tolerances are chosen as examples of critical tolerances, while dimensional and angular errors are considered at the same time. It can be seen that the distribution of resulting part dimensions may not closely follow the normal distributions.
- The tolerance transfer method is applied on part formed by bending (parallel and non-parallel) and punching operations jointly. It can be applied on all bending-like and cutting operations easily and extended

to other sheet metal forming operations.

- A machining error-based cost model is proposed for tolerance synthesis. The model is based on cost analysis for single sheet metal forming operation, and is applied to a case of geometric tolerance. By this method, the influence of factors on final error are explored. For example, angular errors are demonstrated to be a key factor of final machining errors by case studies.

7.2 Future Work

The main future work of this project comprises:

1. The sheet metal operation studied in this research should be extended from only bending-like and punching to all operations listed in table 2.2.
2. The system can be applied on the interlink between more CAx systems and representing engineering intent better, for example, the influence of tolerance transfer results on design stage. Some artificial intelligence (AI) techniques, such as fuzzy logic, knowledge-base technologies, and genetic algorithms, are applicable.
3. The presented work focused on the theoretical exploration of data association between knowledge, feature and geometry and feature evolution of form features. More rules and algorithms for feature evolution should be concluded in detail for non-forming features.
4. Other geometrical tolerances, such as perpendicularity and angularity tolerances, should be included in a tolerance transfer model.
5. Based on associative feature evolution and tolerance transfer method, the associative process planning process achieved automatically is a promising research direction.
6. The tolerance synthesis process should be extended to statistical tolerancing (Monte Carlo simulation) and the mathematical model should be optimized by AI techniques, for example, the calculation of a_t .

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Appendix A

Abbreviation Glossary

Abbreviation, Term

AI, artificial intelligence, 19
AFDB, associative feature-based database, 66
ANN, artificial neural network, 38
BA, bend allowance, 13
CAD, computer aided design, 1
CAM, computer aided manufacturing, 1
CAPP, computer aided process planning, 1
DLM, direct linearization method, 23
DFZone, distribution function zone, 30
GA, genetic algorithm, 38
GD&T, geometrical dimensioning and tolerancing, 2
GT, group technology, 37
MCS, machine coordinate system, 121
PACV, proportioned assembly clearance volume, 33
PDT, product data translator, 33
RSS, root sum square, 23
SDT, small displacement torsor, 26
SME, the Society of Manufacturing Engineers, 36
SMF, sheet metal forming, 9
TTRS, technologically and topologically related surfaces, 33
VDM, variational dimension model, 24
VSA, variation simulation analysis, 35

VSM, variational solid models, 24

WCS, workpiece coordinate system, 121