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A FRAMEWORK OF COMPUTER-AIDED SHORT-RUN SPC PLANNING

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SUMMARY

The accuracy of critical quality characteristics directly determines the acceptance or rejection of the products, customer satisfaction, and organization reputation. This research proposes to identify critical quality characteristics and associated manufacturing processes with focus on the application of Statistical Process Control (SPC). The target application is mould making, which is a typical one-off, very small-batch production.

The application of SPC can be divided into two phases: planning and implementation. For short-runs, the planning phase is the bottleneck, which entails the formation of part families and determines corresponding data collection requirements. To ensure the homogeneity of the part family members, statistical design of experiment and analysis of variance are applied. To simplify the statistical analysis and reduce the experimental runs, extensive preliminary analyses based on the process factor properties and application are proposed to be applied first. The end milling process is used to illustrate the proposed method, and data collected from industry is used to demonstrate the statistical analysis.

To improve the efficiency of SPC planning and the adoption of computer-integrated manufacturing, a framework of computer-aided short-run SPC planning system using group technology classification and coding concept is proposed. A secondary code appended to the Opitz code is proposed for coding the critical features. Part family formation results obtained from the analysis of historical data are coded with the proposed coding scheme and maintained in the reference database. Machining resource information is classified and stored in the database to facilitate coding, and system updating.

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NOMENCLATURE

SYMBOLS

ε	error
ϕ	Diameter
μ	Mean of a sample group
σ	Standard variance
D	Dimension
x, y, z	Cartesian coordinate system
X	Individual measurement
$\overline{X}$	Average of measurements
$\overline{\overline{X}}$	Average of average
R	Range
$\overline{R}$	Average of ranges
S^2	Deviation
S	Standard Deviation

SUBSCRIPTS AND SUPERSCRIPTS

Plotpoint	Plot point in control chart

i	Part type number
j	Sample number
ij	j_{th} part of i_{th} part type
n	Sample size

ABBREVIATIONS

ANOVA	Analysis of Variance
CAD	Computer-aided Design
CAM	Computer-aided Manufacturing
DB	Database
CI	Confidence Interval
CL	Center Line
CMM	Coordinate Measuring Machine
CNC	Computer Numerical Control
CUSUM	Cumulative Sum
DF	Degree of Freedom
EDM	Electric Discharge Machining
EWMA	Exponential Weighted Moving Average
HRC	Hardness of Rockwell
LCL	Lower Control Limit
MR	Moving Range

MiniTab®	General Statistical Software
StDev	Standard Deviation
SPC	Statistical Process Control
UCL	Upper Control Limit

CHAPTER 1

INTRODUCTION

1.1 Background

Quality is one of the important issues for manufacturers wishing to have the leading edge in the global market. With the increased pressure for high-quality and low-cost products, manufacturers are looking for cost effective tools to facilitate quality assurance.

Statistical Process Control (SPC) is a collection of powerful tools useful in achieving defect-free products (Montgomery, 2001). SPC originated when Shewhart control charts, such as Average and Range charts, were invented by W. A. Shewhart at Western Electric during the 1920's. In the later years, Histogram, Check Sheet, Pareto Chart, Cause and Effect Diagram, Defect Concentration Diagram, and Scatter Diagram were developed and combined with the Control Chart in quality and process control, which are deemed as the "Magnificent Seven". Control Chart is the most effective and on-line tool to estimate process status (stable or unstable) and capability (capability and non-capability) by charting the sample measurements of the products. The availability of rational homogenous subgroups through periodic sampling is the basic assumption of constructing classical control charts. Control chart and process capability study have been successfully applied in mass and repetitive production for quality assurance.

Today, the move towards small-batch and short-cycle products, such as aircraft articles, metal forming dies, and injection mould components, has created great challenges for the application of SPC in the traditional way. In addition, pressure to enhance productivity, improve quality, and reduce cost in the manufacturing sector has led to computer-integrated manufacturing. In the area of statistical process control, smoothly interface with various production information and timely feedback of process performance is crucial. Hence, to keep pace with this trend, there is clearly the need to develop an effective approach for the implementation of SPC in small-batch manufacturing.

1.2 Problem Statements

SPC is referred to as prevention-oriented or process-oriented quality control (Sullivan, 1986). The underlying concept is that good-quality products can be achieved as long as the manufacturing process is stable and capable. SPC is concerned with the processes as well as the products. No process can produce absolutely perfect products due to process variations arising from background noise or assignable causes. The background noise is the natural process variability coming from the cumulative influence of many small and unavoidable causes, such as material variation, environment, etc. A process that works with only background noise is taken to be in statistical control. Assignable causes, such as tool breakage, power surge, or loosen fixture, can cause sudden process shift. A process, working with background noise and assignable causes, is deemed as out-of-control. SPC aims to remove assignable causes and reduce background noise. The control chart is a tool that graphically displays the appearance and influence of variances induced by assignable causes. 20 to 25 homogenous subgroups with size of 4 to 5 samples are needed to set up the Shewhart control charts (Duncan, 1986, Griffith, 1996, Montgomery, 2001).

In the present dynamic market, the need for very small-batch, high-variety and short-lifecycle products has increased. The processes to produce such products are also becoming more complex, highly variable and flexible. To improve productivity, highly automated manufacturing systems, such as flexible manufacturing systems, have been extensively adopted. Such products, manufacturing processes and production systems create problems for the implementation of SPC in the traditional way because: (1) insufficient data to properly estimate process characteristics for newly developed products, (2) infeasible to make periodic sampling for the formation of rational subgroups, (3) inadequate to support corrective action, (4) cumbersome to administer control charts for variety of quality characteristics (Cheng, 1989). Given these issues associated with the application of SPC in small-batch manufacturing, short-run SPC concept has been applied.

Fundamentally, short-run SPC focuses on the process and using group technology part family concept to increase the number of samples by combining data with different target values but a common process. The conventional part family formation approach, which is based on design and/or manufacturing requirements, is not directly applicable in this situation (Lin, 1997). The part family members come from different processes (production cycles) where the involved machines, materials, cutters, etc. are different. Some of these factors may have systematic influence on the mean of the pooled quality characteristics, some may not. To ensure the effectiveness of the control chart, quality characteristics that can be grouped into one family must be homogeneous. Hence, statistical analysis has been applied to identify homogeneous family members. However, existing work on short-run SPC concentrates on medium small-batch size (large-than 20) where several types of components are produced intermittently and alternatively. The factors that may contribute to the variability of the quality characteristics are limited; so the problem is rather simple. For the situation of very small-batch size and high-precision requirement, such as the die and mould manufacturing, the problem is more challenging. For instance, the batch size in mould making rarely exceeds 10 and may be very small, e.g. 1 or 2. The order of a batch of injection mould is typically one-off. The involved manufacturing processes, process factors, and factor settings to create the main parts (core and cavity), might be different from one part to another. In such cases, to accumulate sufficient data for control charting, many factors will be involved in the statistical analysis. Existing methods are inappropriate in solving this type of part family formation problem.

On the other hand, the application of short-run SPC includes two phases: planning and implementation (Lin, 1997). The planning phase entails the part family formation analysis and determines associated data collection requirements. The implementation phase involves part family control charting and interpretation. Today, in order to gain competitive advantage, computer-integrated manufacturing has been broadly applied. Thus, much automation and computerization work has been done on SPC to be applicable to a computer-directed environment and enhance its feedback efficiency.

However, these works focus on the implementation stage. For instance, neural network has been employed to automatically recognize general control chart patterns, and framework of expert system has been proposed to facilitate decision making on process diagnosis (Pham and oztemel, 1995, Tannock, Wort and Savage, 1990, Amjed and Jay, 1996). Pyzdek (1989) and Griffith (1996) emphasized that the planning phase was critical to small batches or short runs. Conducting statistical analysis for part family identification is the most important, but quite time consuming, for short-runs. If it were done after data collection, the feedback of the process status will be seriously impeded, which may result in improper corrective actions.

1.3 Research Objectives

SPC has been successfully applied in process industry and mass production, and some attempts have been made in small-batch production, as shown in Figure 1.1.

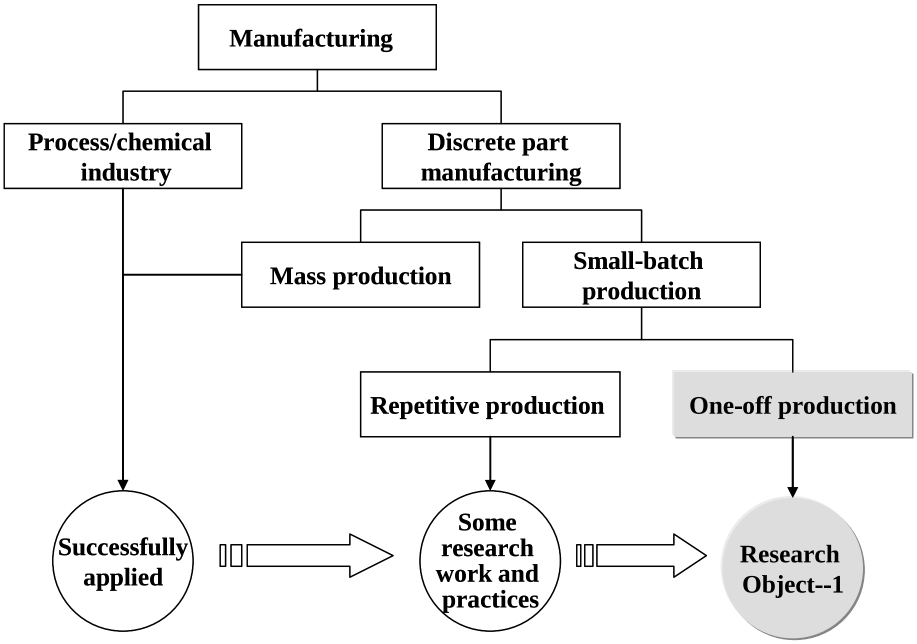


Figure 1.1 One of the Research Objectives

However, there are still some problems to be overcome to extend the application of the SPC to one-off and very small-batch production. One of the objectives of this research is to develop an effective approach for implementation of short-run SPC in such situation. In order to achieve this objective, an alternative part family formation method and statistical analysis procedure are proposed. Injection mould components and associated manufacturing processes are used to illustrate the difficulties of application of existing approach and the application of proposed approach.

The second objective is to develop a framework of computer-aided short-run SPC planning system. In order to achieve this objective, a group technology classification and coding (GTCC) concept is proposed. This invokes a 29-digit hybrid structure code appended to the Opitz code and a supportive database, which consists of two portions: machining resources database and family formation reference database. The supportive database is constructed modularly to facilitate information retrieval and system updating.

1.4 Outline of the thesis

There are six chapters in this thesis. Chapter 1 outlines the problems and the specific objectives of this research.

Chapter 2 contains a literature review of related research works on short-run SPC and group technology. The significance of this research is presented.

Chapter 3 illustrates the properties of injection mould components, corresponding manufacturing processes, and measurement equipment. The difficulties of the application of existing methods are explained.

Chapter 4 discusses the proposed part family formation approach, including identification of critical quality characteristics and processes, classification of various machining resources information, preliminary analysis with the knowledge of properties and application of the process factors, and statistical experiments and analysis. Case studies and results are presented.

Chapter 5 describes the framework of the proposed short-run SPC planning system. The proposed group technology classification and coding scheme is presented. The construction of the supportive database is discussed. A case study has been done and the results show that the proposed approach works effectively.

Chapter 6 lists the main contributions of this research work and a number of recommended future works are proposed.

CHAPTER 2

LITERATURE REVIEW

A short-run problem can be characterized in several ways, but the problem typically narrows down to insufficient or untimely data for calculating control limits (Griffith, 1996). To timely obtain sufficient data, the focus should be on the process to identify homogenous part family members from a common process, and use coded data for short-runs. In fact, the focus on the process is fundamental in SPC regardless of the production batch size. Homogenous part families and coded data allow parts with different target dimensions and/or tolerance values to be charted together.

2.1 Data transformation methods

Over the years, several data transformation methods have been developed by Bothe (1988), Cullen (1987), Evans (1993), and Crichon (1988). The specification and appropriate application area for the most representative ones are addressed below:

Bothe's approach

A data transformation method proposed by Bothe (1988) uses the value of deviation-from-nominal as the individual data point in control chart. Thus far, this approach is the most convenient and broadly used one. It is suitable for process variability that is approximately the same for all part types (Al-Salti et al, 1992).

Bothe and Cullen's approach

To be applicable to the situation that the variation of the process differs significantly between different types of parts, another data transformation approach has been proposed by Bothe and Cullen (1987). The value of the deviation from nominal is divided by the range of the part type (Bothe et al., 1989). The specification of their approach has two versions based on the requirements of different control charts (to be presented in next section) that can be used in short runs.

For Individual Chart, the plot point is

$$X_{\text{plotpoint}} = \frac{X_A - \text{nominal}}{\overline{R}_A} \tag{2.1}$$

where X_A is the measured value of one part of type A, and $\overline{R}_A$ is the historical average range of part type A. It can be calculated using equation (2.2):

$$\overline{R}_A = \frac{\sum_{j=1}^{m} R_{Aj}}{m} \tag{2.2}$$

where R_{Aj} is the range of the j_{th} historical subgroup of part type A. m is the number of historical subgroups of part type A.

For Average and Range charts, the plot points are:

$$\overline{X}_{\text{plotpoint}} = \frac{\overline{X}_A - \overline{\overline{X}}_A}{\overline{R}_A} \tag{2.3}$$

$$R_{\text{plotpoint}} = \frac{R_A}{\overline{R}_A} \tag{2.4}$$

where $\overline{X}_A$ is the average of measured value of part type A. It can be calculated using equation (2.5):

$$\overline{X}_A = \frac{\sum_{i=1}^{n} X_{Ai}}{n} \tag{2.5}$$

where X_{Ai} is the i_{th} measured value of part type A, and n is the number of measurements.

$\overline{\overline{X}}_A$ is the mean of $\overline{X}_A$. It can be calculated using equation (2.6):

$$\overline{\overline{X}}_A = \frac{\sum_{j=1}^{m} \overline{X}_{Aj}}{m} \tag{2.6}$$

where $\overline{X}_{Aj}$ is the j_{th} subgroup of part type A, and m is the number of subgroups of part type A.

$\overline{R}_A$ is the historical average range of part type A, which can be calculated using equation 2.2.

The limitation of this approach is that it depends on appropriate estimation of the average range of each part type based on the historical data. For newly developed parts and one-off production, it is not that simple to apply (Al-Salti et al, 1992).

Evans and Hubele's approach

In another data transformation approach proposed by Evans and Hubele, the value of deviation from nominal is divided by the tolerance of the part type A (Evans et al., 1993). For different control charts, this approach also has associated specification.

For Individual Chart, the plot point is

$$X_{plotpoint} = \frac{X_A - \text{nominal}}{T_A} \tag{2.7}$$

where X_A is the measured value of one part of type A, and T_A is the tolerance of part type A.

For Average and Range Charts, the plot points are:

$$\overline{X}_{\text{plotpoint}} = \frac{\overline{X}_A - \overline{\overline{X}}_A}{2T_A} \tag{2.8}$$

$$R_{\text{plotpoint}} = \frac{R_A}{2T_A} \tag{2.9}$$

where $\overline{X}_A$ is the average of the measured value of part type A. It can be calculated using equation 2.5. $\overline{\overline{X}}_A$ is the mean of $\overline{X}_A$. It can be calculated using equation 2.6. T_A is the tolerance of part type A.

This approach is suitable to situation where the tolerances of different part types are significantly different and the variances of involved processes vary with the different tolerances.

Crichton's approach

In this approach, the deviation from nominal is divided by the nominal value (Crichton, 1988). This method is used when process variability differs significantly from one part to another and increases with the nominal size.

For Individual chart, the plot point is

$$X_{\text{plotpoint}} = \frac{X_A - \text{nominal}}{\text{nominal}} \tag{2.10}$$

where X_A is the measured value of one part of type A.

For Average and Range chart, the plot points are:

$$\overline{X}_{\text{plotpoint}} = \frac{\overline{X}_A - \overline{\overline{X}}_A}{\overline{\overline{X}}_A} \tag{2.11}$$

$$R_{\text{plotpoint}} = \frac{R_A}{\overline{\overline{X}}_A} \tag{2.12}$$

where $\overline{X}_A$ is the average of measured value of part type A. It can be calculated using equation 2.5. $\overline{\overline{X}}_A$ is the mean of $\overline{X}_A$. It can be calculated using equation 2.6.

2.2 Control Charts for Short Runs

Control chart is a powerful tool to detect and quantify the assignable causes that can cause a process to be out of control. Based on the process performance that the control chart displays, other SPC tools can be applied to facilitate the location of the root causes and the operator can make a decision on corrective actions. Control charts can be classified into two categories: control charts for variables and control charts for attributes. In cases that quality characteristics cannot be conveniently represented numerically, the terminology “defective” or “non-defective” is used to identify the inspected items and control charts for such quality characteristics are attribute control charts. Control charts for quality characteristics that can be conveniently represented quantitatively are variable control charts. In this research, variable control charts are used.

The most commonly used variable control charts include:

- Average and Range (X bar and R) Charts
- Average and Standard Deviation (X bar and S) Charts
- Individual and Moving Range (X and MR) Charts

Control charts mentioned above are usually called Shewhat control charts, as they have been developed by Dr. Walter A. Shewhat in 1920’s. These charts can be used in both mass and small-batch production if the underlying distribution of the data is normal. Usually, the Average and Range charts are used when the sample size is less than 6. When the sample size is larger than 6, Average and Standard Deviation charts are more efficient. In cases, such as automated inspection, very slow production rate, and some chemical processes, the Individual and Moving Range charts are very useful. However, Shewhat control charts are not sensitive to small shifts. Two alternative control charts can be applied if small shifts are expected.

- Cumulative Sum Control (Cusum) Chart
- Exponentially Weighted Moving Average (EWMA) Control Chart

In addition, the Individual and Moving Range Charts are very sensitive to the assumption of normal distribution. Even moderate departure from normality can seriously affect the performance of the control chart, such as the average run length. But well-designed EWMA is robust to non-normality. Hence, combining Individual and Moving Range Charts and EWMA is a proper procedure to effectively detect process shifts for short runs (Montgomery, 2001).

2.3 Part Family Formation for Short-run SPC

In simple and repetitive small-batch manufacturing, parts are manufactured with constant material, process factors and factor settings, but different in dimensions. After data transformation, quality measurements, with different nominal values, but generated from a common process, are naturally pooled together for control charting. But in some small-batch manufacturing cases, such homogenous data are either too few or have to wait relatively long interval to obtain. To gain sufficient data in time, quality characteristics generated from different materials, process factors (e.g. machine or cutter type), or factor settings (e.g. cutter diameter) have to be considered to be grouped together. The grouped quality measurements can be plotted in the same control chart or similar control chart settings.

As mentioned earlier, when only background noises exist in the process, the process is in statistical control; That is, the process mean and variability are stable and predictable. When assignable causes disturb the process, the process mean may be shift or the process variability may be inflated, as shown in the upper part of Figure 2.1.

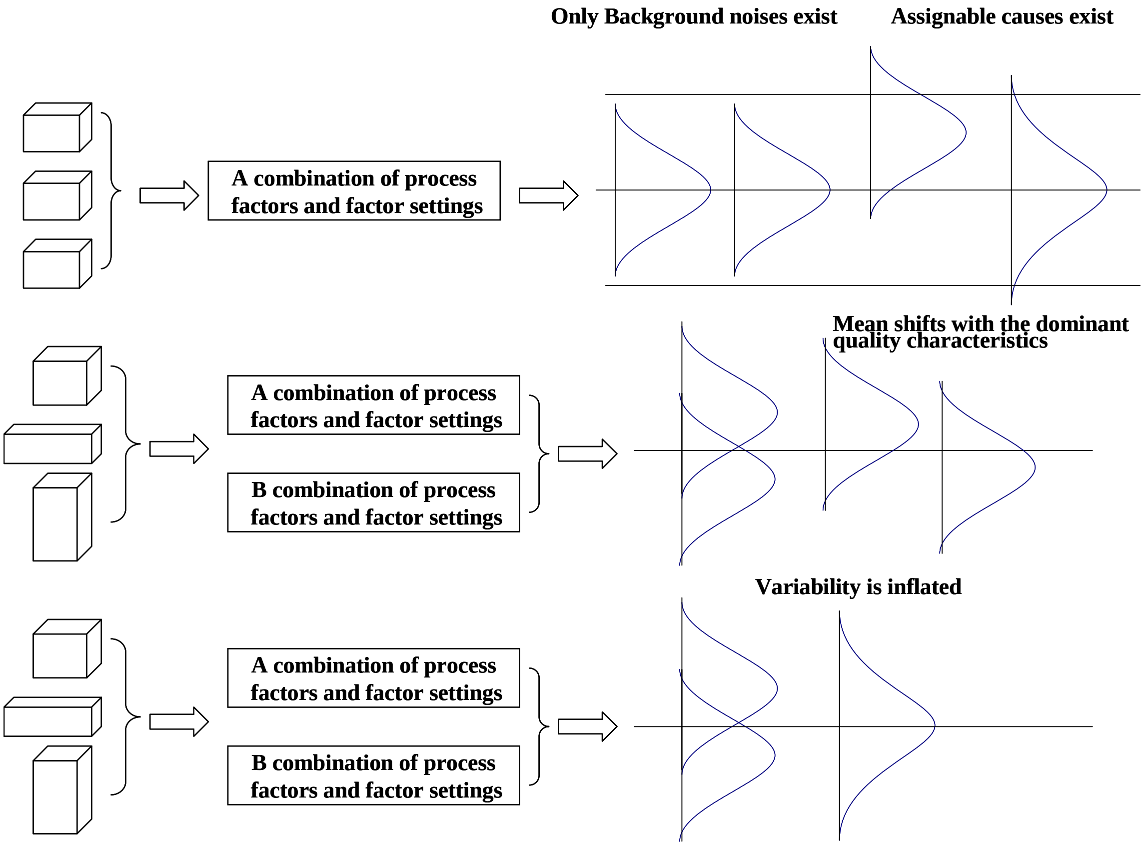


Figure 2.1 Similar Influences of Assignable Causes and Heterogeneous Data

However, when plotting the quality measurements from different combinations of part materials, process factors, or factor settings, the control chart may display unreasonable process status. If any factor has systematic influence on the quality characteristics, the process mean may vary with the involvement of that factor or the process variability is inflated, as if the assignable causes exist as shown in Figure 2.1. Hence, heterogeneous data can make the control chart ineffective. Some researchers have applied statistical analysis to identify the homogenous family members. In the following, reported methods pertaining to SPC-based family formation are reviewed and the limitations of these methods are highlighted.

Koons and Luner's approach

Koons et. al.(1991) assume the same manufacturing process as a common process and define a manufacturing lot as a subgroup. The validity of this assumption is tested by statistical analysis. Prior to the test, the predetermined quality characteristics of each part is measured and transformed by *Deviation from Nominal*. Then the subgroup variances are displayed in a Variance (S^2) Chart. The limits of the variance chart are calculated using the chi-square distribution.

$$\text{LCL} = \chi^2_{0.999} \frac{\bar{S}^2}{(n_j - 1)} \tag{2.13}$$

$$\text{UCL} = \chi^2_{0.001} \frac{\bar{S}^2}{(n_j - 1)} \tag{2.14}$$

The subgroups that exceed the control limits are excluded and analyzed separately. Then multiple regression analysis is performed on the *subgroup variances* to identify the effects of process factors. In their case, since the subgroups were unequal in size, weighted least squares were used. Because all the operating factors were categorical, dummy variables were used in the regression model. Based on the results of regression analysis, material was found to have systematic influence. The assumption of a common process was rejected and the process studied (end milling) was divided into a number of sub-common processes according to the material types.

In the preceding study, the problem was relatively simple. Firstly, the lot size was not too small (e.g. ranging from 12 to 48 units) and different types of parts were produced alternatively, so sufficient data could be collected to form meaningful subgroups and set up control limits. For one-off, very small-batch manufacturing, there is no basis for rational subgroups. In addition, the differences in the part materials, process factors and factor settings of different batches are usually not too much, so that the factors involved in the statistical analysis are limited. Otherwise, the regression model would become very large, which is not an efficient method. In regression analysis, the dummy variables required are one less than the total number of categories. If there are 4 factors with each having 5 levels, the number of dummy variables required is 19 (4×5-1=19). For one-off, very small-batch manufacturing, sufficient data is difficult to obtain from a single batch, but the involved part material, process factors and factor settings may differ from one batch to another. Hence, many dummy variables may have to be induced in the analysis. Another caution is that for unbalanced experimental design, the weights are arbitrarily assigned by the analyst, which may not reflect the true relationship between dependent and independent variables.

Kimbler and Sudduth's approach

Kimbler et. al., (1992) have proposed a "scaled method". Means of a mixture of parts, if they share a common process or distribution, are plotted together with modified control limits. Observation from a part type "*i*" is scaled by

$$y_i = \frac{x_i - a_i}{b_i} \tag{2.15}$$

The constants of a_i and b_i are obtained from

$$\frac{u_1 - a_1}{b_1} = \frac{u_2 - a_2}{b_2} = \mathrm{K} = \frac{u_m - a_m}{b_m} = u_g \tag{2.16}$$

and $\frac{\sigma_1}{b_1} = \frac{\sigma_2}{b_2} = \mathrm{K}\,\frac{\sigma_m}{b_m} = \sigma_g$ (2.17)

For n parts, if the scaling constants are perfectly selected, several different observations would have a common distribution with mean μ_g and standard deviation σ_g. Therefore, parts can be freely mixed without affecting the control chart. If a single part, however, has a scaled standard deviation that differs from the other, then its distribution will be different from what is expected. Hence, the points plotted from this part will be inconsistent with the rest of the chart, which will lead to errors in interpretation of the chart. To cope with this problem, they define a search function, and based on it they summarize a range of deviations for a single part from the overall scaled deviation, which has a tolerant probability of charting errors. The operator can then decide whether this part should be plotted with others.

Practically, the perfect scale parameters are hard to obtain and the selection of tolerant probability is subjective. Moreover, for one-off, very small-batch manufacturing, homogenous subgroups cannot be formed.

Evans and Hubele's approach

Evans and Hubele proposed a method based on the boring process. Quality characteristics from a batch of 21 parts, each of which had 22 boring-hole features, were collected. The 22 boring holes had 16 unique dimensions and were slightly different in geometry, which could be made with 4 distinct operations on 2 different machines. Based on their relationship with each type of boring holes, the measurements were arranged hierarchically, as shown in Figure 2.2. Other information of process factors associated with each part, such as the operator, operation sequence, boring bar holder, etc. was also collected.

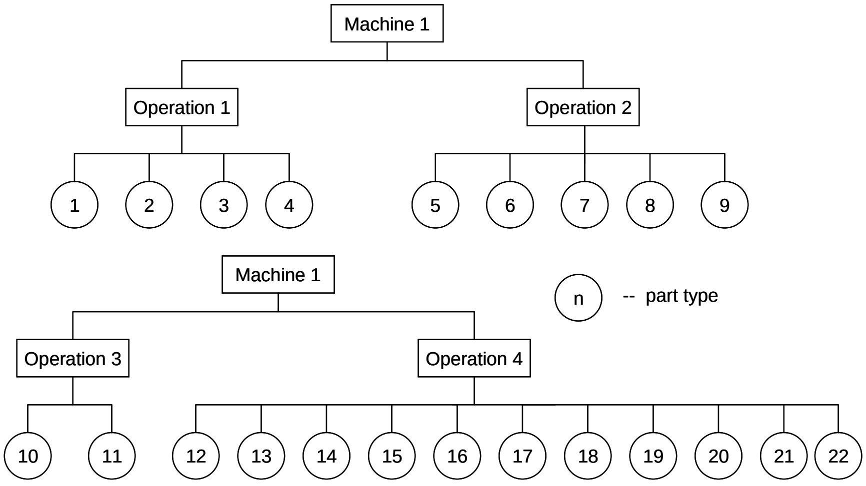


Figure 2.2 Complete Data Hierarchy

One-way ANOVA was applied to analyze the influence of machine and operation on quality measurements of different types of boring-holes. Prior to the analysis, data were transformed according to equation 2.7 and Leven's method (Levene, 1960). Then one-way ANOVA was firstly performed to test the homogeneity of variances on the transformed data along the data hierarchy. If differences in variances inferred, multiple comparisons performed to identify subsets of part data with equal variance. Otherwise, form a preliminary family with data sets with homogeneous variances. Secondly, one-way ANOVA was conducted to test equality of means on the preliminary family. If that fails, multiple comparisons are conducted to identify subsets of part data with equal means. Part families are formed for data sets with homogeneous variances and equal means. The process factors associated with each part are used to identify family membership.

As the part features (boring holes) are very similar, the machining process factors and factor settings to make different types of boring holes are slightly different. From Figure 2.2, it can be seen that only 2 machines and 4 operations are induced in the analysis. However, for complicated situations, such as the manufacture of core and cavity inserts of die and mould, the part features are highly varying, and the involved machining processes, process factors, and factor settings might be different from one feature to another. However, the batch size is very small. To obtain enough data, more factors have to be derived, e.g. the cutter, part material, etc. One-way ANOVA is characterized as a method of one-factor-at-a-time. In this case, a large number of tests are needed, which is very costly and time consuming. However, the results may be suspected due to its incapability of detecting interactions. On the other hand, there is a dependent relationship between the operations and the machines in this study. But with the application of CNC machining centers, one operation can be conducted by different machines, and one machine can perform many operations. Therefore, there will be many combinations between the process factor of machine and operation, which increase the complexity of the statistical analysis.

2.4 Group Technology Classification and Coding Concept Applied in SPC

To keep pace with the trend of computer-integrated manufacturing, several computerization methods have been developed to facilitate SPC, such as automatic data collection, control charting, and chart pattern recognition, etc. But for short-runs, the planning phase is an important bottleneck and to reduce the entire lead time, advanced computerized techniques should be applied.

Basically, group technology classification and coding (GTCC) is one of the major methods for solving family formation and viewed as amenable to a computer-based technology (Tatikonda, et. al, 1989). Here, GTCC system is proposed to be applied to facilitate computer-aided short-run SPC planning. The distinguished benefit of using GTCC is that it can facilitate not only information retrieval for planning, but also trace-back for process diagnosis, as shown in Figure 2.3.

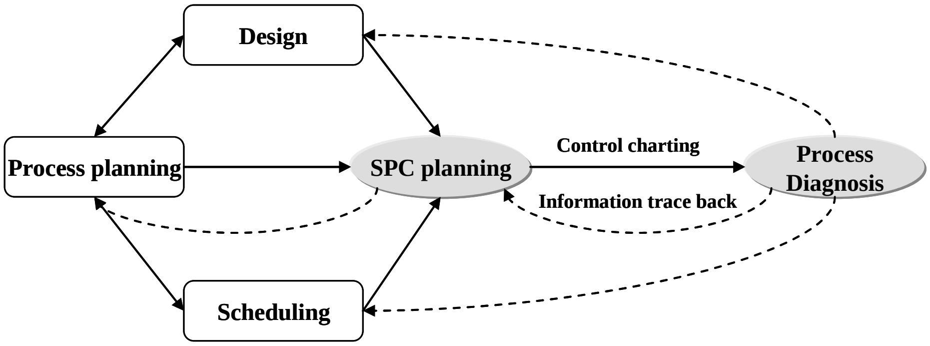


Figure 2.3 Benefit of using GTCC

A GTCC code is a string of numerical, alphabetical or alphanumerical characters that compactly describe the object attributes. There are generally three types of coding structure: hierarchical, chain, and hybrid, as shown in Figure 2.4. In a hierarchical structure, each code position is qualified by its preceding digit, which can include more information. In a chain structure, every digit represents a distinct bit of information, which is independent of the previous and easier to construct and manipulate. The hybrid code structure is a mixture of the hierarchical and chain structures, and has advantages of both. Most of existing classification and coding systems adopt the hybrid structure.

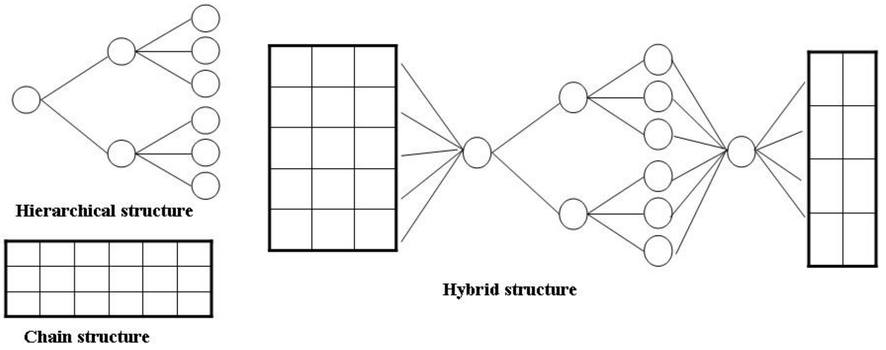


Figure 2.4 Coding Structures

Cheng (1989) suggested coding potential factors that might affect part family formation and using the code fields corresponding to the significant factors to identify part family members. He did not propose any special coding system to adopt but assumed that the potential factors could be coded with an existing GTCC system. For a given new part, potential factors and their relationship (hierarchical, chain, or hybrid) are arbitrarily chosen, which is based on the judgment of the user. For complex processes, the reduction in the number of factors and factor-level combinations can be difficult to achieve.

Currently, many commercial and non-proprietary GTCC systems have been developed to facilitate design and process planning information retrieval, production scheduling, and tooling grouping etc. Properties of some of the well-known systems are summarized in Table 2.1.

Table 2.1 Attributes of some well-known classification and coding systems

	Opitz	**MICLASS**	**DCLASS**	**CODE**	**KK-3 (rotational components)**
D_1	Part class	Main shape	Basic shape	Part class	Parts name
D_2	Main shape	Shape elements		Main shape	
D_3	Rotational machining				Materials
D_4	Plane surface machining	Position of shape elements	Form features	Shape elements	
D_5	Additional holes teeth and forming	Main dimensions	Size		Major dimensions: Length
D_6	Dimensions		Precision	Thickness/outside diameter	Major dimensions: Diameter
D_7	Material	Dimension ratio	Material	Width	Primary shapes and ratio of major dimensions
D_8	Original shape of raw material	Auxiliary dimension		Length	External surface
D_9	Accuracy	Tolerance codes			
D_{10}					
D_{11}		Material codes			
D_{12}					Forming
D_{13}					Cylindrical surface
D_{14}					Internal surface
D_{15}					
D_{16}					
D_{17}					End surface
D_{18}					Nonconcentric holes
D_{19}					
D_{20}					Noncutting process
D_{21}					Accuracy

Thus far, there has not been any reported system that allows coding for SPC planning. The particular requirements of GTCC system for facilitating short-run SPC planning are as follow:

- Differentiating quality characteristics that co-exist in a part;
- Describing some part properties and process information in detail, e.g. the machine number, operation type, etc. Part properties and process factors that have systematic influence on quality characteristics can be used to identify part family members;
- Smoothly interfacing other stages of the lifecycle of a component, e.g. design, process planning, and scheduling as shown in Figure 2.3. The detailed part or process information is specified during those stages and stored in associated database.

However, it can be seen from Table 2.1 that existing systems are primarily geometry-based. The information described by these systems essentially aims to differentiate dimensions according to geometry so that the size and overall shape of the part can be inferred. The manufacturing information implied by the auxiliary shape elements, material and accuracy in these systems is quite general. With the broad application of CNC machining centers and EDM machines, similar form features can be created by different machines or operations and different form features can be created by the same machine or operation. In fact, the general manufacturing requirements must be entailed by process planning and scheduling. Given these problems, one feasible solution is to induce a secondary code to an existing code. Such a coding scheme facilitates short-run SPC planning and also builds upon the functions of the existing system. Thus, there is minimal duplication in the coding system and the integration of information exchange of different stages can be enhanced if employed appropriately.

2.5 Summary

It can be concluded from the above review that some attempts have been made to apply short-run SPC, such as data transformation methods, design and selection of control charts, and part family formation approaches. Much of the existing work concentrates on repetitive small-batch production, and the part with similar and simple features. Not much has been done for the increasing situation of one-off, very small-batch manufacturing of parts with complicated geometric features, such as aerospace and aircraft parts, inserts of dies and moulds. Furthermore, most of the computerization work has been focused on control charting and chart pattern recognition. To make the application of short-run SPC more efficient, work on the planning phase is needed.

To develop a short-run SPC implementation approach that is suitable to both simple and complex small-batch production and adaptive to computer-directed manufacturing environments, the following problems need to be properly solved:

- An effective and efficient part family formation approach.
- An efficient part family membership identification approach for newly developed parts.
- A computer-aided part and process information retrieval and trace-back system.

CHAPTER 3

INJECTION MOULD COMPONENTS AND MANUFACTURING

Injection mould manufacturing is a typical one-off, very small-batch process. In this chapter, the basic properties of mould components and associated manufacturing processes are first introduced.

Nowadays injection molding is the most broadly used method in producing plastic parts. The molding process involves phases of plasticizing (mixing and external heating), injection (filling of the mould cavity), cooling (cooling of the material in the mould cavity), and ejection of the molded part. Figure 3.1 shows a schematic diagram of an injection molding machine set-up.

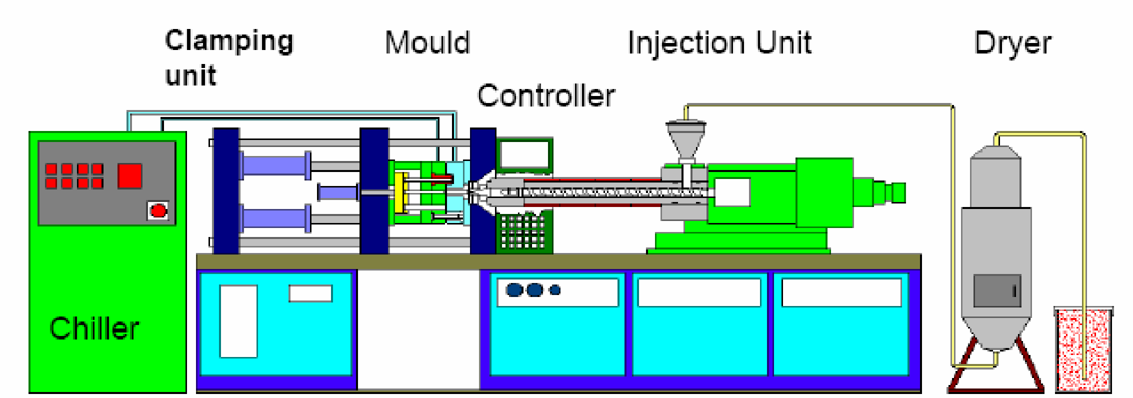


Figure 3.1 An Injection Molding System

An injection mould is a mechanical tool into which plastic is filled at high pressure and temperature. The injection mould is the master of the plastic parts in terms of dimensions and forms; thus, precision is one of the most distinguished requirements. From a mould, one to millions of parts can be produced; so steel is commonly used for its preferred service life.

3.1 Injection mould components

Injection mould assemblies consist of both supportive and functional components, as shown in Figure 3.2.

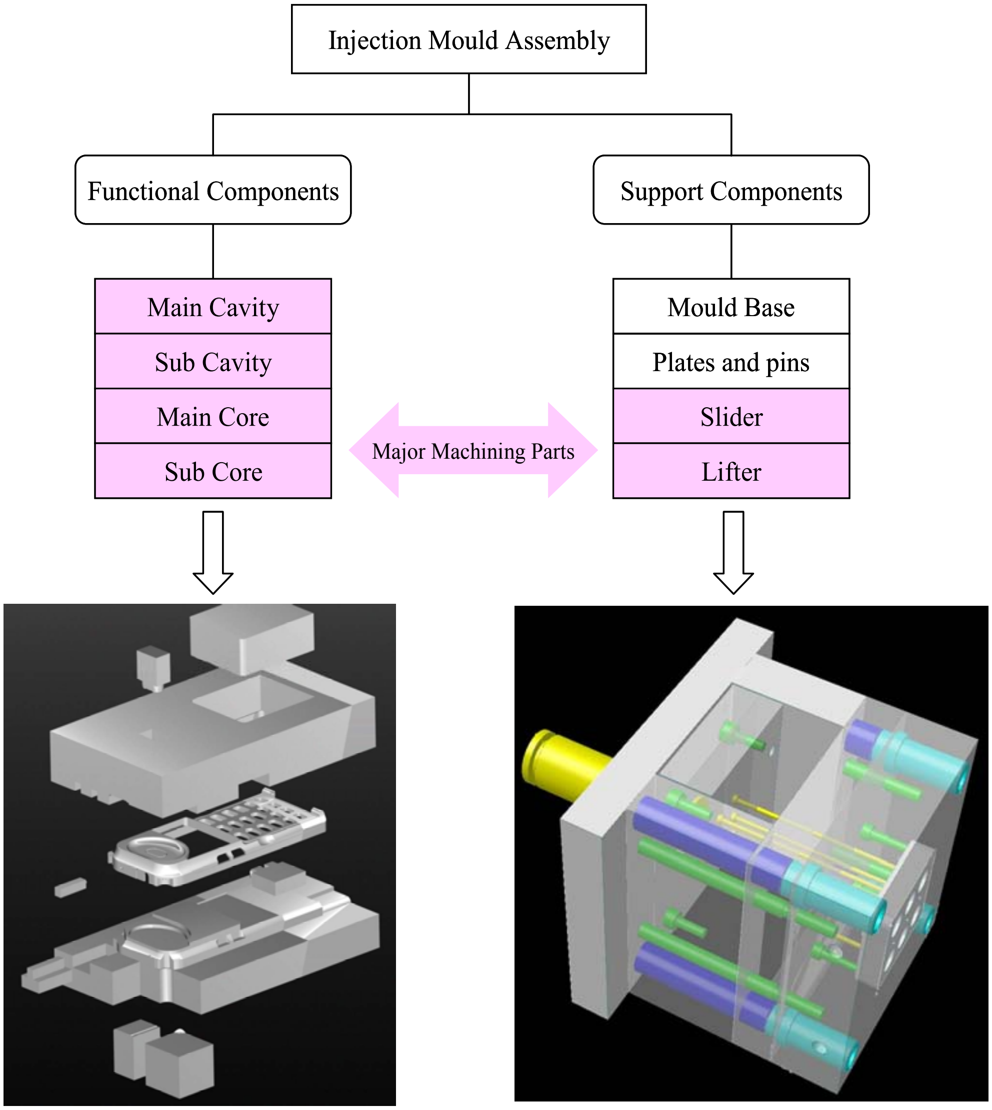


Figure 3.2. Major Injection Mould Components

The supportive components ensure the overall function of the mould assembly, such as ejection, alignment and so on. To reduce production time, most of the supportive components can be ordered as standard components. Sliders and lifters are major supportive components that used to be customized.

The functional components directly form the main body of the plastic parts that generally are core and cavity inserts. Each batch of core and cavity insert is unique and varies with the plastic parts to be molded. For example, the cavity and core inserts, as shown in Figure 3.3, are different from that shown in Figure 3.2.

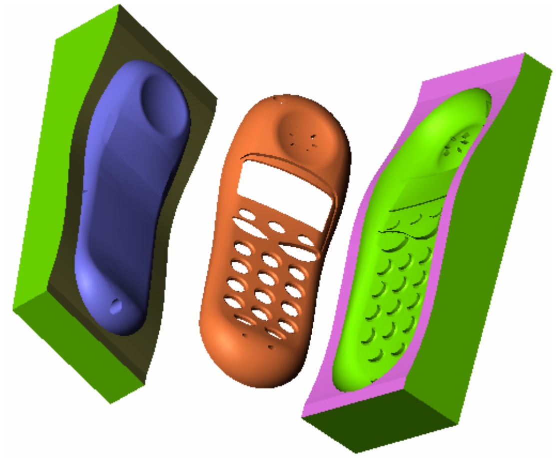


Figure 3.3 The Plastics Product and corresponding Core and Cavity Insert

Hence, the manufacturing of the core and cavity inserts is one-off. Due to the high cost, quality, etc., the batch size is usually very small, seldom exceeding 10 units. Such properties of the mould components make it difficult to apply existing approaches which are based on subgroups, similar features or repetitive production as discussed in chapter 2. Injection mould components are usually machined out of high-hardness tool and die steel blocks. The properties of several broadly used steels are shown in Table 3.1.

Table 3.1 Properties of several broadly used tool and die steels

Metal Grades	**Composition**	**Characteristics**	**Hardness**
ASSAB 8407	C0.37% C_r5.3% Mo1.4% Mn0.4% Si1% S0.003%	High alloy, oil and air hardening steel	Approx. surface hardness after tempering at 550ºC is 55 HRC
ASSAB 718HH	C0.33% C_r1.8% Mo0.02% Mn1.40% Si0.30% Ni0.8% S0.008%	Pre-hardened machinable plastic injection mold steel	Approx. surface hardness after tempering at 200ºC is 52HRC
ASSAB Starvax	C0.38% C_r13.6% Mn0.5% Si0.8% V0.3%	High chrome plastic injection mold steel with excellent polishability. Good corrosion resistance	Approx surface hardness after tempering at 300 ºC is 50HRC
ASSAB 618HH	C0.4% C_r1.9% Mn1.5% Mo0.2%	Pre-hardened plastic injection mold steel with high polishability	Approx. surface hardness after tempering in the 200ºC- 620ºC is 55HRC-46HRC

The required dimensional and positional accuracy of mould components could be down to ±5µm to avoid misfit between core and cavity inserts. The surface finish value of Ra = 1 µm is necessary in many cases (Dewes et al., 1998). Due to the variety of the geometry on the core and cavity inserts, different types of high-precision measurement equipment are used in the mould fabrication workshops. The digital height gauge is usually used to measure linear dimensions, and the optical comparator is employed to check profiles of very small and intricate geometries, such as extremely small and deep cavities. In most cases, the coordinate measurement machine (CMM) is used to measure various quality characteristics for its flexibility and programmability. The measurement results are the coordinate values of predetermined points on the insert features.

3.2 Injection mould manufacturing

In general, the main processes of developing an injection mould assembly consist of design, production preparation, manufacturing, inspection, assembly, testing and modification, as shown in Figure 3.4.

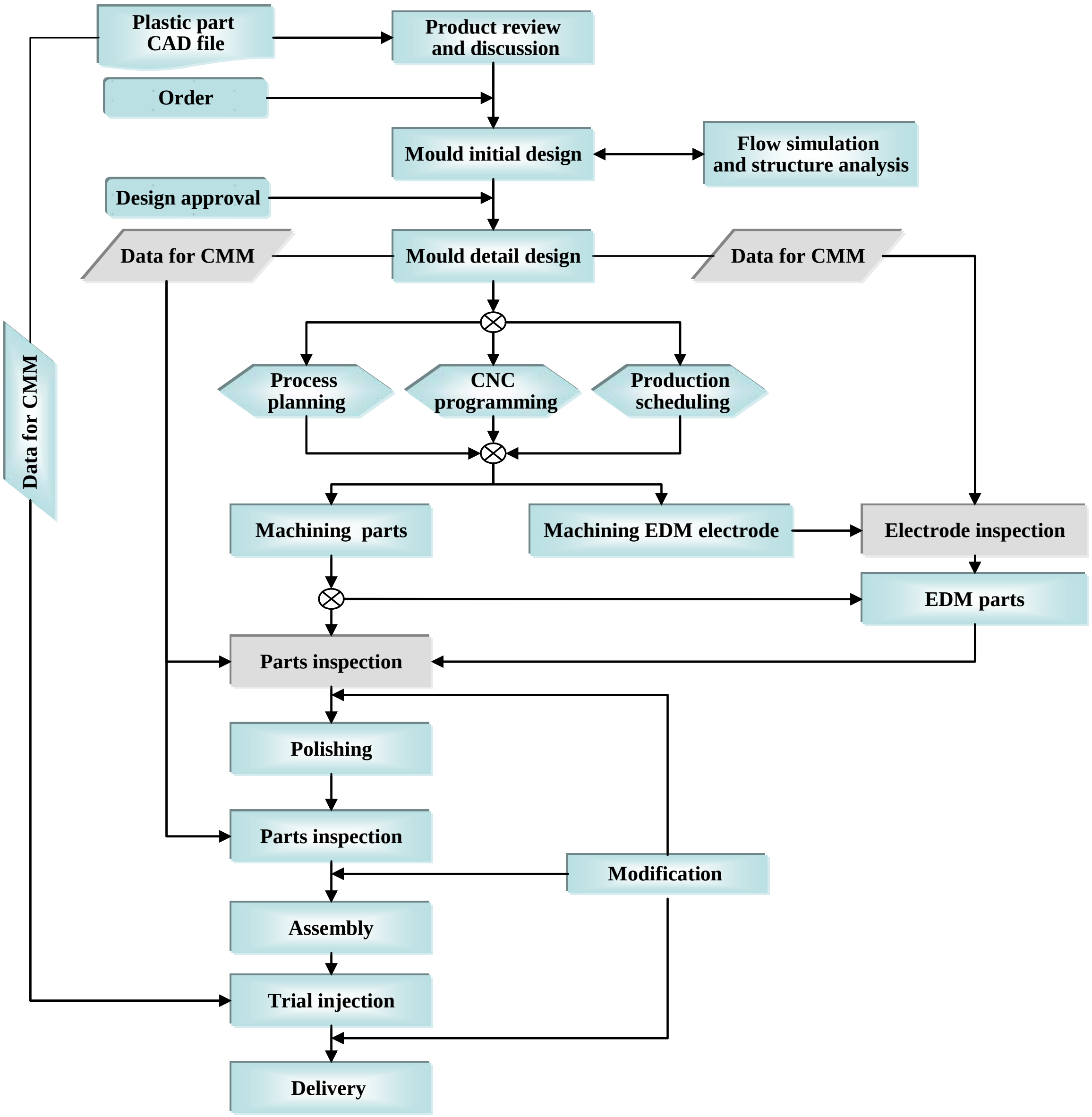


Figure 3.4 Flowchart of the Injection Mould Development Process

Injection Mould Design

Before formal design, the plastic product is reviewed in terms of manufacturability and tooling requirements. Then the confirmed CAD file of the product is used for mould design to ensure the accuracy of the data transformation from customer to the mould manufacturer. Upon completion of flow simulation and structural analysis, mould layout, parting line, cooling lines, etc. are decided, and then detail feature design can start. According to the customers' requirements, quality characteristics to be checked are indicated in the formal CAD model of the mould components. Such information will be sent to the CMM for measurement. The CAD model is also used for electrode design and measurement as indicated in Figure 3.4.

Production Preparation

Upon completion of the mould design, production preparation consisting of process planning, CNC programming, and production scheduling, starts. In the process planning stage, suitable machining operations, operating factors and operation sequence for creating each part features are figured out. The operation sequence is determined according to the geometric constraints, quality requirements and so on. In most cases, the applied operations, operating factors and operation sequence are different from one part to another due to the high variety of part geometry. The datum surface, work holding method, and the clamping facility are also selected.

In the CNC programming stage, tool path is generated, and cutters and cutting conditions in each cycle are selected from database. The program usually is global and can be used by different CNC machines or CMM. During production scheduling, machining tasks are assigned to specific machines. With the broad capability of CNC machining centers in modern workshop, one machine can conduct many types of operation. However, depending on the years of use, accuracy, capability, etc., some machines are only used in roughing for maximum material removal. Some are mainly used in finishing operations at light depth of cut and low feed rate.

Major Machining Processes and Operations

Based on the documents generated in the production preparation stage, the machinists can start to machine the components. Due to the highly varying and intricate geometry (e.g. sculptured surfaces, deep cavities, and sharp corners) of the core and cavity inserts, many machining processes are involved.

The major material removal operations include milling, drilling, and electrical discharge machining (EDM). With the introduction of high speed machining (HSM) the application of milling processes in die/mold production is expanding (Fallböhmer, et al. 1996). HSM offers the possibility to cut down on lead time by diminishing the effort for finishing and polishing operations. Among the variety of milling operations, face milling and end milling play a key role. EDM processes are used for machining complicated geometries, such as sharp corners, deep through holes or cavities, after milling, drilling and so on operations. The advantage of this process is that its performance is independent of the workpiece hardness. In addition, drilling is also a very important process for machining cooling channels, ejecting and locating holes, etc. To achieve desired dimensional accuracy and surface finish of some critical features, reaming and tapping operations are often used after rough milling or drilling.

Further, grinding and polishing are also necessary operations. Grinding is conducted before finishing operations to obtain flatness mating surfaces between the core and cavity inserts. Polishing is performed at last to remove the scratches and obtain mirror surfaces. To obtain desired hardness and wear resistance, some materials, e.g. ASSAB 8407 and 618HH, should be hardened by heat treatment before grinding and finishing operations. Others may not need it, e.g. ASSAB 718HH.

Others

Injection moulds are high-precision and expensive tools. Thus, quality control is one of the crucial steps throughout the manufacturing process. CMM is often used for this purpose by sorting out of quality characteristics out-of-specification. After rework on non-conforming features, mould components are assembled for tryout. Appropriate modification and correction are conducted before delivering to the customer.

3.3 Summary

It can be seen from the above discussion that injection mould manufacturing is a typical one-off, very small-batch process. The geometric features of the main components are highly varying. Consequently, forming subgroups from identical products produced by a particular process is impossible. In addition, part family identification for newly developed products is difficult. Further more, many types of machining operations are required to make a part. With the application of CNC machining centers, one operation can be conducted by different machines. Such situation is more complex than the target application of existing approaches reviewed in chapter 2.

CHAPTER 4

FAMILY FORMATION FOR APPLICATION OF SPC IN VERY SMALL-BATCH MANUFACTURING

In small-batch manufacturing, statistical process control cannot be routinely applied in the conventional way due to insufficient data. Group technology part family concept is borrowed to increase the number of samples. In this situation, to ensure the effectiveness of the control chart, the quality characteristics grouped together should have certain degree of homogeneity. Due to the high variation of the part and manufacturing being one-off and typically in very small-batch, the problem of forming homogeneous part families is more challenging. In this chapter, an alternative part family formation method is proposed.

4.1 Identify crucial quality characteristics and associated manufacturing processes

Quality characteristics related to the customer satisfaction or quality/productivity improvement purpose are crucial, as they directly determine the acceptance or rejection of the products or the business success. Here, critical quality characteristics are proposed to be taken as process control characteristics. During the planning stage, crucial quality characteristics should be firstly identified.

For instance, among the large number of injection mould components, the core and cavity inserts are the critical components, being the master of the plastic products to be molded in terms of geometry, dimension, and surface appearance. Hence, they are the major concern of customers. Therefore, the quality characteristics on them are taken as critical and are to be given more attention and effort for control. The focus of this research is the dimensional accuracy. Due to the tight tolerance and complicated geometry, the dimensional accuracy of such components is mainly inspected by CMM. When mould design has been approved by the customer, the part coordinate system, datum face, and points on critical features to be checked by the CMM are indicated in the CAD model, as shown in Figure 4.1. Among x, y, and z coordinates of a specific point, the one has subscript is to be recorded. Accordingly, these will be identified for SPC purpose.

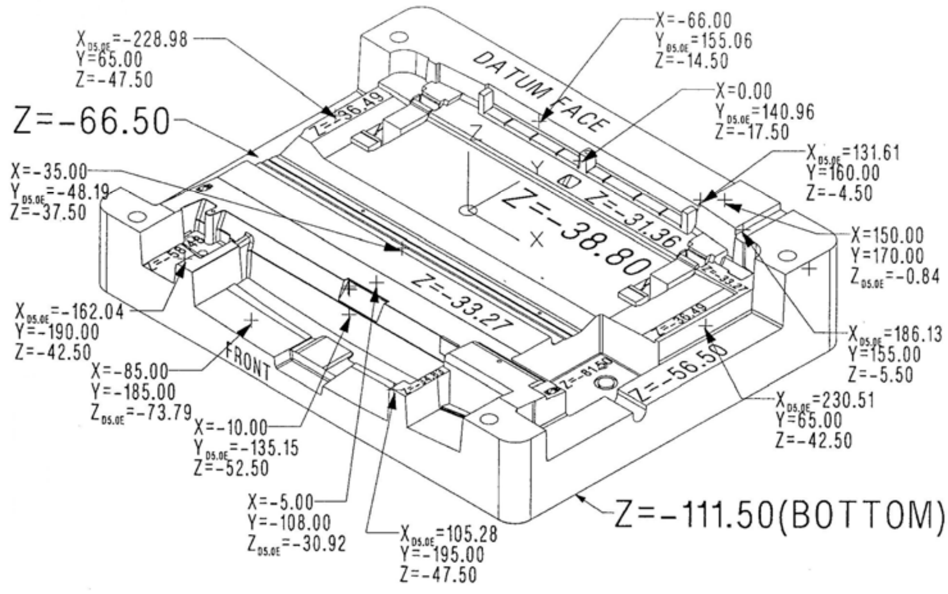


Figure 4.1 Quality Characteristics to Be Measured

Since the purpose of SPC is to monitor and improve the performance of the process, the critical quality characteristics must be related to the corresponding manufacturing process. Here, the focus of the application of short-run SPC will be on the processes associated to the accuracy of the critical quality characteristics.

Due to the variety of geometric features, many machining processes or operations may be involved in mould making. Generally, before heat treatment or grinding, the operations are taken as roughing operations. After that, the operations are semi-finishing and finishing, which are critical to the final dimensional accuracy of the part. Figure 4.2 graphically describes the commonly used operations and their relative sequence in mould making.

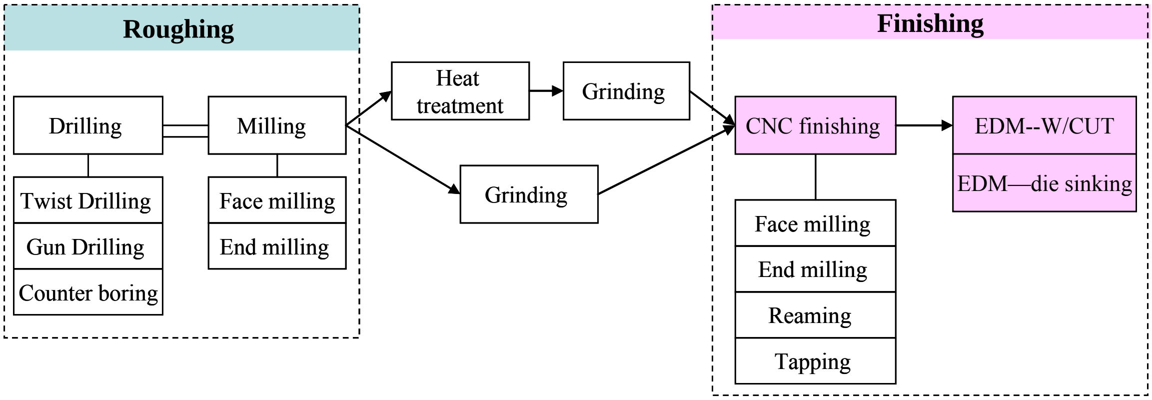


Figure 4.2 Major Machining Processes and Operations

At the roughing stage, twist drilling, gun drilling and counter boring are often used to make cooling holes, ejecting holes, locating holes, etc. Other drilling operations are occasionally used. Most of the non-rotational features are machined out by face milling or end milling operations. At the finishing stage, face milling, end milling, reaming, tapping, EDM—W/Cut, and EDM-die sinking are the major operations to achieve high dimensional accuracy. Accordingly, efforts of applying SPC should be concentrated on the operations in the finishing stage.

4.2 Classify machining resource information

Each machining operation has its particular properties and is performed by specific combination of the machine, cutter, etc. As process factors can have systematic influences on the quality characteristics, the information on various machining resources should be classified before further analysis, especially those often used in the finishing operations. The purpose is to simplify the statistical analysis.

Firstly, from the view of function, machines in a mould making process can be clustered into groups of EDM die-sinking, EDM –W/cut, grinding, and milling/drilling. From the view of productivity and maintenance, some machines in the milling/drilling group are only used for roughing, some are only used for finishing, some are only used for machining graphite EDM electrode, and others are only used for machining non-graphite EDM electrode. Correspondingly, machines in this group are further divided into groups for Roughing, Finishing, and graphite electrode making and non-graphite electrode making, as shown in Figure 4.3. Then, the family formation analysis will be applied to the machine groups used for finishing and electrode making.

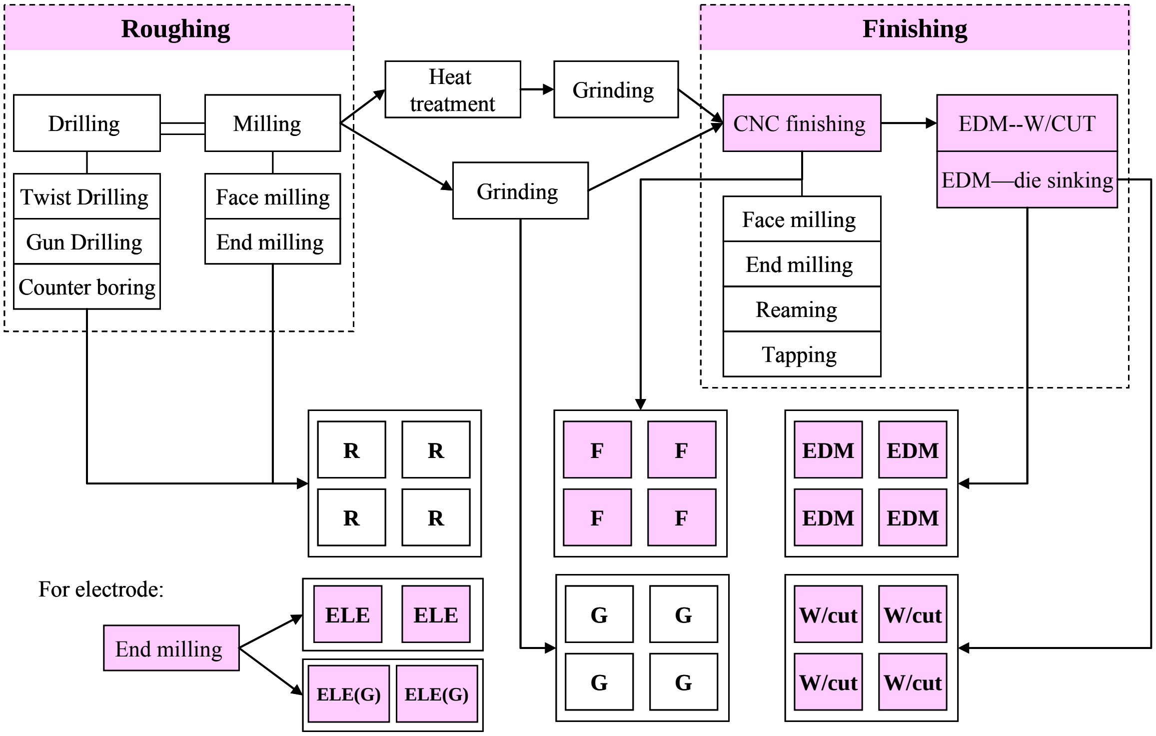


Figure 4.3 Machine Groups

Secondly, other process factors, such as cutters and cutting conditions, may also have significant influence on the quality characteristics. The main differences of the cutters and cutting conditions that are often used in the aforementioned operations are listed in Table 4.1.

Table 4.1 Properties of Cutters and Cutting Conditions

Operation	**Machine group**	**Major parameters**	**Cutter/electrode**
End milling	F	Cutting speed, depth of cut, feed rate	End mill, Bullnose mill, ball nose; HSS/carbide; diameters
Face milling	F		Insert geometry and number (diameter)
Reaming	F		Rose/fluted/shell/expansion/adjustable reamers; HSS/carbide, diameter
Tapping	F		Tapered/collapsible taps; HSS, diameter
End milling	ELE		End mill, Bullnose mill, ball nose; HSS/carbide; diameters
Grinding	G		Wheel grade and structure
EDM die-sinking	EDM (die-sinking)	Capacitance, discharge current, pulse duration, charge frequency	Graphite, copper, brass
EDM W/cut	(EDM) W/cut		

The cutters used in the same operation are mainly different in geometry, material properties, and diameter. For example, the end mill, the bullnose mill, and the ball nose cutters are three types of cutters broadly used in the end milling operation. The differences in geometry are as shown in Figure 4.4. Due to the high hardness of the material used in injection mould manufacturing, carbide cutters are commonly used in finishing operations. In the grinding operation, the cutting tool is a grinding wheel that has a different structure and hardness grade. In the EDM die-sinking operation, the geometry of the electrode varies with the features to be made. Electrodes are mainly machined out of graphite, copper, and brass. In the EDM wire-cut operation, the cutting tools are metallic wires, which is mainly brass.

Figure 4.4 Differences in Geometry of End Milling Cutters

The cutting condition is another factor that can induce systematic influence on the quality characteristics. In general, cutting speed, depth of cut, and feed rate are the most important cutting parameters in chip removal machining operations. In the EDM process, discharge current, on-time and off-time pulse duration are the key processing parameters. However, to reduce operating errors and increase working efficiency, standardized cutting conditions are often used. The value is selected from a database according to the workpiece material and the chosen cutter. Hence, it can be taken as a dependent variable, whose effects can be reflected by the variables that it depends on.

4.3 Preliminary analysis to simplify the statistical analysis

The statistical design of experiment is an important tool to identify homogeneous SPC-based part families. To efficiently collect and analyze data, and get reasonable results, the experiments should be well planned, e.g. how to select factors and factor levels. In the current application, an operation is proposed to be taken as a process to be studied, raw materials or pre-machined parts are taken as inputs, and the quality measurements are outputs. The factors or variables that may affect the process can be classified in two groups, controllable and uncontrollable variables (factors), as shown in Figure 4.5.

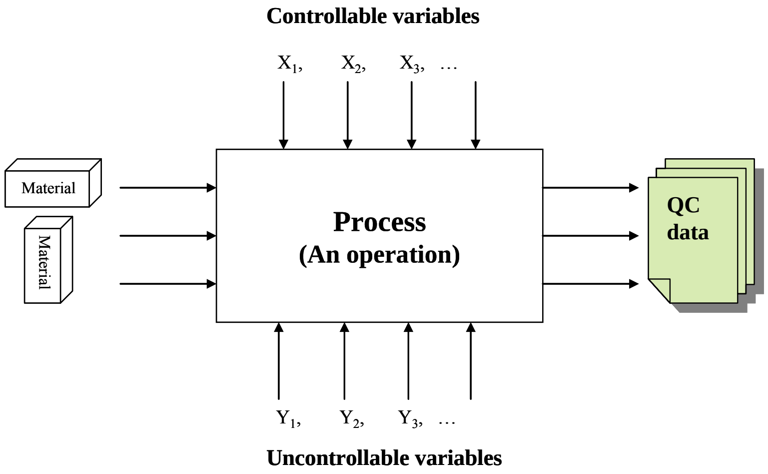


Figure 4.5 Model of Statistical Experiment

The controllable factors can be purposely varied, e.g. the machine or material used. On the other hand, the uncontrollable factors cannot be varied as desired, e.g. environment, part geometry, etc. Identification of independent, influential controllable factors on the output of the process is the purpose of this analysis. Factors that have systematic influence serve as the basis to bring together the SPC-based part family members. To simplify the statistical analysis, preliminary analysis with domain knowledge or understanding of the specific applications should be performed to prioritize the potential factors, and determine its levels.

For instance, consider the finishing end-milling operation for mould making as a process; thus the pre-machined parts are the process input. The difference in the input lies in its material properties, feature geometry and size. The difference in the resulting feature geometry and size can be affected by the cutters and machining conditions chosen. Hence, the feature geometry and size are also dependent variables.

Materials of different categories, such as copper, graphite, and steel have distinct properties, and the cutters and cutting conditions employed to process these materials can have significant differences, and thus they may not be combined or grouped accordingly. But materials in the same category, e.g. ASSAB 718HH, ASSAB 618HH, and similar types of tool and die steels, have similar properties, e.g. chemical composition or hardness. To obtain sufficient data, measurements generated from different tool and die steels should be considered to be group together. Hence, statistical analysis can be performed to judge the feasibility of such grouping. Therefore, materials of the same category are proposed to be studied in the statistical analysis. However, among a category of materials, the selection of specific types in the analysis should correlate it to the crucial quality characteristics discussed earlier, and the particular mould making application. For example, in a local mould making company, ASSAB 718HH, ASSAB 618HH, ASSAB 8407, and ASSAB Stavax are the materials mainly used for manufacturing core and cavity inserts, sliders, and lifters, but ASSAB 760, ASSAB Holdax, etc., are mainly used for mould base and plate which are standard components. Hence, for this company, the analysis on the material category of tool and die steels should focus on the materials used in the fabrication processes, which are ASSAB 718HH, ASSAB 618HH, ASSAB 8407, and ASSAB Stavax. Similarly, the preliminary analyses can be performed on the other types of material based on the critical properties and specific application.

The finishing end milling operation is performed by machines in the Finishing Group (Figure 4.3). Each machine has a specific capability, which may have significant influence on the process. Hence, the machine factor will be included in the statistical analysis.

According to a previous study (Cao, 2004), the quality measurements generated from flat end mills and Bullnose mills cannot be combined with those of ballnose cutters. Quality measurements made by large diameter of end mills (Ø > 6) and end mill(R) cutters (Ø > 12 & R=0.5) cannot be combined with those of small diameter. This study has been conducted on one specific machine (Makino V55), so the conclusion may not be applicable to other machines. In addition, Cao has based the study of the cutter factor on a particular workpiece material when studying the cutter factor; thus, the conclusion may not be applicable to the different types of materials.

Collectively, machine, material, and cutters are the three factors to be analyzed in the statistical analysis. The level of the machine factor is the machine number in the Finishing Group. For a particular category, the level of the material factor is the type of materials that are usually used for manufacturing key components in a specific purpose. According to the conclusion of Cao's study (Cao, 2004), the cutter factor is classified into three levels: ballnose, large diameter of end mills, and small diameter of end mills. The end mills include flat end mills and bullnose mills.

For other machining operations, preliminary analysis according to the factor properties and application is performed in the similar way. The recommended factors for statistical analysis of face milling, reaming, and tapping operations are machine, workpiece material, cutter type (geometry), and cutter diameter (large/small). The classification of cutter size can be based on experiential knowledge or according to Equation (4.1).

$$\text{Coded value} = 2(\text{Actual} - \text{Medium})/\text{Range} \qquad (4.1)$$

where, *Actual* is the specific cutter diameter; *Medium* is the medium diameter value among the cutters of a particular type; *Range* equals the largest diameter value minus the minimum diameter value in that type.

If the coded value is "+", the cutter diameter is taken as large, otherwise, it is small. The purpose is to reduce the factor levels involved in the statistical analysis as the statistical experiments and analyses with many factors and factor levels are very costly and time consuming.

4.4 Statistical experiments to identify homogenous part family members

Statistical design of experiment (DOE) is a systematic approach to vary the controllable variable in a process and analyze the effects of these process factors on the output (Montgomery, 2001). Analysis of variance (ANOVA) is the primary method of the statistical analysis in experimental design. Here, K-way ANOVA (explained in Appendix D) is proposed to be applied for statistical analysis, which can concurrently investigate the influence of multiple factors. K is the number of interested factors. Theoretically, there is no limit on K. When some of the factors have many levels, the experiments with three or more factors can require many runs. However, extensive preliminary analyses based on the critical factor properties and application can largely reduce the factor number and level necessary for statistical analysis. In addition, random ANOVA model and coded value calculated by Equation 4.1 can be used to further reduce the experimental runs.

If the levels of a factor are randomly selected from a population of many possible levels, the factor is a random factor and conclusions are useful to all levels in the population. If the levels of a factor represent the entire population of a factor level or if the levels are selected in a specific manner, the factor is a fixed factor and the conclusions pertain only to the levels that are considered in the analysis. An ANOVA model is called a fixed model if all the factors are fixed, random if all the factors are random, and mixed if some factors are fixed and others are random. Hence, in some cases, random or mixed model can be used to reduce the experimental runs if one or more factors have many levels.

The basic assumptions of ANOVA model include the following (Eisenhart, 1947):

1. The experimental (residual) errors are randomly and normally distributed,
2. The experimental errors have a homogeneous variance,
3. The experimental errors are independent of the main effects, interactions, and of each other.

Oftentimes, one or more of the above assumptions will be violated. Previous studies (Bartlett 1947, Box 1954[a, b]) regarding the consequences of departure from these assumptions concluded that moderate departures from normality are of little concern in the fixed effects ANOVA model with equal sample size (balanced model). And if the assumption of homogeneous variance is violated, the F-ratio is only slightly affected in the balanced model, so the results are acceptable. However, in unbalanced designs (unequal sample size), the problem is more serious. Therefore, well-controlled, balanced experimental design is proposed instead of unbalanced design that has been used in existing studies. In addition, data collected from a stable process is preferred to historical data. Historical data may induce erroneous results due to the historical process properties, e.g. trend or stratification. The proposed procedure of the statistical experiment and analysis is given below and shown in Figure 4.6.

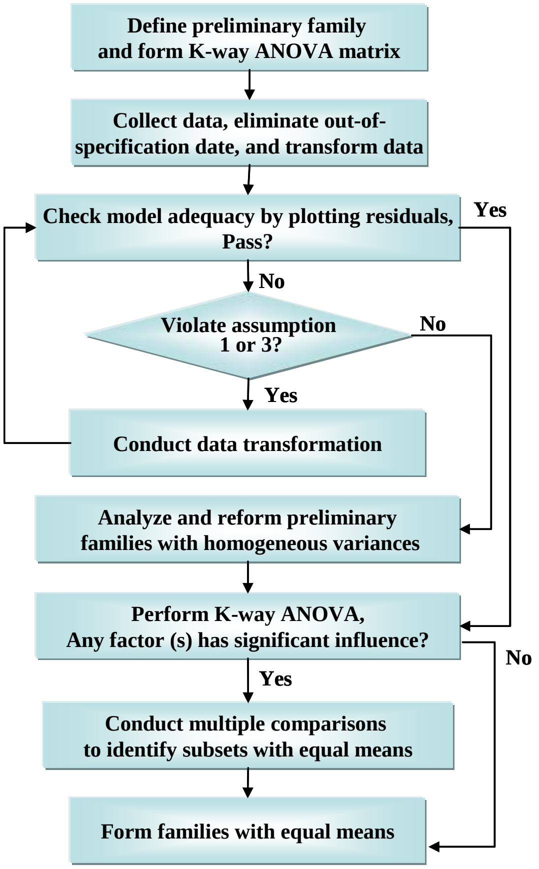


Figure 4.6 The Experiment and Statistical Analysis Procedure

- Quality measurements from the same operation and measured by the same measurement equipment is taken as a preliminary family. Based on extensive preliminary analyses, the K-way ANOVA matrix is formed with critical process factors and associated factor levels.

- Accordingly, data are collected from a well-controlled process and transformed. The purpose of this transformation is to use data with different normal and tolerance values. Out-of-specification quality measurements are excluded from statistical analysis, as such data are taken to be related to special causes.

- Before performing ANOVA, the assumptions are checked by 4 plots: normal probability plot of the residuals (normality assumption), residuals versus the run order (independence assumption), residuals versus the fitted values, and residuals versus the fitted value of each factor (equal variance assumption). Most statistical software package will construct these plots on request. If there is no violation on the normality or independence assumption, or both, proceed to the next step. Otherwise, the original data can be transformed to make the transformed data conform to the assumptions. Extensive transformation methods are available for this purpose, and considerable research has been done on the selection of a suitable transformation (Neter, et al. 1996). In general, one transformation can remedy different departures from the assumption. Several usually used transformations are summarized in Table 4.2. If the residual plot versus any factor indicates that the assumption of homogeneous variance is seriously violated, further analysis, e.g. multiple comparison with paired Levene's test, is necessary to divide the preliminary family into a number of sub-families with homogeneous variances.
- Then K-way ANOVA is conducted to identify significant factor(s). If no factors have significant influence, the preliminary family is deemed as a meaningful SPC-based part family. The operating factors and part properties associated with the family members are used to identify the membership. Otherwise, multiple comparisons are performed to identify levels of the significant factor that have the

equal means. Here, the Fisher's test (Jason, 1996) is proposed to be used. The SPC-based part families are formed with subsets of data with equal means.

Table 4.2 Several Usually Used Data Transformation Methods

Transformation Function	**Conditions of the Application**
$Y^{'} = \sqrt{Y}$	when s_i^2 is proportional to $\overline{Y_i}$
$Y^{'} = \log Y$	when s_i is proportional to $\overline{Y_i}$
$Y^{'} = \frac{1}{\sqrt{Y}}$	when s_i is proportional to $\overline{Y_i}^{\frac{3}{2}}$
$Y^{'} = \frac{1}{Y}$	when s_i is proportional to $\overline{Y_i}^{2}$

4.5 Case studies

Case studies were conducted to illustrate the proposed statistical analysis method. One is the finishing end milling operation that directly affects the final dimensional accuracy of the mould parts. The other one is the finishing end milling operation on the EDM tools making the mould parts. Milling is an operation to remove away materials by feeding a workpiece past a rotating multiple-tooth cutter. The action by the multiple teeth around the milling cutter provides a fast method of machining. The machined surface may be flat, angular, curved or any combination of shapes. The cutter in end milling generally rotates about a vertical axis perpendicular to the workpiece, as shown in Figure 4.7. It can also be tilted to the machine surfaces in some machines.

The experiment was conducted in a local injection mould manufacturing company. Before the experiment, machining resource information were collected, classified, and extensive preliminary analyses were conducted.

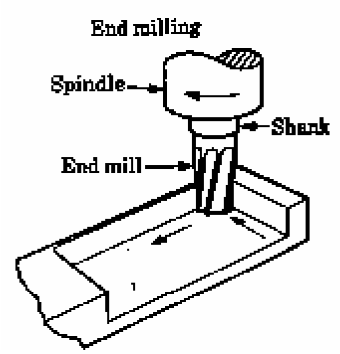


Figure 4.7 End Milling Operation

4.5.1 Case Study 1—the finishing end milling operation on mould parts

In the company, three CNC machines are used for finishing operations, the properties of which are shown in Table 4.3. Thus, for the machine factor, there are three levels, Mori Seiki SV-500, Mori Seiki NVD5000 (1), and Mori Seiki NVD5000 (2).

Table 4.3 Properties of Machines in the Finishing Group

Properties	**Mori Seiki SV-500**	**Mori Seiki NVD5000 (1&2)**
Table size	52" x 23.6"	43.3" x 23.6"
Table Travels	30" x 20" x 20"	31.5" x 20.1" x 20.1"
Spindle Speed	10,000RPM (up to 20K)	12000RPM
Feed rate	1-16m/min	1-20m/min

The core and cavity inserts, sliders and lifters are mainly machined out of tool and die steel of ASSAB 718HH, ASSAB 618HH, ASSAB 8407, or ASSAB Stavax. Accordingly, for the material factor, there are four levels. The choice of the cutter levels is based on the conclusion of Cao's study (Cao, 2004). Correspondingly, a 3-way ANOVA matrix is formed, as shown in Table 4.4.

Table 4.4 The 3-way ANOVA Matrix

Cutter	**Machine (F)**											
	Moki Seiki SV-500				Mori Seiki NVD-5000(1)				Mori Seiki NVD-5000(2)			
	Material (ASSAB)				**Material (ASSAB)**				**Material (ASSAB)**			
	8407	718 HH	Stavax	618 HH	8407	718 HH	Stavax	618 HH	8407	718 HH	Stavax	618 HH
End mill (Large)	P-1	P-2	P-3	P-4	P-5	P-6	P-7	P-8	P-9	P-10	P-11	P-12
End mill (Small)	P-1	P-2	P-3	P-4	P-5	P-6	P-7	P-8	P-9	P-10	P-11	P-12
Ball nose	P-1	P-13	P-3	P-4	P-14	P-6	P-7	P-8	P-15	P-10	P-16	P-12

Each cell is a particular combination of the three factors. Data were collected from various features of 16 parts (P-1 to P-16). The sample parts are shown in Appendix A-1. Data of out of tolerance case or needing rework were excluded. To reduce the variability induced by assignable causes, data of the same cell were collected from the same setup. To increase the variability in the cell, data for ballnose cutters were collected from largest diameter (R10) and relatively small diameter (R1). Such selection also can better present the whole population of the ballnose cutters. The operation on Parts 1, 2, 3, 4, and 13 were conducted by CNC machine Moki Seiki SV-500. The operation on Parts 5, 6, 7, 8, and 14 were conducted by Moki seiki NVD (1), and the operation on Parts 9, 10, 11, 12, 15, and 16 were conducted by Moki seiki NVD (2). Parts 1, 5, 9, 14, and 15 were machined out of the ASSAB 8407. Parts 2, 6, 10, and 13 were machined out of the ASSAB 718HH. Parts 3, 7, 11 and 16 were machined out of Stavax, and Parts 4, 8, and 12 were machined out of ASSAB 618HH. Measurements of the quality characteristics of the features that were generated from ballnose cutters were put into the last row. Measurements of the quality characteristics of the features that were generated from small-diameter end mills and large-diameter end mills were put into the second and third last row respectively. With the data filtered according to the aforementioned consideration, it therefore does not necessary mean that Parts 2, 5, and 11 did not require ballnose milling, or Parts 13, 14, and 16 did not require end-milling.

Equal amount of data were collected for each of the cell, so that the underlying 3-way ANOVA model is a balanced model. For 3-factor factorial experiment, there are at least two replicates in each cell to compute an error sum of squares. But if more data are available, the result will be more reliable. To avoid disturbing the normal production, only two replicates was collected. The raw data were transformed according to Equation (4.2).

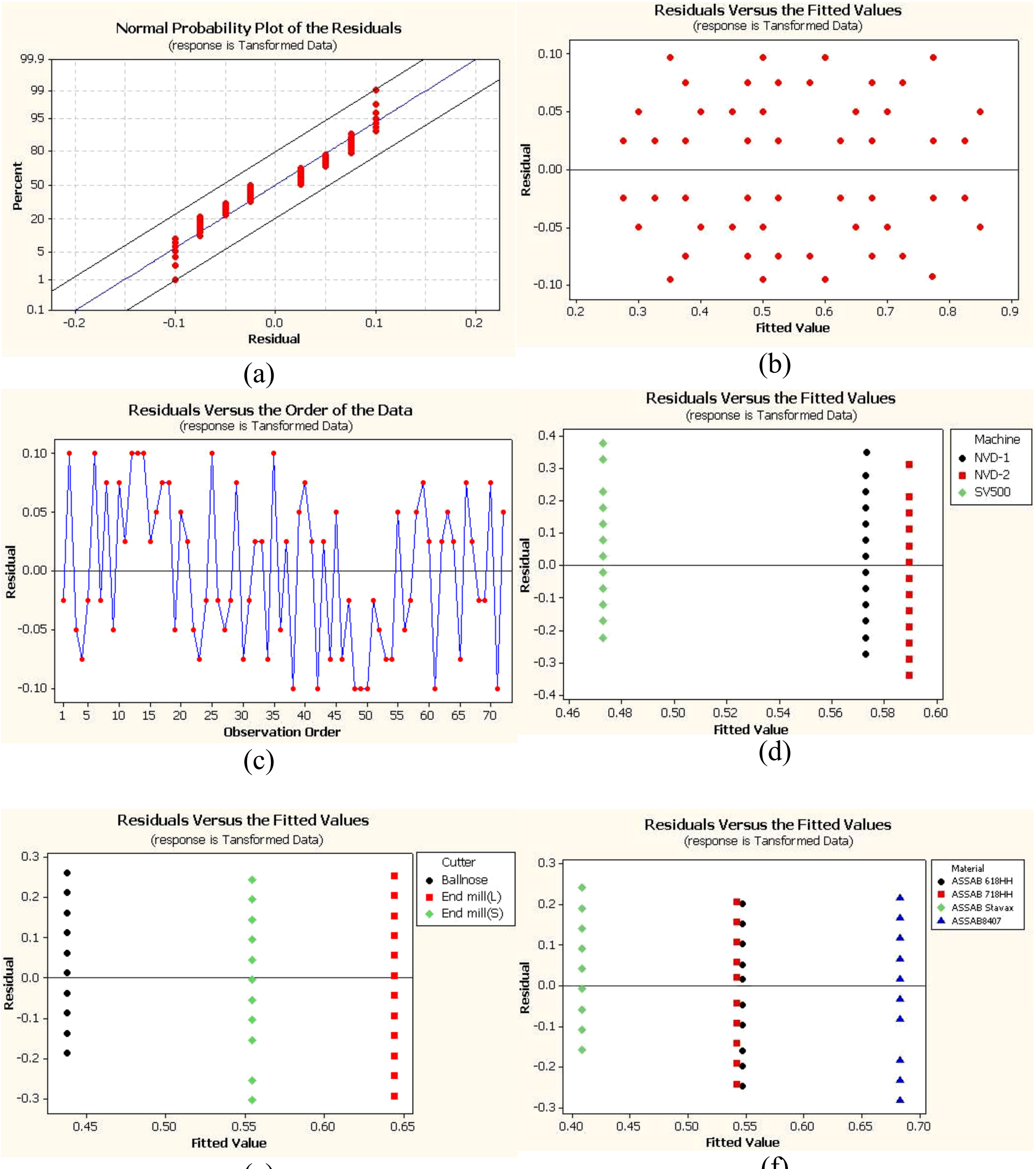
$$Y = \frac{X - \text{Nominal}}{T} \tag{4.2}$$

where X is the coordinate measurement, T is its tolerance value, and Y is the transformed value.

The raw and transformed data are shown in Appendix A-2. The transformed data were input into Minitab@ (commercial statistical software) for statistical analysis. Based on the method proposed in Section 4.4., the adequacy of the ANOVA model (normality, independence, and equal variability assumptions) are first checked, with results shown in Figure 4.8.

The normal probability plot of residuals (Figure 4.8a) does not fall exactly along a straight line passing through the center of the plot, but it does fall between a pair of parallel lines. Thus there is no strong evidence to reject the normality assumption

(Montgomery, 2002). In addition, as this ANOVA model is a balanced model, moderate departure from normality is of little concern (Bartlett 1947, Box 1954$^{a,\ b}$).



(a) (b) (c) (d) (e) (f)

Figure 4.8 Model Adequacy Checking

The independence assumption is checked by plotting the residuals against the run order (Figure 4.8c). There is no pattern, such as sequences of positive and negative residuals.

Thus, there is no strong evidence to reject the independence assumption (Neter, et. al, 1996, Montgomery, 2002).

The equal variability assumption is checked by plotting the residuals versus the fitted value, and residuals versus the fitted value of each factor. The graph of residuals versus fitted values (Figure 4.8b) does not reveal any unusual or diagnostic pattern (e.g. proportional or curvilinear). Hence, there is no need to perform data transformation and make the transformed data conform to the equal variability assumption (Neter, et. al, 1996, Montgomery, 2002).

In the plot of residuals versus levels of the cutter factor (Figure 4.8e), the vertical spread in the residuals of Ballnose is less than that of other cutters, which indicates that Ballnose results in slightly lower variability than other cutters to some extent. In the plot of residuals versus levels of the material factor (Figure 4.8f), the vertical spread in the residuals of Stavax is less than that of other materials, while 8407 is larger. Thus, there is some indication that Stavax results in slightly lower variability than other materials, and 8407 has somewhat more variability. But slight departure from the equal variability assumption, F-ratio is only slightly affected in the balanced model (Bartlett 1947, Box 1954[a, b]), so in general, the model adequacy can be accepted. If there is great difference in the variability, follow-up experiments (multiple comparisons) can be conducted to confirm the findings, and the preliminary family is reformed with homogeneous variances. The results of the balanced 3-way ANOVA are shown in Table 4.5.

It can be seen that about 70 percent of the variability in the quality measurements is explained by the underlying balanced 3-way ANOVA model. The significant effects are at $\alpha=0.05$ level. According to the p-value, machine, cutter and material are all significant factors (P-values<0.05), and there are no significant interaction effects (P-values>0.05). Subsequently, multiple comparisons, Fisher's test, were conducted to identify levels of the significant factor that have the equal means. Part families are formed with subsets of data with equal means. The results are shown in Tables 4.6, 4.7, and 4.8.

Table 4.5 Minitab ANOVA (Balanced Design) for the case study

ANOVA: Tansformed Data versus Cutter, Machine, Material

```
Factor    Type   Levels  Values
Cutter    fixed       3  Ballnose, End mill(L), End mill(S)
Machine   fixed       3  NVD-1, NVD-2, SV500
Material  fixed       4  ASSAB 618HH, ASSAB 718HH, ASSAB Stavax, ASSAB8407

Analysis of Variance for Tansformed Data

Source                   DF        SS        MS      F      P
Cutter                    2  0.513403  0.256701  31.19  0.000
Machine                   2  0.191111  0.095556  11.61  0.000
Material                  3  0.680938  0.226979  27.58  0.000
Cutter*Machine            4  0.040972  0.010243   1.24  0.310
Cutter*Material           6  0.071042  0.011840   1.44  0.227
Machine*Material          6  0.071667  0.011944   1.45  0.223
Cutter*Machine*Material  12  0.095417  0.007951   0.97  0.497
Error                    36  0.296250  0.008229
Total                    71  1.960799

S = 0.0907148   R-Sq = 84.89%   R-Sq(adj) = 70.20%
```

Table 4.6 MiniTab Multiple Comparison on the Levels of the Factor of Machine

```
Fisher 95% Individual Confidence Intervals
All Pairwise Comparisons among Levels of Machine

Simultaneous confidence level = 87.89%

Machine = NVD-1 subtracted from:

Machine    Lower   Center    Upper  -------+---------+---------+---------+--
NVD-2    -0.0756   0.0167   0.1089            (------*-------)
SV500    -0.1922  -0.1000  -0.0078   (-------*------)
                                    -------+---------+---------+---------+--
                                        -0.12      0.00      0.12      0.24

Machine = NVD-2 subtracted from:

Machine    Lower   Center    Upper  -------+---------+---------+---------+--
SV500    -0.2089  -0.1167  -0.0244  (------*-------)
                                    -------+---------+---------+---------+--
                                        -0.12      0.00      0.12      0.24
```

When machine NVD-1 is subtracted, the result corresponding to machine NVD-2 is the pairwise comparison result between the means of machine NVD-1 and NVD-2. It can be seen that the lower boundary is “-0.0756”, and the upper boundary is “0.1089”. As the range from “-0.0756” to “0.1089” contains zero, there are no significant differences in these two means (Jason, 1996, Neter, 1996, Montgomery, 2002). Hence, data generated from machine NVD-1 and NVD-2 can be combined when the potential influence of other factors has been isolated. Subsequently, the result corresponding to machine SV500 is the pairwise comparison result between the means of machine NVD-1 and SV500. The lower boundary is “-0.1922”, and the upper boundary is “-0.0078”. As the range from “-0.1922” to “-0.0078” does not contain zero, there are significant differences in these two means (Jason, 1996, Neter, 1996, Montgomery, 2002). Hence, the resulting data of these two machines cannot be combined.

When machine NVD-2 is subtracted, the result is the pairwise comparison result between the means of machine NVD-2 and SV500. The lower boundary is “-0.2089” and the upper boundary is “-0.0244”. As the range from “-0.2089” to “-0.0244” does not contain zero, there are significant differences in these two means. Hence, the resulting data of machine NVD-1 and NVD-2 cannot be combined together.

The result of the multiple comparison tests among the levels of the cutter are shown in Table 4.7. As none of the ranges contain zero, there are significant differences in the means between all pairs of cutter. Hence, data generated from these three types of cutter cannot be combined together. This result is in accordance with Cao’s study on the cutter factor. However, the data in this study were *evenly* collected from different machines and types of workpiece materials, so the irrelevant factor influence was randomized. Thus, the result here is more reliable.

Table 4.7 MiniTab Multiple Comparison on the Levels of the Factor of Cutter

```
Fisher 95% Individual Confidence Intervals
All Pairwise Comparisons among Levels of Cutter

Simultaneous confidence level = 87.89%

Cutter = Ballnose subtracted from:

Cutter        Lower  Center   Upper  ----+---------+---------+---------+-----
End mill(L)  0.1228  0.2062  0.2897                          (------*------)
End mill(S)  0.0333  0.1167  0.2001                   (------*------)
                                     ----+---------+---------+---------+-----
                                      -0.12      0.00      0.12      0.24

Cutter = End mill(L) subtracted from:

Cutter         Lower   Center    Upper
End mill(S)  -0.1730  -0.0896  -0.0062

Cutter       ----+---------+---------+---------+-----
End mill(S)  (------*-----)
             ----+---------+---------+---------+-----
              -0.12      0.00      0.12      0.24
```

The result of the multiple comparison tests among the levels of the material are shown in Table 4.8. According to the range value, there is no significant difference between the means of the ASSAB 618HH and 718HH, but there are significant differences between the means of 618HH to that of Stavex and 8407. Similarly, there are also significant differences between the means of 718HH to that of Stavex and 8407. And there are significant differences between the means of Stavex and 8407. Thus, the quality measurements generated from 618HH and 718HH can be combined together. The quality measurements generated from Stavex, and 8407 cannot be combined with other material.

Table 4.8 MiniTab Multiple Comparison on the Levels of the Factor of Material

```
Fisher 95% Individual Confidence Intervals
All Pairwise Comparisons among Levels of Material

Simultaneous confidence level = 80.02%

Material = 618HH subtracted from:

Material       Lower    Center     Upper
718HH       -0.03896  -0.00667   0.02562
ASSAB 8407   0.01104   0.04333   0.07562
Stavax      -0.07340  -0.04111  -0.00882

Material    ---------+---------+---------+---------+
718HH                    (----*----)
ASSAB 8407                       (----*-----)
Stavax             (----*-----)
            ---------+---------+---------+---------+
                  -0.060     0.000     0.060     0.120

Material = 718HH subtracted from:

Material       Lower    Center     Upper
ASSAB 8407   0.01771   0.05000   0.08229
Stavax      -0.06673  -0.03444  -0.00215

Material    ---------+---------+---------+---------+
ASSAB 8407                        (----*-----)
Stavax              (----*-----)
            ---------+---------+---------+---------+
                  -0.060     0.000     0.060     0.120

Material = ASSAB 8407 subtracted from:

Material     Lower    Center     Upper
Stavax    -0.11673  -0.08444  -0.05215

Material  ---------+---------+---------+---------+
Stavax    (----*----)
          ---------+---------+---------+---------+
                -0.060     0.000     0.060     0.120
```

Conclusions

Based on the extensive preliminary analyses with the knowledge of the critical properties and specific application of the end milling process factors, and statistical experiments and analyses with real data, the conclusions are as follows:

1. Machine, material, and cutter (geometry and diameter) are three factors that have systematic influence on the quality characteristics.

2. Quality characteristics generated from the machine of Moki Seiki SV-500 cannot be grouped with those of Moki Seiki NVD-1 and Moki Seiki NVD-2, as shown in Figure 4.9. This might due to the specific machining capability of different brands or models of machine.

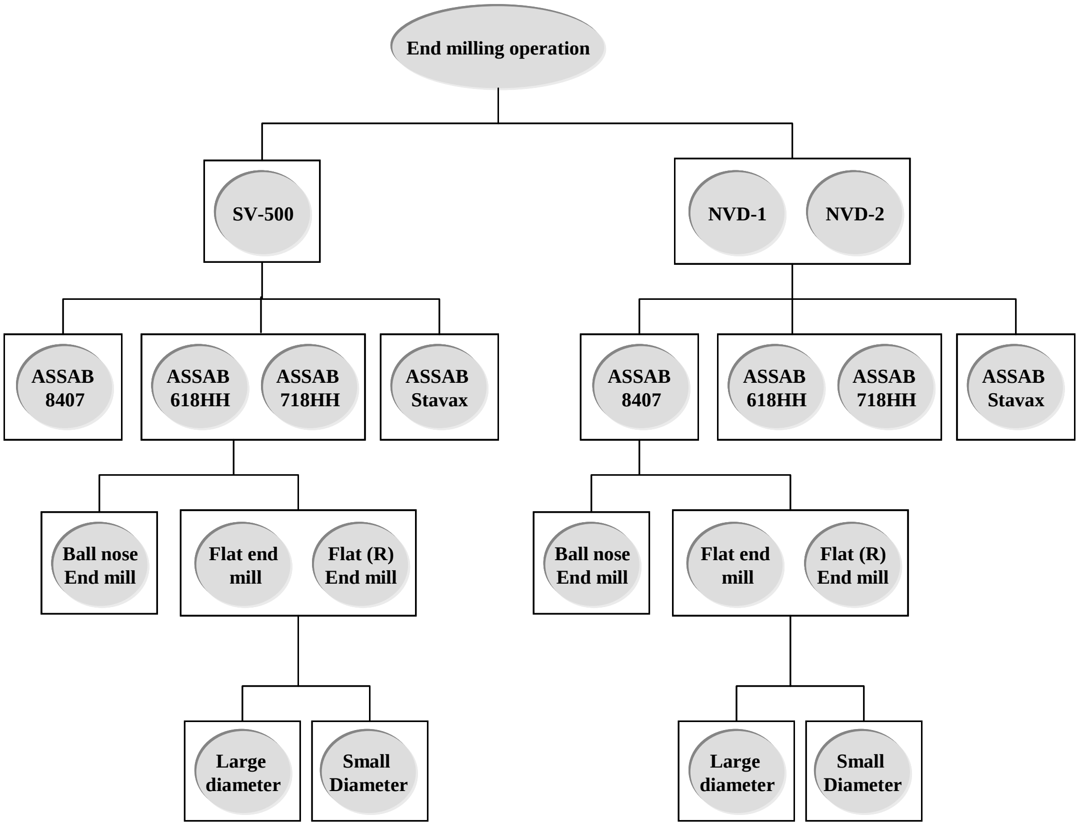


Figure 4.9 Statistical Analysis Results for the End Milling Operation

3. For each machine group (SV-500 / NVD (1&2)), quality characteristics machined out of the material of ASSAB 618HH and 718HH cannot be grouped with those of 8407 and Stavax. Quality characteristics machined out of 8407 cannot be grouped with that of Stavax, as shown in Figure 4.9. According to the properties of these materials, 718HH and 618HH are pre-hardened materials and their hardness is approximate 52HRC. However, 8407 needs heat treatment before the finishing operation and the required surface hardness is 55HRC, which is higher

than that of other materials. Stavax also needs heat treatment before finishing, but the required surface hardness is relatively lower, which is 50HRC. The differences in heat treatment and hardness might also be the reason of the significant difference. Thus such implication can be taken as reference for analyzing other processes with similar materials.

4. For particular machine and material combination (e.g. SV500 and 618HH/718HH), quality characteristics associated to the ballnose type of cutter cannot be grouped with those of flat end mill and bullnose mill. Subsequently, quality measurements made by large diameter of end mills (Ø > 6) and bullnose mill (Ø > 12 & R=0.5) cannot be combined with those of small diameter mills, as shown in Figure 4.9. The ballnose cutters have more significantly different geometry to the end mills and bullnose mill. Hence, both the cutter geometry and size appear to have significant influence on the quality characteristics. On the other hand, the ballnose cutters are mainly used for machining filleted corners and freeform features, while end mills are used for machining flat and regular features. Thus, feature geometry might also be a contributor. Such implications may be taken as reference to analyze other processes, e.g. drilling. The gun drills and twist drills have very different geometry, and the diameter of twist drills can be as large as Ø 30 mm and as small as Ø1 mm. Quality characteristics associated with gun drills and twist drills can be divided into different preliminary families. And data associated with twist drills can be further divided into different groups according to diameter size. The differentiation of large and small size of diameter can base on Equation 4.1.

Above results are grouping criteria for the data generated from the end milling operation of this company. Database can be maintained accordingly.

4.5.2 Case Study 2—the end milling operation on EDM electrodes making mould parts

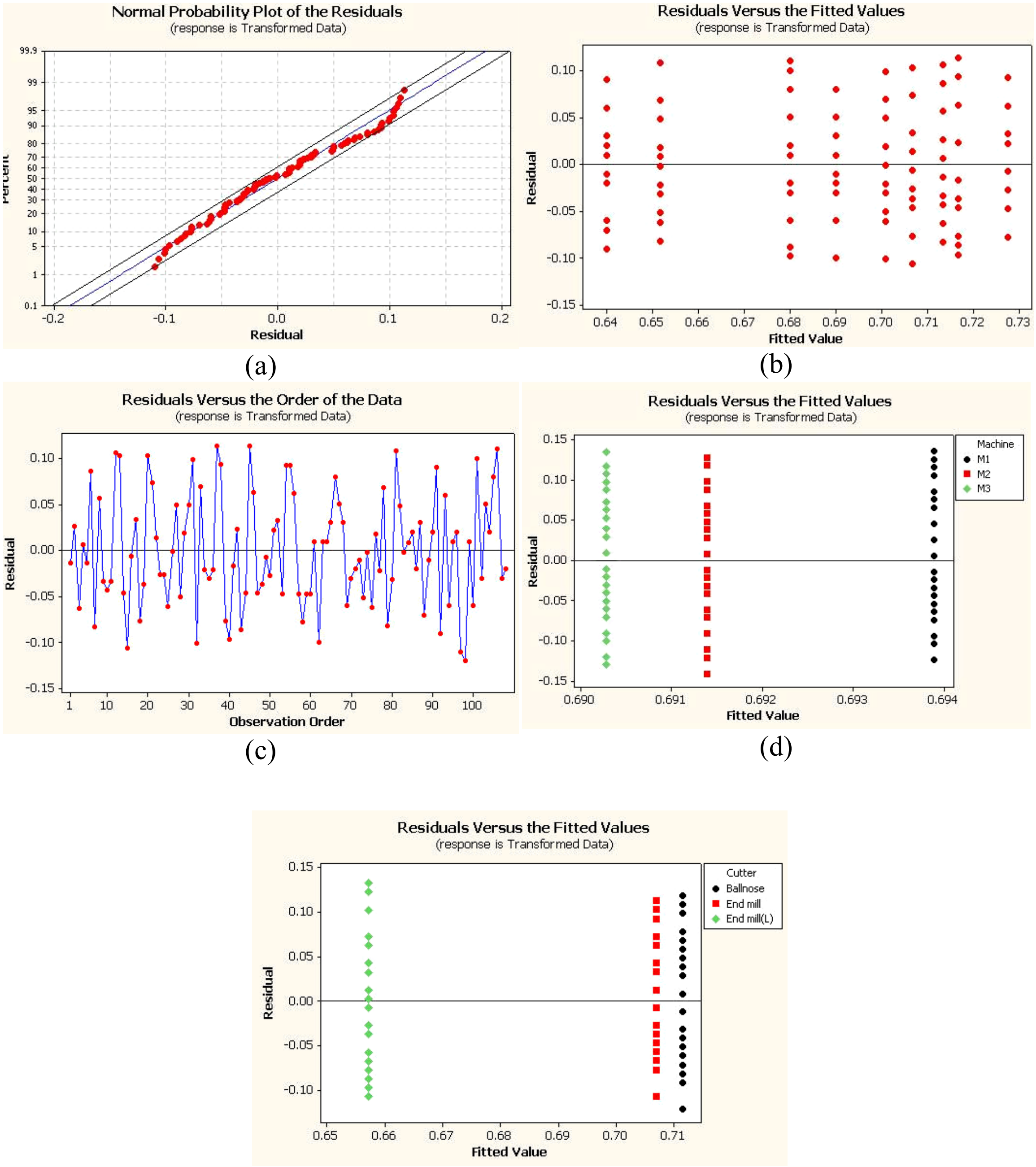
End milling is also an important operation to manufacturing EDM electrodes. The commonly used materials for electrodes are copper, brass, and graphite. As each of these materials has distinct properties, data generated from them are firstly divided into separate preliminary families.

In the mould making company, there are three CNC machines: Robodrill T21 (×3), for machining non-graphite electrodes. The ballnose, flat end mills, and bullnose mills are also commonly used cutters. Hence, for the "preliminary copper family", machine and cutter are two factors to be investigated. For the factor of machine, there are three levels. Based on the previous studies, the factor of cutter is classified into three levels: ballnose, large diameter of end mils and small diameter of end mills. The end mills include flat end mills and bullnose mills. Thus, a 2-way ANOVA matrix is formed as shown in Table 4.9.

Table 4.9 The 2-way ANOVA Matrix

Machine / **Cutter**	Robodrill T21--(1)	Robodrill T21--(2)	Robodrill T21--(3)
Ballnose	P-1, P-2, P-3, P-4	P-9, P-10, P-11	P-15, P-16, P-17, P-18, P-19
End mill (l)	P-2, P-5, P-6, P-7, P-8	P-9, P-12, P-13, P-14	P-15, P-16, P-20, P-21, P-22
End mill (S)	P-1, P-2, P-3, P-6, P-7, P-8	P-9, P-10, P-11, P-13, P-14	P-17, P-16, P-20, P-21, P-22

Data were collected from various features of 22 copper electrodes. For each combination of the process factors (cell), there were 12 measurements. Before statistical analysis, the data were transformed by Equation 4.2. The raw data givenare in Appendix A-3. Then the data were input into Minitab@ and the model adequacy was checked as shown in Figure 4.10.



(a) (b)

(c) (d)

(e)

Figure 4.10 Model Adequacy Checking

The normal probability plot of residuals (Figure 4.10a) does not fall exactly along a straight line passing through the center of the plot, but it is between two parallel bounds.

The graph of residuals versus fitted values (Figure 4.10b) does not reveal any unusual or diagnostic pattern, thus, there is no need to transform the data. The independence assumption is checked by plotting the residuals against the run order (Figure 4.10c). There is also no pattern. Hence, there is no strong evidence to reject the assumption of normality, homogeneous variance, and independence. In the plot of residuals versus the levels of cutter types (Figure 4.10e), there is indication that the large diameter end mill results in slightly larger variability than the other materials. In general, the model adequacy is acceptable. The results of the balanced 2-way ANOVA are shown in Table 4.10.

Table 4.10 Minitab ANOVA (Balanced Design) for the case study

ANOVA: Transformed Data versus Machine, Cutter

```
Factor   Type   Levels  Values
Machine  fixed       3  M1, M2, M3
Cutter   fixed       3  Ballnose, End mill, End mill(L)


Analysis of Variance for Transformed Data

Source           DF        SS        MS     F      P
Machine           2  0.000246  0.000123  0.03  0.969
Cutter            2  0.065113  0.032556  8.32  0.000
Machine*Cutter    4  0.019787  0.004947  1.26  0.289
Error            99  0.387283  0.003912
Total           107  0.472430
```

The factor of machine is not significant, as the P-value is larger than the significant level of 0.05. However, the cutter is a significant factor, as the P-value is smaller than 0.05. Consequently, multiple comparisons were conducted to identify the specific differences and the results are shown in Table 4.11.

When the ballnose cutter is compared to the large- and small- diameter end mills, the range of "-0.03355 to 0.02466" contains zero, but the range of "-0.08328 to -0.02506" does not contain zero. Thus, there are no significant differences in the means between the ballnose and small-diameter end mills, but there are significant differences between that of the ballnose and large-diameter end mills. When the small-diameter end mills compares to the large-diameter end mills, the range of "-0.07833 to -0.0078" does not contain zero, which shows that there are significant differences in the means. Hence, data generated from the ballnose and small-diameter end mills can be combined together, but cannot be combined with those of large-diameter end mills.

Table 4.11 MiniTab Multiple Comparison on the Levels of the Factor of Cutter

```
Fisher 95% Individual Confidence Intervals
All Pairwise Comparisons among Levels of Cutter

Simultaneous confidence level = 87.85%


Cutter = Ballnose subtracted from:

Cutter          Lower    Center     Upper
End mill(S)  -0.03355  -0.00444   0.02466
End mill(L)  -0.08328  -0.05417  -0.02506

Cutter       -------+---------+---------+---------+--
End mill(S)            (-----*-----)
End mill(L)  (-----*-----)
             -------+---------+---------+---------+--
                 -0.050     0.000     0.050     0.100


Cutter = End mill(S) subtracted from:

Cutter          Lower    Center     Upper
End mill(L)  -0.07883  -0.04972  -0.02061

Cutter       -------+---------+---------+---------+--
End mill(L)   (-----*-----)
             -------+---------+---------+---------+--
                 -0.050     0.000     0.050     0.100
```

Conclusions

Based on the preliminary analysis, the end milling operations for machining different materials of EDM electrode are taken as different processes. The data generated from them are defined as different preliminary families. For machining of copper electrodes, the statistical analyses show that cutter is a significant factor. The data generated from large-diameter end mills cannot be combined with those generated from ballnose and small-diameter end mills, as shown in Figure 4.11. The database can be maintained accordingly.

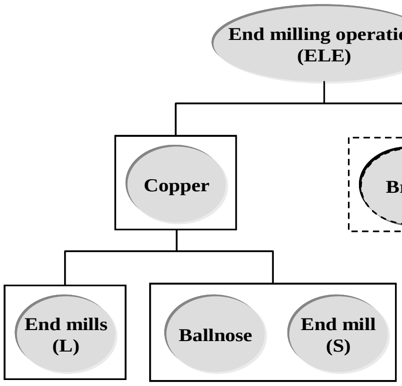


Figure 4.11 Family Formation Analysis Results

4.6 Summary

In this chapter, an alternative family formation method for application of SPC in very small-batch manufacturing is proposed.

Firstly, the critical quality characteristics and associated manufacturing processes should be identified. The critical quality characteristics are taken as process control characteristics. The focus of the application of short-run SPC is on the processes associated with the accuracy of the critical quality characteristics.

Next, the machining resource information is collected and classified to simplify the follow-up statistical analyses.

Then, preliminary analyses, based on the factor properties and specific application, are performed to prioritize the potential factors and determine the factor levels.

Finally, the statistical experiment and analytical procedure are effectively demonstrated with case studies according to the proposed approach.

CHAPTER 5

FRAMEWORK OF COMPUTER-AIDED SHORT-RUN SPC PLANNING SYSTEM

With the development of CMM software, database and network technologies, it becomes more and more convenient to manage measurement data and export them to databases for statistical analyses. All these facilitate the development of computer-directed and database-supported quality assurance systems. However, the existing works primarily concentrate on computer-aided control charting, chart pattern recognition, and general out-of-control diagnosis for mass production or process industry. For low-volume, discrete part manufacturing, SPC planning is the bottleneck of process performance feedback, but critical to the effectiveness of the downstream work. Hence, to improve efficiency and effectiveness, there is clearly a need to develop a computer-aided short-run SPC planning system.

In the following section, a framework of computer-aided short-run SPC planning system and supportive database structure are proposed. A group technology classification and coding (GTCC) system is customized and applied to facilitate the integration of computer-integrated manufacturing and SPC system, and information retrieval.

5.1 Framework of computer-aided short-run SPC planning system

For one-off, very small-batch manufacturing cases, the part properties, necessary manufacturing operations, and the involved operating factors are different from one batch to another. Performing statistical analysis for each batch to identify SPC-based part families is too time-consuming. Besides the statistical analysis, necessary information needs to be collected from different life cycle stages, such as design, process planning, scheduling, and measuring, etc. A framework for a computer-aided short-run SPC planning system in virtue of GTCC system is proposed, as shown in Figure 5.1.

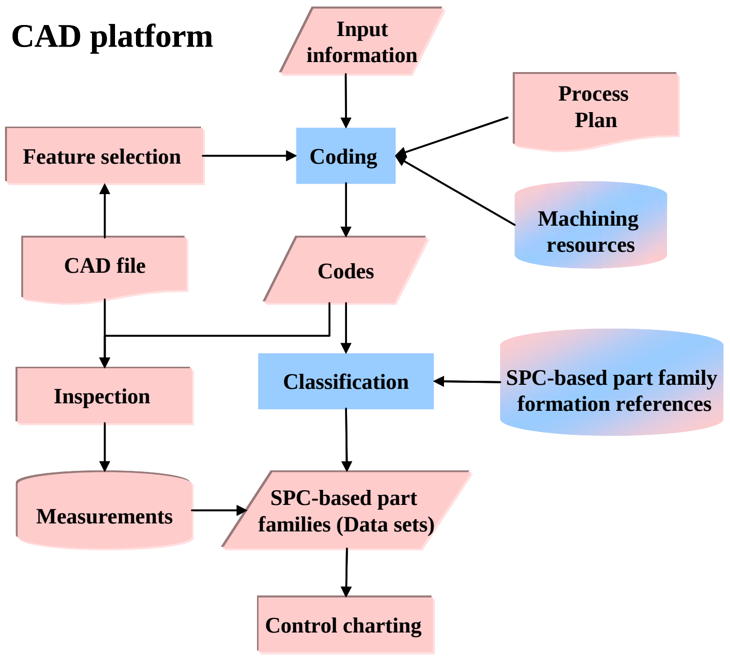
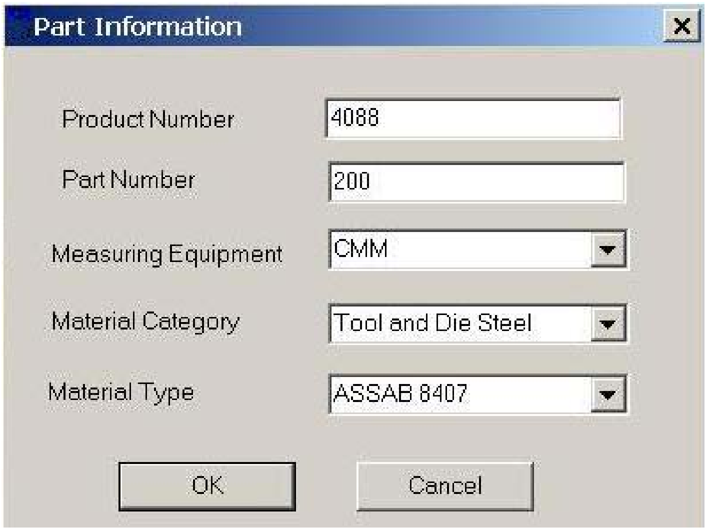


Figure 5.1 A Framework of Computer-aided Short-run SPC Planning System

Currently, the framework has not been computerized. To facilitate depicting, it is assumed that the database, process planning file, etc. are available and the relevant information can be retrieved by the program.

After confirmation of the part design, process planning, and production scheduling, short-run SPC planning can start. In the CAD environment (e.g. Solidworks or Unigraphics), general part information, such as the product number, part number and so on are input as required, as shown in Figure 5.2. The process planning file of the part is retrieved based on the product and part number. The process planning file can be generated by some commercial software, such as IMOLD™. Then the operator can select the geometrical features associated to the critical quality characteristics to be measured. The relevant process information (e.g. the machine and the cutter used) of each feature is extracted from the process planning file. Accordingly, the ID of the process factors and the part material are retrieved from the machining resource database for coding. The selected features are coded with a modified Opitz GTCC scheme.



Product Number	4088
Part Number	200
Measuring Equipment	CMM
Material Category	Tool and Die Steel
Material Type	ASSAB 8407

Figure 5.2 Part Information Input Interface

The feature codes serve as ID to facilitate communicating with the measurement system and database. The feature codes also facilitate bringing together quality measurements belonging to the same family by finding a match-able code from the reference database. The feature codes can help in cause-finding after control charting, as shown in Figure 5.3.

The structure of a supportive database and the group technology classification and coding system is discussed in the following sections.

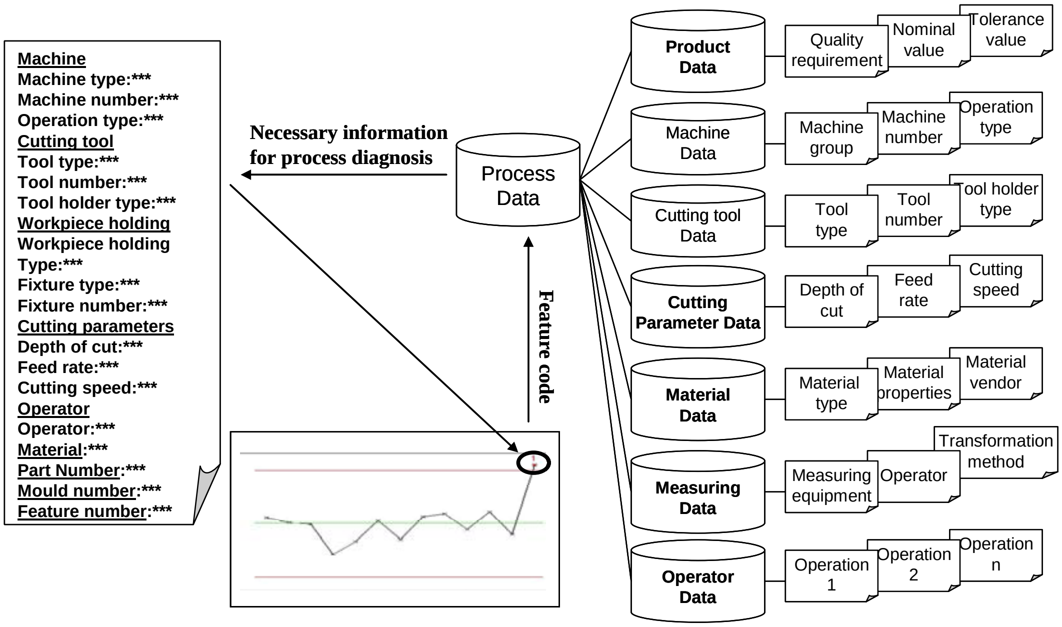
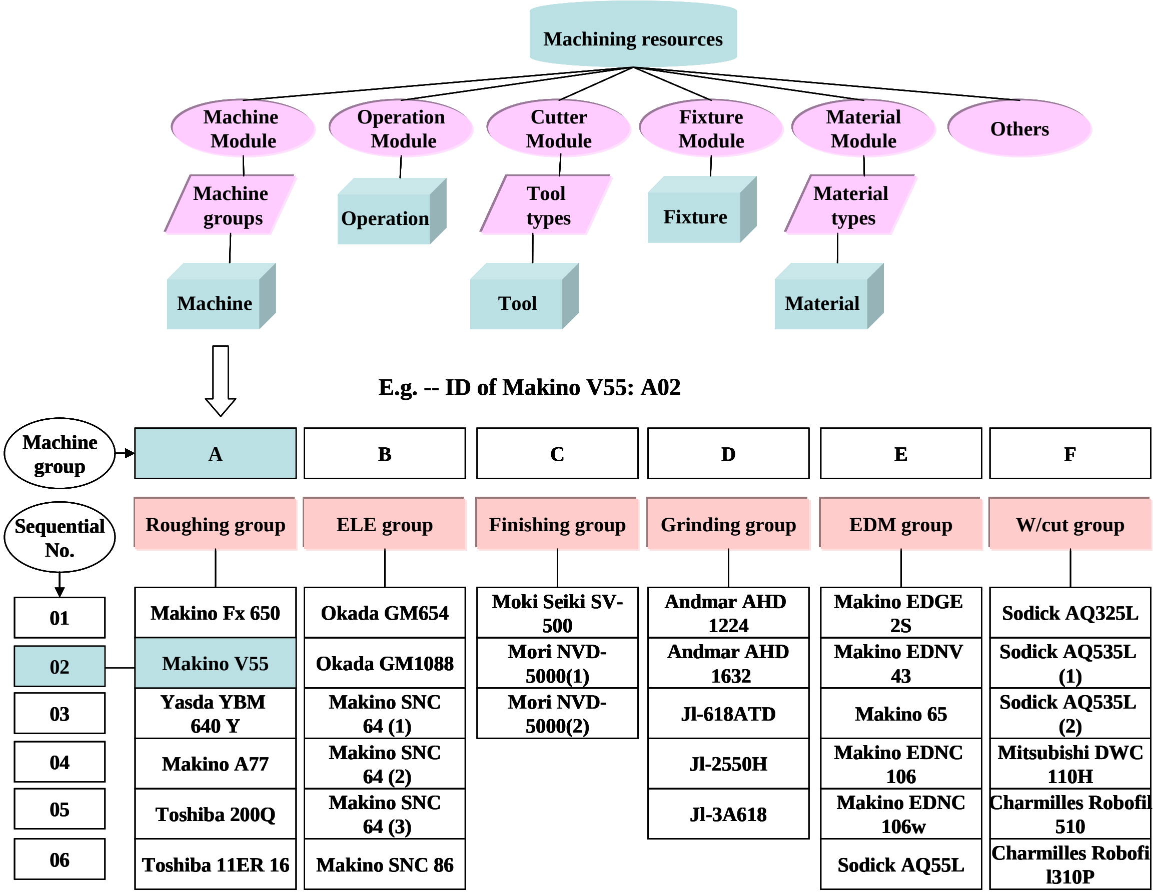


Figure 5.3 Feature Codes Facilitate Information Retrieval for Process Diagnosis

5.2 Structure of machining resource database

With the continuous development of technologies in the manufacturing industry, the equipment, device and operating method applied in production is changing fast. To facilitate updating of the SPC planning system, the machining resource ID number in the database is proposed to be used for coding. Thus, if the machining resource database is updated appropriately, the correct coding information is available. In addition, a well-constructed machining resource database will enable efficient information retrieval for process diagnosis, as discussed earlier. Hence, for a specific manufacturing firm, the various data on machining resource, such as the machine type, cutter diameter and so on, need to be suitably collected, classified and modularly stored in the database, as show in Figure 5.4. For example, the various machines in a local mould manufacturing company are classified into six groups: Roughing Group, ELE Group, Finishing Group, Grinding Group, EDM Group, and W/cut Group. A, B, C, D, E, and F are their respective identifier. The individual machine in a group has a sequential number, the length of which depends on the amount of the machine. The ID of a machine is defined by the machine type identifier and its sequential number. For example, with reference to Figure 5.4, the ID of roughing machine Makino V55 is “A02”, as “A” is the identifier of the roughing group, and “02” is the sequential number of Makino V55 in the group. The structure and contents of other modules are presented in Appendix B. Based on the proposed structure, the machining resource database can be customized with commercial database management system, such as Microsoft Access.



Machine group	A	B	C	D	E	F
Sequential No.	Roughing group	ELE group	Finishing group	Grinding group	EDM group	W/cut group
01	Makino Fx 650	Okada GM654	Moki Seiki SV-500	Andmar AHD 1224	Makino EDGE 2S	Sodick AQ325L
02	Makino V55	Okada GM1088	Mori NVD-5000(1)	Andmar AHD 1632	Makino EDNV 43	Sodick AQ535L (1)
03	Yasda YBM 640 Y	Makino SNC 64 (1)	Mori NVD-5000(2)	Jl-618ATD	Makino 65	Sodick AQ535L (2)
04	Makino A77	Makino SNC 64 (2)		Jl-2550H	Makino EDNC 106	Mitsubishi DWC 110H
05	Toshiba 200Q	Makino SNC 64 (3)		Jl-3A618	Makino EDNC 106w	Charmilles Robofil 510
06	Toshiba 11ER 16	Makino SNC 86			Sodick AQ55L	Charmilles Robofi l310P

Figure 5.4 Machining Resource Database

5.3 Group technology classification and coding scheme

Due to the further and detailed information required to identify the SPC-based part family membership, existing GTCC systems are not feasible to be applied directly. The Opitz primary and supplementary code is chosen as the overall code for its ease of customization and broad application (Opitz, 1970). A 29-digit secondary code appended to the Opitz code is proposed, as shown in Figure 5.5.

As discussed in Section 4.4, data of a feature produced by a particular operation and measured by a different equipment are firstly divided into different preliminary families; that is, the operation type and measurement equipment are important factors for family membership identification.

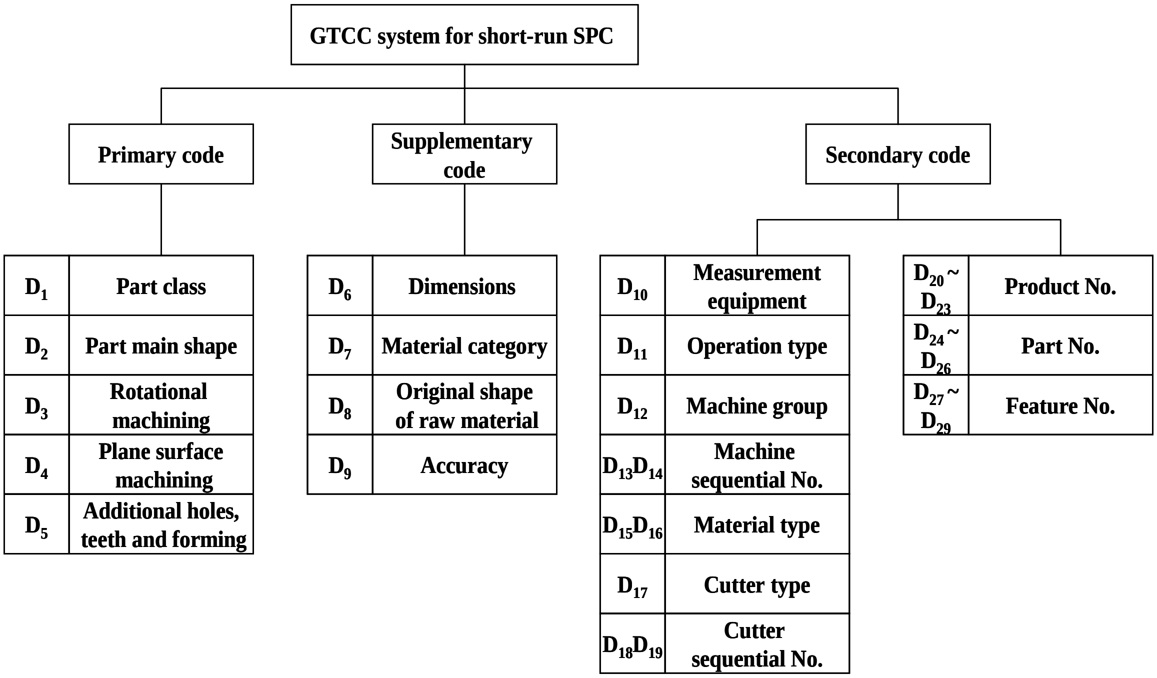


Figure 5.5 GTCC System for Short-run SPC

Earlier studies (given in section 4.5) have shown that machine, material and cutter properties are potential factors that affect the formation of families. Hence, these three factors are also important for family membership identification. In total, five factors are considered in the GTCC system, from D_{10} to D_{19}. As each digit is coded by the ID number of that factor, the definition of each level of these digits is in accordance with the definition of each entity in the machining resource database module. For example, the coding information for the finishing end milling operation on tool and die steels is shown in Figure 5.6 The values of $D_{13}D_{14}$, $D_{15}D_{16}$ and $D_{18}D_{19}$ depend on those of D_{12}, D_7 and D_{17} respectively. The data associated with $D_{13}D_{14}$ are linked to the value of D_{12} which is C (Finishing Group). The data associated with $D_{15}D_{16}$ are linked to the value of D_7 which is A (Tool and die steels). And the data associated with $D_{18}D_{19}$ are linked to the value of D_{17} which is A (flat end mill). All the data shown in the figure are based on the information of the machining resource database discussed in the previous section.

D_{10}	Measurement equipment
1	CMM
2	Digital height gauge (1)
3	Digital height gauge (1)
4	Optical comparator
--	--

D_{11}	Operation type
A	End milling
B	Face milling
C	Twist drilling
D	Gun drilling
…	…

D_{12}	Machine group
A	Roughing group
B	ELE group
C	Finishing group
D	Grinding group
…	…

$D_{13}D_{14}$	Machine sequential No.
01	Moki Seiki SV-500
02	Mori NVD-5000(1)
03	Mori NVD-5000(2).
04	--
--	--

D_7	Material category
A	Tool and die steels
B	Copper and its alloys
C	Other metals
D	graphite
…	…

$D_{15}D_{16}$	Material type
01	ASSAB 718HH
02	ASSAB 618HH
03	ASSAB 8407
04	ASSAB Stavax
…	…

D_{17}	Cutter type
A	Flat end mill
B	End mill (R)
C	Ball nose
D	Face mill
…	…

$D_{18}D_{19}$	Cutter sequential No.
01	Ø 12
02	Ø 10
03	Ø 8
04	Ø 6
…	…

Figure 5.6 Sample Information of the Coding Information

To facilitate the differentiation of the quality characteristics and manipulation of information, an index code (D_{20} to D_{29}) consisting of product, part and feature number is added. The definition and length are flexible, but the recommended specification is shown in Figure 5.5.

The data for generating the index code are obtained from the user input on Product No., Part No., and the manufacturing sequence of the part features. The information for generating the value of D_{10} (measurement equipment), D_7 (material category) and $D_{15}D_{16}$ (material type) is obtained from the user input. The information required for generating other secondary code digits can be extracted from the process planning file. Then, corresponding factor ID numbers can be retrieved from the machining resource database for coding. The procedure is shown in Figure 5.7.

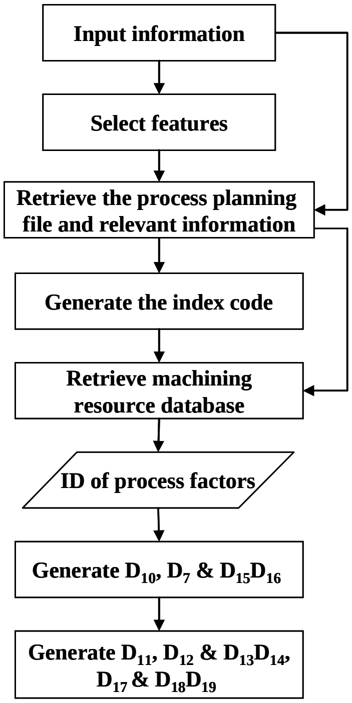


Figure 5.7 The Proposed Coding Procedure

For example, for the part shown in Figure 5.8, the input information is shown in Figure 5.9. The features associated to the critical quality characteristics to be measured by a CMM are selected by an operator using a CAD software, Solidworks. Suppose the features are Faces 1, 2, 3, and 4, Slot 1, and Pocket 1, as indicated on the part.

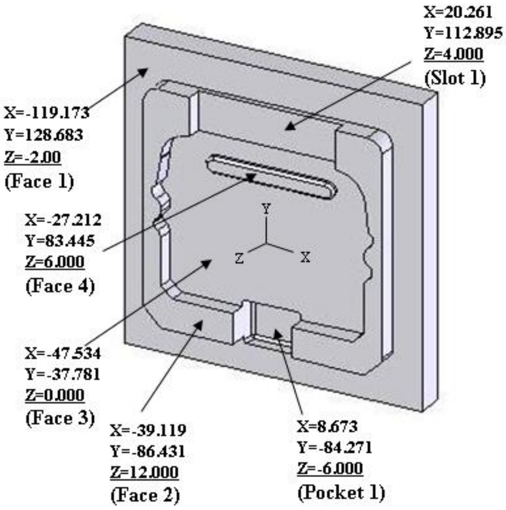
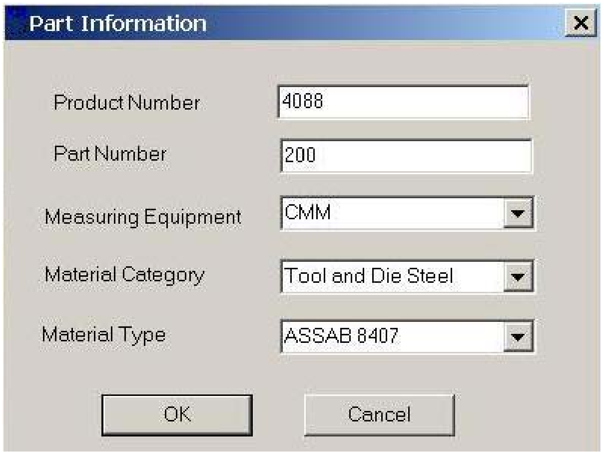


Figure 5.8 Critical Quality Characteristics and Associated Features


Part Information

Product Number: 4088

Part Number: 200

Measuring Equipment: CMM

Material Category: Tool and Die Steel

Material Type: ASSAB 8407

Figure 5.9 Input Part Information

Based on the input information of the product (mould assembly) and part (mould component) number, the process planning file is retrieved and the values of $D_{20}D_{21}D_{22}D_{23}$

(Product No.) and $D_{24}D_{25}D_{26}$ (Part No.) for all the selected features are generated, as shown in table 5.1.

Table 5.1 Codes of the Selected Features of the Part Shown in Figure 5.8

GTCC system for short-run SPC			**Step 1**	**Step 2**	**Step 3**	**Step 4**	**Step 5**	**Step 6**
			Face 1	Face 3	Face 4	Pocket 1	Slot 1	Face 2
Primary code	D_1	Part class	6	6	6	6	6 (non-rotational)	6
	D_2	Part main shape	1	1	1	1	1 (step to one end & no shape elements)	1
	D_3	Rotational machining	0	0	0	0	0 (no hole & break through)	0
	D_4	Plane surface machining	9	9	9	9	9 (all others)	9
	D_5	Additional holes, teeth and forming	0	0	0	0	0 (no auxiliary holes)	0
Supplementary code	D_6	Dimensions	9	9	9	9	9 (length/thickness: 10/1)	9
	D_7	Material category	A	A	A	A	A (tool and die steel)	A
	D_8	Original shape of raw material	1	1	1	1	1 (block)	1
	D_9	Accuracy	2	2	2	2	2 (0.02)	2
Secondary code	**D_{10}**	Measurement equipment	1	1	1	1	1 (CMM)	1
	D_{11}	Operation type	A	A	A	A	A (end milling)	C (face milling)
	D_{12}	Machine group	C	C	C	C	C (Finishing group)	C
	$D_{13}D_{14}$	Machine sequential No.	01	01	01	01	01 (Moki Seiki SV-500)	01
	$D_{15}D_{16}$	Material type	03	03	03	03	03 (ASSAB 8407)	03
	D_{17}	Cutter type	A	A	A	B (bullnose mill)	A (flat end mill)	D (Face mill)
	$D_{18}D_{19}$	Cutter sequential No.	01	03	04	24	01	01
	D_{20}~D_{23}	Product No.	4088	4088	4088	4088	4088	4088
	D_{24}~D_{26}	Part No.	200	200	200	200	200	200
	D_{27}~D_{29}	Feature No.	001	002	003	004	005 (Step 5)	006

The cavity inserts are defined as 1XX, core inserts are defined as 2XX, slider assemblies are defined as 3XX, and so on. In this case, the part is the main core; so the part number is 200. Similarly, the part number for main cores of other mould assemblies is also 200. However, if the part is not a main core, the part number might be 201, 202, 210, etc. which depends on the designer's allocation. Then, according to the selected features, relevant processing information is extracted, as shown in Table 5.2.

Table 5.2 Extracted Processing Information

Steps	**Feature name**	**Operation type**	**Machine type**	**Machine used**	**Cutter type and diameter**
Step1	Face 1	End milling	CNC_Finishing	Moki Seiki SV-500	Flat End mill ϕ12
Step 2	Face 3	End milling	CNC_Finishing	Moki Seiki SV-500	Flat End mill ϕ8
Step 3	Face 4	End milling	CNC_Finishing	Moki Seiki SV-500	Flat End mill ϕ6
Step 4	Pocket 1	End milling	CNC_Finishing	Moki Seiki SV-500	End mill ϕ4R0.5
Step 5	Slot 1	End milling	CNC_Finishing	Moki Seiki SV-500	Flat End mill ϕ12
Step 6	Face 2	Face milling	CNC_Finishing	Moki Seiki SV-500	Face mill ϕ25

Based on the operation step, the value of $D_{27}D_{28}D_{29}$ (feature No.) of each feature is generated. For example, "slot 1" will be machined in step 5; so its feature number is "005". Currently, the feature number is derived manually to demonstrate the framework. In future, the value can be assigned by the computerized GTCC system.

Subsequently, based on the user input on the measurment equipment, material category, and material type, the machining resource database is retrieved, and then the values of D_{10} (measurement equipment), D_7 (material category) and $D_{15}D_{16}$ (material type) of the selected features are generated. As all the features will be measured by a CMM, referring to Figure 5.6, the value of D_{10} of all the features is "1". The part will be machined out of tool and die steel of ASSAB 8407 based on the input information. Thus, referring to Figure 5.6, the value of D_7, and $D_{15}D_{16}$ of all the features is "A" and "03" respectively.

According to the extracted process planning information, as shown in Table 5.2, the machining database is retrieved, and thus the corresponding data (ID number) for generating D_{11} (operation type), D_{12} (machine group), $D_{13}D_{14}$ (machine sequential no.), D_{17} (cutter type), and $D_{18}D_{19}$ (cutter sequential no.) are obtained.

For example, according to Table 5.2, the "slot 1" will be machined by *end milling operation* on CNC machine, *Moki Seiki SV-500* in the F*inishing Group*. Referring to the module of operation type in Figure 5.6, the value corresponding to the end milling operation is "A", so D_{11} is "A". Similarly, referring to the module of machine group, the value corresponding to the Finishing Group is "C", so D_{12} is "C". And the sequential number corresponding to Moki Seiki SV-500 in the finishing group is "01", so $D_{13}D_{14}$ is "01". Based on Table 5.2, the "Slot 1" will be machined by *flat end mill*, the diameter of which is *12mm*. Referring to the module of cutter type in Figure 5.6, the value corresponding to the flat end mill is "A", so D_{17} is "A". And the sequential number corresponding to Ø12 is "01", so $D_{18}D_{19}$ is "01".

D_1 toD_5 and D_6 to D_9 are based on the Optiz primary and supplementary code (Opitiz, 1970). These digits describe the overall information of the part. Hence, the features belonging to the same part have the same value in each of these code digits.

The code values of all the selected features on the part shown in Figure 5.8 are listed in Table 5.1. Some of the meaning of each digit value is also indicated in the cells.

5.4 Construction of family formation reference database

To improve the efficiency of family membership identification, a supportive family formation reference database is proposed. From extensive analyses, the rules to group quality characteristics generated from various operations and operating factor combinations into SPC-based families of a specific manufacturing form have been obtained. However, the process properties and machining resources of the firm will change gradually with time and the grouping rules will be difficult to update.

A way to solve this problem is coding the historical data that have been employed for the family formation analysis with the proposed secondary code (the index code is not necessary). Thus, the criteria for family membership identification are groups of codes, as shown in Figure 5.10 and Table 5.3.

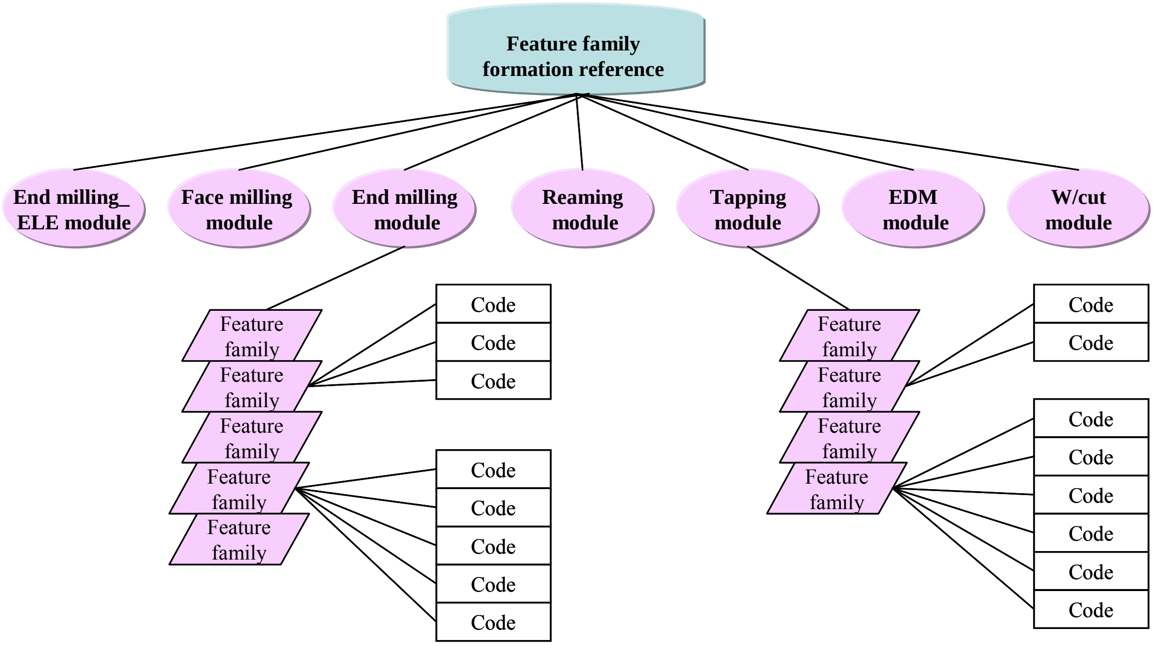


Figure 5.10 Structure of Family Formation Reference Database

If the GTCC system can find a match-able code from a specific family, the membership of the new quality characteristics is identified. To facilitate information retrieval, the reference database is divided into different modules according to the definition of the machining operation type, e.g. the end milling module corresponds to various families associated to the end milling operation.

Table 5.3 Partial Information of the Family Formation Reference Database

End milling module			Identification results		
Family Name	**Family ID**	**Family Member**	Index code	Normal value (mm)	measurements
CMM_SV500_8407_END MILL_1	1_C01_A03_A_1	A_1_A_C01_03_A05	*NA*		
		A_1_A_C01_03_A06	*NA*		
		A_1_A_C01_03_A07	*NA*		
		A_1_A_C01_03_A08	*NA*		
		A_1_A_C01_03_B20	*NA*		
		… …			
		A_1_A_C01_03_B24	4088_200_004 (Pocket 1)	-6.000	
CMM_SV500_8407_END MILL_2	1_C01_A03_A_2	A_1_A_C01_03_A01	4088_200_005 (Slot 1)	4.000	
			4088_200_001 (Face 1)	-2.000	
		A_1_A_C01_03_A02	*NA*		
		A_1_A_C01_03_A03	4088_200_001 (Face 3)	0.000	
		A_1_A_C01_03_A04	4088_200_001 (Face 4)	6.000	
		… …			
… …	… …	… …			
*NA—None of the feature code matches the corresponding family member (code)					

For example, referring to Table 5.1, the value of D_7, D_{10} to D_{19} of Slot 1 is "A_1_A_C_01_03_A_01". In the end milling module, the GTCC system find a matchable code in the family of "CMM_SV500_8407_END MILL_2", as shown in the filled cell of Table 5.3. Then the index code "4088_200_005" is employed by the GTCC system to mark the membership of Slot 1 and its normal value is retrieved. After inspection, the measurement can be linked and transformed for control charting.

5.5 Case studies

Case studies based on real data collected from a local mould manufacturing company have been conducted to demonstrate the application of the proposed short-run SPC planning system to accumulate sufficient data for control charting. Parts manufactured in different batches with different batch sizes were selected, as shown in Figures 5.11, 5.13, and 5.14.

Case Study 1

The main cavity, shown in Figure 5.11, had been manufactured in 4 pieces, and the input part information is shown in Figure 5.12. The part and the part associated mould assembly share the same part and product number. The feature quality characteristics have the same normal value. The measured value on different pieces is taken as first, second, third and forth measurements.

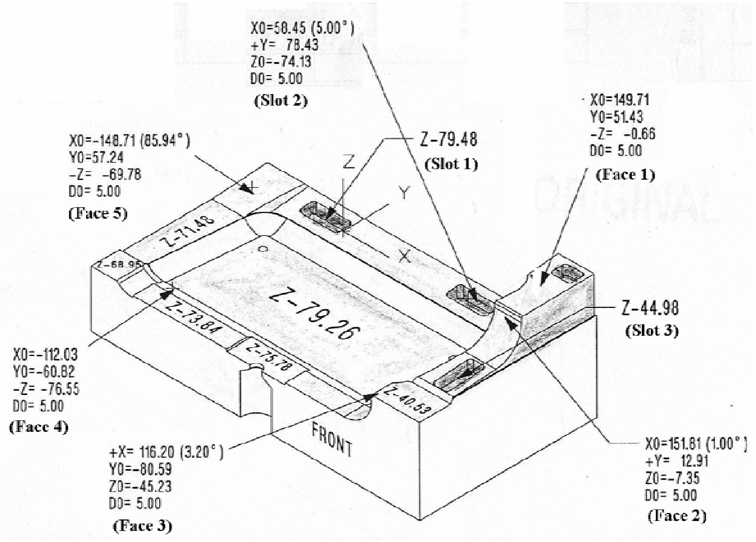
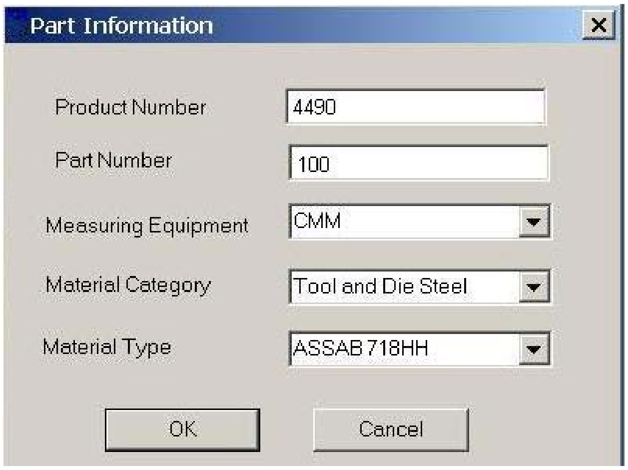


Figure 5.11 Main Cavity of Injection Mould Assembly 4490 (4 pieces)

The part process planning file, as shown in Appendix C-1, was retrieved based on the product and part number by the SPC planning system, assuming the existence of the program. In the CAD environment, the operator selected the features associated with the quality characteristics to be measured by CMM. Then, the processing information of all the selected features could be extracted by the SPC planning system, as shown in Table 5.4. Correspondingly, the ID number of each factor was retrieved from the machining resource database by the GTCC system. Based on the proposed coding scheme, the GTCC system generated the code for each of the feature, as shown in Table 5.5 A & B. Likewise, the processing information of the selected features of the other parts was extracted and the corresponding sets of code were generated, as shown in Appendix C-2 to C-9.



Product Number: 4490
Part Number: 100
Measuring Equipment: CMM
Material Category: Tool and Die Steel
Material Type: ASSAB 718HH

Figure 5.12 Required Input Part Information

Table 5.4 Extracted Processing Information

Steps	**Feature**	**Operation type**	**Machine type**	**Machine used**	**Cutter type & size**
Step 6	Face 1	End milling	CNC_Finishing	Moki Seiki SV-500	Ballnose R3
Step 9	Face 2	End milling	CNC_Finishing	Moki Seiki SV-500	Ballnose R10
Step 10	Face 3	End milling	CNC_Finishing	Moki Seiki SV-500	Flat End mill ϕ6
Step 13	Face 5	End milling	CNC_Finishing	Moki Seiki SV-500	End mill ϕ6R0.5
Step 17	Face 4	End milling	CNC_Finishing	Moki Seiki SV-500	End mill ϕ4R0.5
Step 23	Slot 1,2,3	End milling	CNC_Finishing	Moki Seiki SV-500	Flat End mill ϕ6

Table 5.5 A Code of Each Feature and Interpretation

GTCC system for short-run SPC			**Step 6**	**Step 9**	**Step 10**	**Step 13**	**Step 17**	**Step 23**
			Face 1	Face 2	Face 3	Face 5	Face 4	Slot 1, 2, 3
Primary code	D_1	Part class	6	6	6	6	6 (non-rotational)	6
	D_2	Part main shape	1	1	1	1	1 (step to one end & no shape elements)	1
	D_3	Rotational machining	0	0	0	0	0 (no hole & break through)	0
	D_4	Plane surface machining	9	9	9	9	9 (all others)	9
	D_5	Additional holes, teeth and forming	1	1	1	1	1 (auxiliary holes not related by drilling)	1
Supplementary code	D_6	Dimensions	4	4	4	4	4 (length/thickness: 5/1)	4
	D_7	Material category	A	A	A	A	A (tool and die steel)	A
	D_8	Original shape of raw material	1	1	1	1	1 (block)	1
	D_9	Accuracy	2	2	2	2	2 (0.02)	2
Secondary code	**D_{10}**	Measurement equipment	1	1	1	1	1 (CMM)	1
	D_{11}	Operation type	A	A	A	A	A (end milling)	A
	D_{12}	Machine group	C	C	C	C	C (Finishing group)	C
	$D_{13}D_{14}$	Machine sequential No.	01	01	01	01	01 (Moki Seiki SV-500)	01
	$D_{15}D_{16}$	Material type	01	01	01	01	01 (ASSAB718HH)	01
	D_{17}	Cutter type	C (Ballnose)	C	A (flat end mill)	B	B (Bullnose mill)	A
	$D_{18}D_{19}$	Cutter sequential No.	04	01	04	22	23	04
	D_{20}~D_{23}	Product No.	4090	4090	4090	4090	4090	4090
	D_{24}~D_{26}	Part No.	100	100	100	100	100	100
	D_{27}~D_{29}	Feature No.	006	009	010	013	017 (Step 17*)	023,024, 025**

* Before step 17, there is only one feature was machined in each step.

** Feature number is allocated based on the machining sequence.

Table 5.5 B Code of Each Feature

Feature Name	D_7_D_{10}_D_{11}_$D_{12}D_{13}D_{14}$_$D_{15}D_{16}$_$D_{17}D_{18}D_{19}$	$D_{20}D_{21}D_{22}D_{23}$_$D_{24}D_{25}D_{26}$_$D_{27}D_{28}D_{29}$	Normal value
Face 1	A_1_A_C01_01_C04	4490_100_006	-0.66
Face 2	A_1_A_C01_01_C01	4490_100_009	12.91
Face 3	A_1_A_C01_01_A04	4490_100_010	116.20
Face 5	A_1_A_C01_01_B22	4490_100_013	-69.78
Face 4	A_1_A_C01_01_B23	4490_100_017	-76.55
Slot 1	A_1_A_C01_01_A04	4490_100_023	-79.48
Slot 2	A_1_A_C01_01_ A04	4490_100_024	78.43
Slot 3	A_1_A_C01_01_ A04	4490_100_025	-44.98

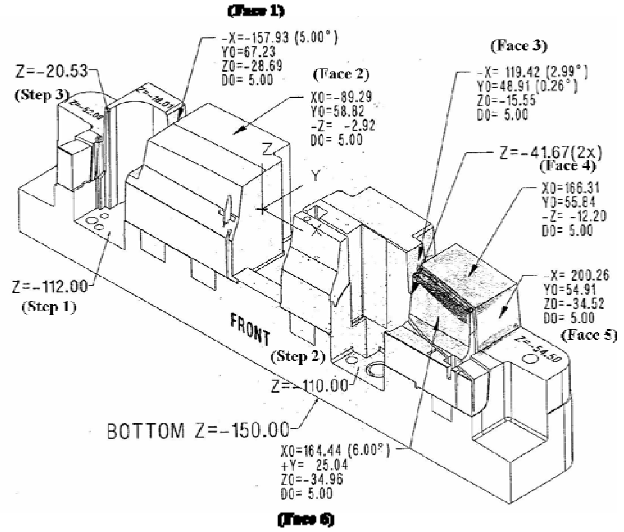


Figure 5.13 Sub-Core of Injection Mould Assembly 4525 (2 pieces)

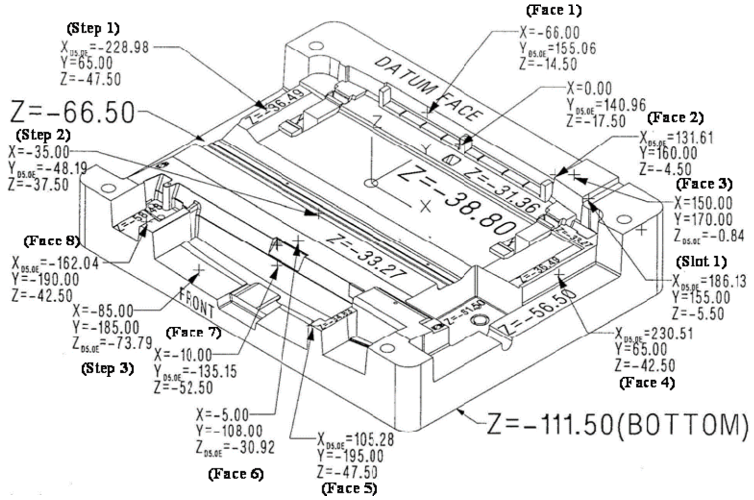
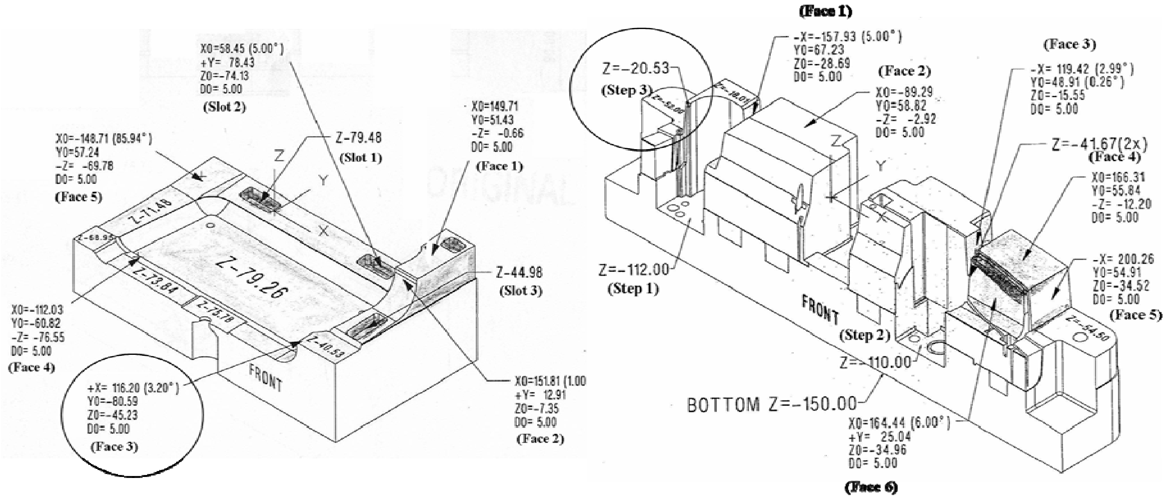


Figure 5.14 Main Cavity of Injection Mould Assembly 4319 (4 pieces)

Table 5.6 Partial Information of the Family Formation Reference Database

End milling module			Identification results			
Family Name	**Family ID**	**Family Member**	Index code	Nominal (mm)	measurements	
					First pc.	Nth. pc.
CMM_NVD5000(2)_718HH_END MILL_1	1_C03_A01_A_1	… …				
		A_1_A_C03_01_A08				
		A_1_A_C03_01_B19	4319_100_012	230.51		
			4319_100_015	-66.50		
		A_1_A_C03_01_B20				
		… …				
CMM_NVD5000(2)_718HH_END MILL_2	1_C03_A01_A_2	A_1_A_C03_01_A01	4319_100_004	131.61		
			4319_100_005	-0.84		
			4319_100_023	-30.92		
			4319_100_024	-135.15		
		A_1_A_C03_01_A02	4319_100_030	105.28		
			4319_100_031	-162.04		
		A_1_A_C03_01_A03	4319_100_028	-73.79		
			4319_100_042	-228.95		
		A_1_A_C03_01_A04	4319_100_006	186.13		
			4319_100_036	-155.06		
		… …				
CMM_SV500_718HH_END MILL_1	**1_C01_A01_A_1**	A_1_A_C01_01_A01	4525_203_008	-157.93		
			4525_203_009	119.42		
			4525_203_015	-2.92		
			4525_203_018	-12.20		
			4525_203_027	-112.00		
			4525_203_029	-110.00		
		A_1_A_C01_01_A02	4525_203_003	200.26		
			4525_203_033	25.04		
		A_1_A_C01_01_A03				
		A_1_A_C01_01_A04	**4490_100_010 (face 3)**	116.20		
			4525_203_004 (step 3)	-20.53		
			4490_100_023	-79.48		
			4490_100_024	78.43		
			4490_100_025	-44.98		
		A_1_A_C01_01_B19				
		A_1_A_C01_01_B18				
		… …				
CMM_SV500_718HH_END MILL_2	1_C01_A01_A_2	A_1_A_C01_01_A05				
		A_1_A_C01_01_A06				
		A_1_A_C01_01_B22	4490_100_013	-69.78		
		A_1_A_C01_01_B23	4490_100_017	-76.55		
		… …				
… …	… …					

According to the family formation reference information, the family membership of each feature was identified, as shown in Table 5.6. It can be seen that features of different part/product number, e.g. **4490_100_010** (face 3) and **4525_203_004** (step 3), as indicated in Figure 5.1, are brought together into the same family of **1_C01_A01_A_1**.



Product No. 4490
Part No. 100

Product No. 4525
Part No. 203

Figure 5.15 Feature Grouped Together From Different Part/Product Number

Here, we assume that the measurement equipment software and database have been appropriate customized. Then the code is employed as an identifier by the SPC planning system to communicate with the measurement equipment and measurement database. The data of the normal value and measured value are shown in Appendix C-10. The main cavity of 4319, the sub core of 4525, and the main cavity of 4490 had been manufactured in 4, 2, and 4 pieces respectively. Correspondingly, for a specific normal value of these parts, there would be 4, 2, and 4 measurements respectively. According to the processing sequence, the collected data of the same family were rearranged and transformed by Equation 4.1, as shown in Appendix C-9.

Then the family control chart could be plotted. As mentioned earlier, with no statistical meaningful subgroups for the very-small batch one-off manufacturing, the most commonly used control chart, which is average and range charts, cannot be applied. The individual-moving range (I-MR) chart uses the individual measurement as the data point after data transformation, which is more suitable to very-small batch cases. Hence, the data of two families were plotted with these two charts, as shown in Figures 5.16 and 5.17.

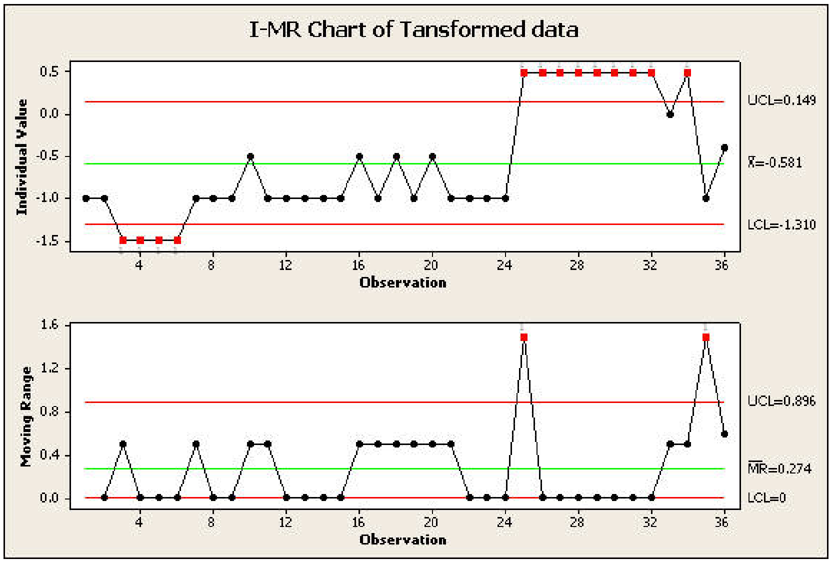


Figure 5.16 Individual and Moving Range chart for Data in the Family of "CMM_NVD5000(2)_718HH_END MILL_2"

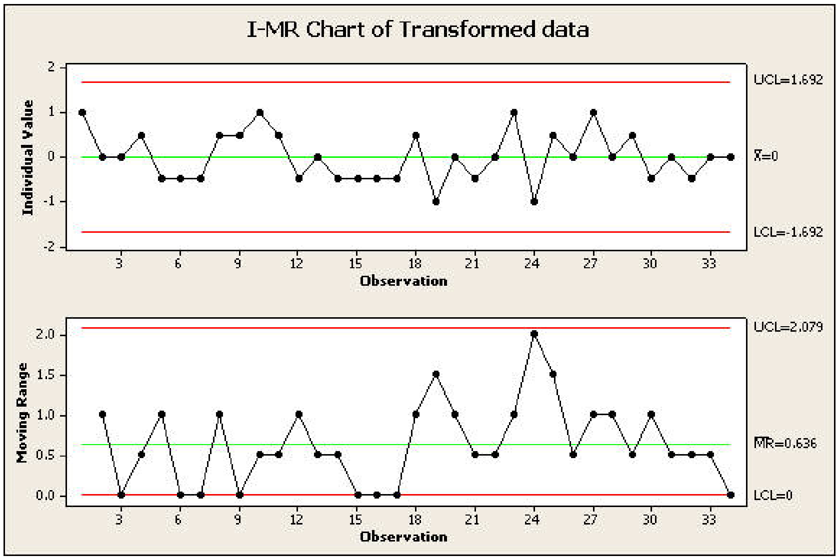


Figure 5.17 Individual and Moving Range chart for Data in the Family of "CMM_SV500_718HH_END MILL_1"

The data of another family are not enough for control charting. Obviously, the charts in Figure 5.16 are abnormal. Some of the data are out of control limits and there is also a "sudden shift in level" pattern. Some special cause might disturb the process. After tracing back various process records, such as the lot traveler, it was found that the first 24 data came from a set-up, and the others came from another set-up. Therefore, “”change in set-up” is suggested as the root cause and set-up standardization is necessary for process improvement purpose.

Conclusion

With the application of the proposed GTCC system, data can be effectively grouped for control charting. However, as this focus is on the design and development of the framework, which has not been computerized, the grouping is conducted manually. To represent the data processing methodology and requirement, the discussion then assumes the program and supportive database are available.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

6.1 Conclusions

Increasing customer expectation of high-performance and low-cost products has set new challenges for product quality control. Statistical process control (SPC), characterized as a technique that seeks quality products via continuous reduction of process variation, has been widely applied in industry. To apply SPC, samples are collected periodically from the process to analyze the process properties and determine suitable actions to maintain the process in control. SPC has gained success in mass and repetitive manufacturing area. But in current dynamic market, the demand for very small-batch and high-variety products is growing. The traditional SPC approach demands huge amount of data and is not suitable for this type of production. Several existing approaches address the application of SPC in repetitive, medium small-batch manufacturing. The objective of this research is to develop an alternative computer-facilitated approach to extend the application of SPC to very small-batch production.

The difficulties of directly applying existing approaches in very small-batch, and computer-directed manufacturing are as follows:

Unlike other short-run productions, in which a certain number of part types are produced alternately, in very small-batch manufacturing, products in one batch can be very different from another in terms of dimension, shape, features, and material. The high variations in products make the part family formation very complex.

There is not sufficient data to form meaningful subgroups due to the little data from a particular process.

Due to the high variation properties, many different machining processes may be involved. Each process may have different combinations of operating factors and factor settings for different parts. Many factors and factor levels may be involved in the statistical analysis. Existing methods that apply one-way ANOVA or multiple regression analysis is not an efficient way.

Performing statistical analysis to identify part families for newly developed products is very time consuming, which does not match the productivity of computer-integrated or automated manufacturing.

This research proposes an alternative approach to overcome the above problems with data collected from industry to illustrate its feasibility.

6.1.1 SPC planning for very small-batch manufacturing

The problem of high variation in product and process properties is solved by combination of extensive preliminary analysis using the knowledge of properties and application of the factors, and statistical design of experiment and analysis.

Firstly, critical quality characteristics and associated manufacturing processes are identified and efforts of application of SPC are proposed that target on them. The clearly identified quality characteristics and processes can simplify the overall problem. Secondly, various machining resources are classified and those mainly used in the critical processes are identified. The purpose of classifying the machining resource information is to identify the potential factors that may have systematic influence on the quality characteristics of different processes. Thirdly, preliminary analysis with the knowledge of the properties and application of the factors is proposed to reduce the number of potential factors and factor levels. As a result, the runs of the statistical experiment are reduced and the statistical analysis is simplified. Fourthly, a statistical experiment and analytical procedure are employed. A K-way ANOVA is proposed and applied to concurrently analyze the influence of multiple factors. A well-controlled balanced experimental design is suggested to reduce the effect of violating the assumption of K-way ANOVA.

The end milling operation for injection mould manufacturing is used to illustrate the proposed approach. A case study has been done based on this operation in a local injection mould manufacturing company, and real data are collected to demonstrate the statistical analysis. The results indicate that the proposed approach is effective.

6.1.2 Framework of computer-aided short-run SPC planning

To improve the identification efficiency of part family membership for new products and facilitate computer-automation, a framework of computer-aided short-run SPC planning is proposed.

A group technology classification and coding (GTCC) system is proposed. GTCC is one of the effective methods for solving part family formation, and viewed as amenable to computer-based technology. The distinguished benefit of using GTCC is that it can facilitate not only information retrieval in the planning phase but also information trace-back in the implementation phase. Currently, many GTCC systems have been developed to compactly describe part properties and process factors. As for SPC application, detailed information is required, and hence, a secondary code appended to the Optiz code is proposed.

Part family formation results obtained from the analysis of historical data are coded with the proposed coding scheme and maintained in the reference database. Machining resource information is classified and stored in the database to facilitate coding, and updating the SPC planning system. For a feature associated to the critical quality characteristics of a new part, the GTCC system generates a code for it based on the proposed coding scheme after retrieval of the necessary part and processing information. Then the GTCC system searches the reference database. If a matchable code is found in a particular family, the quality characteristic is pooled into that family. At the same time, the feature code can be used as an ID by the planning system to communicate with the measurement equipment and measurement database. After accumulating sufficient data in a family, control chart can be plotted.

A case study on several injection mould components has been conducted. The results indicate that the proposed approach works successfully.

6.2 Recommendations for future work

In this research, the author attempt to address the SPC planning issues of one-off, very small-batch manufacturing environments. In particular, the author proposed the use of preliminary analyses, statistical tools, and the group technology classification and coding concept to facilitate the part family identification. However, many problems for the application of SPC in small-batch manufacturing remain unexplored. The potential research issues are as follows.

1. The operator and operation setup may also have influence on the homogeneity of the part family members. However, the analyses did not reveal their effects. Further analyses are necessary to investigate their effects.
2. In this research, the author have discussed how to apply the proposed method in the milling process in detail. For drilling, reaming and trapping processes, the approach can be used in the similar way. However, other important machining processes, such as grinding, EDM die-sinking, and EDM wire-cut, have quite different properties. To achieve a more general and comprehensive level of application, wider studies are required.
3. In this research, the author have investigated the approach to form part families with homogeneous members. However, the effects of part family formation on the performance of various control charts that can be used in small-batch manufacturing are not investigated. Based on their performance, some SPC-based part family criteria may be deduced.
4. With the change of the environment and wear of the machine, the homogeneity of the quality characteristics in a family should be reviewed from time to time. Correspondingly, the family formation reference database is updated periodically for the effectiveness of family membership identification. However, the determination of the period is a problem.
5. Process capability analysis is an important step to quantify the progress of process performance. The commonly used process capability indices are:

$$C_p = \frac{USL - LSL}{6\sigma} \tag{6.1}$$

$$C_{pk} = \min\left\{\frac{USL - \mu}{3\sigma}, \frac{\mu - USL}{3\sigma}\right\} \qquad (6.2)$$

where USL and LSL are the upper and lower specification limits of the product, and μ and σ are the process mean and variability.

For short-runs, once the part families are formed, part family control chart can be established to monitor the process status, and estimate the process mean and variability. But the part family members may have different tolerance values. Hence, how to perform a process capability study in this case is a problem.

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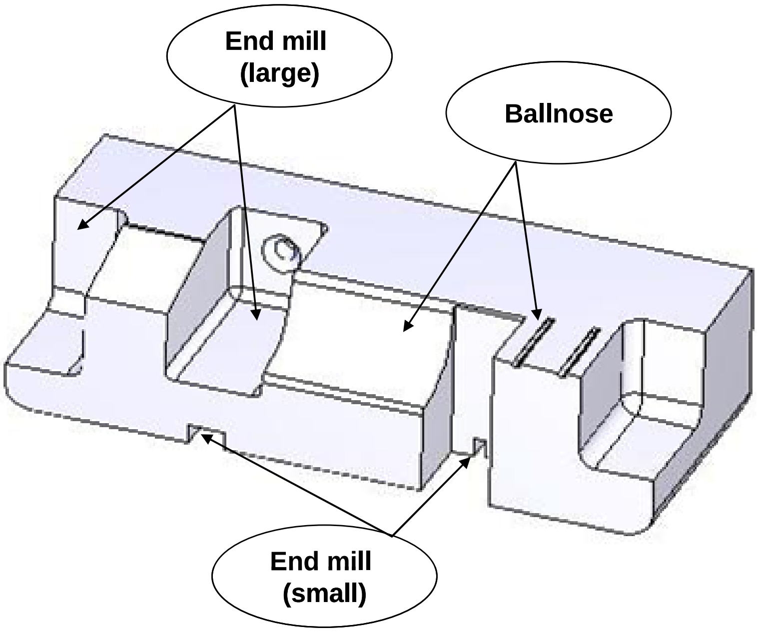
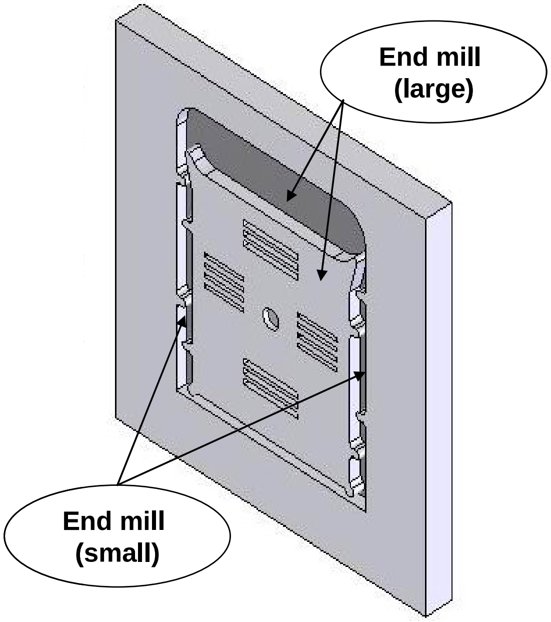
Appendix A

Source Data of Case Studies of Chapter 4

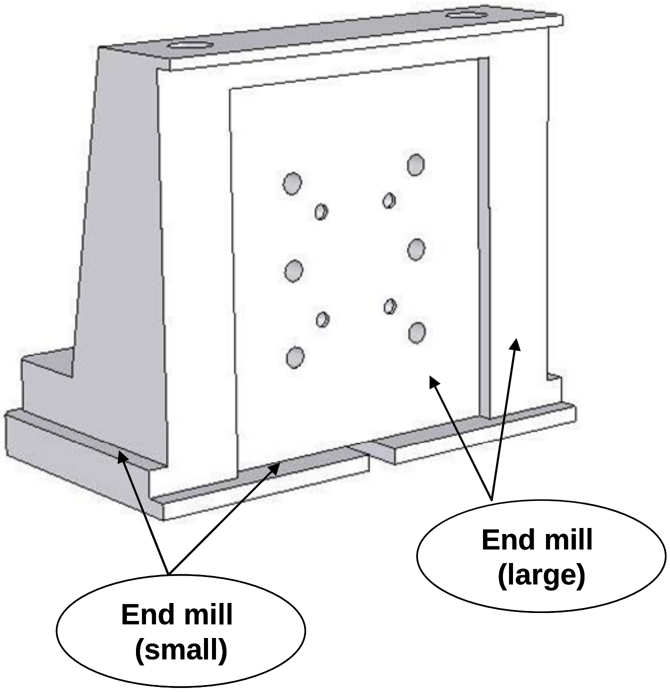
Appendix A-1 Sample parts and features of case study 1



P-1



P-2



P-5

Appendix A-2 Source data of case study 1

Machine: Moki Seiki SV-500						
Cutter	**ASSAB 8407**	**ASSAB 718HH**	**ASSAB Stavax**	**ASSAB 618HH**	**Data Properties**	
End mill (large Ø)	148.339	-9.738	163.605	69.880	Measurement (X)	First
	148.323	-9.750	163.598	69.870	Normal value	
	0.02	0.02	0.02	0.02	Tolerance (T)	
	0.80	0.60	0.35	0.50	Transformed value (Y)	
	117.647	-27.974	198.011	107.242	Measurement (X)	Second
	117.630	-27.994	198.002	107.299	Normal value	
	0.02	0.05	0.02	0.02	Tolerance (T)	
	0.85	0.40	0.45	0.65	Transformed value (Y)	
End mill (Small Ø)	-84.426	-50.070	81.166	-15.565	Measurement (X)	First
	-84.440	-50.100	81.151	-15.576	Normal value	
	0.02	0.05	0.05	0.02	Tolerance (T)	
	0.70	0.60	0.30	0.55	Transformed value (Y)	
	-84.221	96.449	-13.042	-35.060	Measurement (X)	Second
	-84.246	96.441	-13.047	-35.069	Normal value	
	0.05	0.02	0.02	0.02	Tolerance (T)	
	0.50	0.40	0.25	0.45	Transformed value (Y)	
Ballnose	47.390	100.584	8.373	-132.698	Measurement (X)	First
	47.360	100.577	8.368	-132.713	Normal value	
	0.05	0.02	0.02	0.05	Tolerance (T)	
	0.60	0.35	0.25	0.30	Transformed value (Y)	
	28.227	129.808	-35.062	-42.636	Measurement (X)	Second
	28.219	129.800	-35.069	-42.643	Normal value	
	0.02	0.02	0.02	0.02	Tolerance (T)	
	0.40	0.40	0.35	0.35	Transformed value (Y)	

Mori Seiki NVD5000 (1)

Machine	ASSAB 8407	ASSAB 718HH	ASSAB Stavax	ASSAB 618HH	Data Properties	
End mill (large Ø)	28.235	30.560	-28.463	33.084	Measurement (X)	First
	28.219	30.525	-28.493	33.069	Normal value	
	0.02	0.05	0.05	0.02	Tolerance (T)	
	0.80	0.70	0.60	0.75	Transformed value (Y)	
	-42.623	-200.298	19.050	20.391	Measurement (X)	Second
	-42.640	-200.323	19.037	20.361	Normal value	
	0.02	0.05	0.02	0.05	Tolerance (T)	
	0.85	0.50	0.65	0.60	Transformed value (Y)	
End mill (Small Ø)	-25.501	-25.995	19.753	35.694	Measurement (X)	First
	-25.531	-26.008	19.745	35.680	Normal value	
	0.05	0.02	0.02	0.02	Tolerance (T)	
	0.60	0.65	0.40	0.70	Transformed value (Y)	
	-34.435	-200.476	111.443	100.480	Measurement (X)	Second
	-34.444	-200.501	111.433	100.450	Normal value	
	0.02	0.05	0.02	0.05	Tolerance (T)	
	0.45	0.50	0.50	0.60	Transformed value (Y)	
Ballnose	30.271	13.291	-99.562	-8.884	Measurement (X)	First
	30.258	13.282	-99.577	-8.895	Normal value	
	0.02	0.02	0.05	0.02	Tolerance (T)	
	0.65	0.45	0.30	0.55	Transformed value (Y)	
	-253.756	-28.972	41.780	50.688	Measurement (X)	Second
	-253.766	-28.984	41.773	50.663	Normal value	
	0.02	0.02	0.02	0.05	Tolerance (T)	
	0.50	0.60	0.35	0.50	Transformed value (Y)	

Mori Seiki NVD5000 (2)						
Machine	**ASSAB 8407**	**ASSAB 718HH**	**ASSAB Stavax**	**ASSAB 618HH**	**Data Properties**	
End mill (large Ø)	-35.001	-8.400	186.209	-75.590	Measurement (X)	First
	-35.017	-8.440	186.184	-75.605	Normal value	
	0.02	0.05	0.05	0.02	Tolerance (T)	
	0.80	0.80	0.50	0.75	Transformed value (Y)	
	7.903	-24.987	154.766	-58.421	Measurement (X)	Second
	7.858	-25.000	154.775	-58.432	Normal value	
	0.05	0.02	0.02	0.02	Tolerance (T)	
	0.90	0.65	0.45	0.55	Transformed value (Y)	
End mill (Small Ø)	-60.160	19.901	52.608	-20.301	Measurement (X)	First
	-60.200	19.888	52.600	-20.313	Normal value	
	0.05	0.02	0.02	0.02	Tolerance (T)	
	0.80	0.65	0.40	0.60	Transformed value (Y)	
	-10.860	21.614	84.946	10.635	Measurement (X)	Second
	-10.875	21.599	84.935	10.622	Normal value	
	0.02	0.02	0.02	0.02	Tolerance (T)	
	0.75	0.75	0.55	0.65	Transformed value (Y)	
Ballnose	40.439	-176.997	63.980	18.967	Measurement (X)	First
	40.404	-177.003	63.971	18.960	Normal value	
	0.05	0.02	0.02	0.02	Tolerance (T)	
	0.70	0.30	0.45	0.35	Transformed value (Y)	
	-29.551	-3.930	20.273	-15.472	Measurement (X)	Second
	-29.564	-3.939	20.268	-15.841	Normal value	
	0.02	0.02	0.02	0.02	Tolerance (T)	
	0.65	0.45	0.25	0.45	Transformed value (Y)	

Appendix A-3 Source data of case study 2

Machine	Cutter : End mill (Large diameter)			
Robodrill T21--(1)	Measurement (X)	Normal value	Tolerance (T)	Transformed value (Y)
	49.526	49.514	0.02	0.60
	47.504	47.491	0.02	0.65
	54.568	54.509	0.1	0.59
	54.915	54.895	0.02	0.67
	90.159	90.140	0.03	0.63
	46.146	45.110	0.05	0.72
	35.858	35.841	0.03	0.57
	30.031	30.000	0.05	0.62
	36.078	36.040	0.05	0.76
	62.234	62.220	0.02	0.70
	49.052	49.039	0.02	0.65
	64.192	64.159	0.05	0.66

Machine	Cutter : End mill (Small diameter)			
Robodrill T21--(1)	Measurement (X)	Normal value	Tolerance (T)	Transformed value (Y)
	7.005	6.991	0.02	0.70
	2.907	2.870	0.05	0.74
	8.281	8.268	0.02	0.65
	6.263	6.227	0.05	0.72
	7.953	7.939	0.02	0.70
	3.496	3.480	0.02	0.80
	9.242	9.223	0.03	0.63
	7.947	7.924	0.02	0.77
	4.543	4.509	0.05	0.68
	2.508	2.488	0.03	0.67
	9.894	9.860	0.05	0.68
	6.244	6.203	0.05	0.82

Machine	**Cutter : End mill (Ballnose)**			
	Measurement (X)	Normal value	Tolerance (T)	Transformed value (Y)
Robodrill T21--(1)	16.167	16.142	0.03	0.83
	14.503	14.422	0.1	0.81
	10.424	10.392	0.05	0.64
	15.279	15.248	0.05	0.62
	13.099	13.085	0.02	0.70
	21.796	21.759	0.05	0.74
	26.569	26.550	0.03	0.63
	26.699	26.679	0.03	0.67
	32.091	32.066	0.03	0.83
	15.556	15.517	0.05	0.78
	7.011	6.991	0.03	0.67
	16.176	16.142	0.05	0.68

Machine	**Cutter : End mill (Large diameter)**			
	Measurement (X)	Normal value	Tolerance (T)	Transformed value (Y)
Robodrill T21--(2)	35.874	35.841	0.05	0.66
	30.031	30.000	0.05	0.62
	36.060	36.040	0.03	0.67
	62.237	62.220	0.03	0.57
	21.258	21.239	0.03	0.63
	64.192	64.159	0.05	0.66
	54.917	54.895	0.03	0.73
	90.151	90.140	0.02	0.55
	37.790	37.776	0.02	0.70
	39.819	39.790	0.05	0.58
	63.971	63.958	0.02	0.65
	70.020	70.000	0.03	0.66

Machine	**Cutter : End mill (Small diameter)**			
	Measurement (X)	Normal value	Tolerance (T)	Transformed value (Y)
Robodrill T21--(2)	7.081	7.000	0.1	0.81
	7.533	7.500	0.05	0.66
	7.012	7.000	0.02	0.60
	7.514	7.500	0.02	0.70
	1.696	1.659	0.05	0.74
	4.778	4.759	0.03	0.63
	11.125	11.105	0.03	0.67
	18.422	18.341	0.1	0.81
	7.124	7.085	0.05	0.78
	12.045	12.009	0.05	0.72
	12.949	12.915	0.05	0.68
	8.929	8.895	0.05	0.68

Machine	**Cutter : End mill (Ballnose)**			
	Measurement (X)	Normal value	Tolerance (T)	Transformed value (Y)
Robodrill T21--(2)	14.458	14.422	0.05	0.72
	10.406	10.392	0.02	0.70
	13.100	13.085	0.02	0.75
	21.797	21.759	0.05	0.76
	28.625	28.591	0.05	0.68
	15.558	15.517	0.05	0.82
	18.541	18.500	0.05	0.82
	16.915	16.836	0.1	0.79
	16.971	16.937	0.05	0.68
	16.006	15.993	0.02	0.65
	15.046	15.012	0.05	0.68
	21.044	21.010	0.05	0.68

Machine	Cutter : End mill (Large diameter)			
	Measurement (X)	Normal value	Tolerance (T)	Transformed value (Y)
Robodrill T21--(3)	69.819	69.802	0.03	0.57
	61.007	61.979	0.05	0.56
	53.069	53.000	0.1	0.69
	67.361	67.330	0.05	0.62
	12.039	12.000	0.05	0.78
	53.013	53.000	0.02	0.65
	53.022	53.000	0.03	0.73
	39.085	39.071	0.02	0.70
	29.483	29.445	0.05	0.76
	67.401	67.322	0.1	0.79
	48.054	48.041	0.02	0.65
	53.033	53.000	0.05	0.66

Machine	Cutter : End mill (Small diameter)			
	Measurement (X)	Normal value	Tolerance (T)	Transformed value (Y)
Robodrill T21--(3)	9.033	9.001	0.05	0.64
	18.014	18.000	0.02	0.70
	17.515	17.500	0.02	0.75
	17.513	17.500	0.02	0.65
	18.036	18.000	0.05	0.72
	7.015	7.000	0.02	0.75
	7.516	7.500	0.02	0.80
	7.012	7.000	0.02	0.60
	7.523	7.500	0.03	0.77
	11.133	11.099	0.05	0.68
	9.813	9.793	0.03	0.67
	8.124	8.090	0.05	0.68

Machine	**Cutter : End mill (Ballnose)**			
	Measurement (X)	Normal value	Tolerance (T)	Transformed value (Y)
Robodrill T21--(3)	17.058	17.044	0.02	0.70
	30.410	30.351	0.1	0.59
	10.734	10.720	0.02	0.70
	18.019	18.005	0.02	0.70
	17.627	17.591	0.05	0.72
	16.960	16.937	0.03	0.77
	16.046	16.009	0.05	0.74
	15.051	15.015	0.05	0.72
	21.028	21.009	0.03	0.63
	17.478	17.445	0.05	0.66
	30.361	30.341	0.03	0.67
	29.106	29.072	0.05	0.68

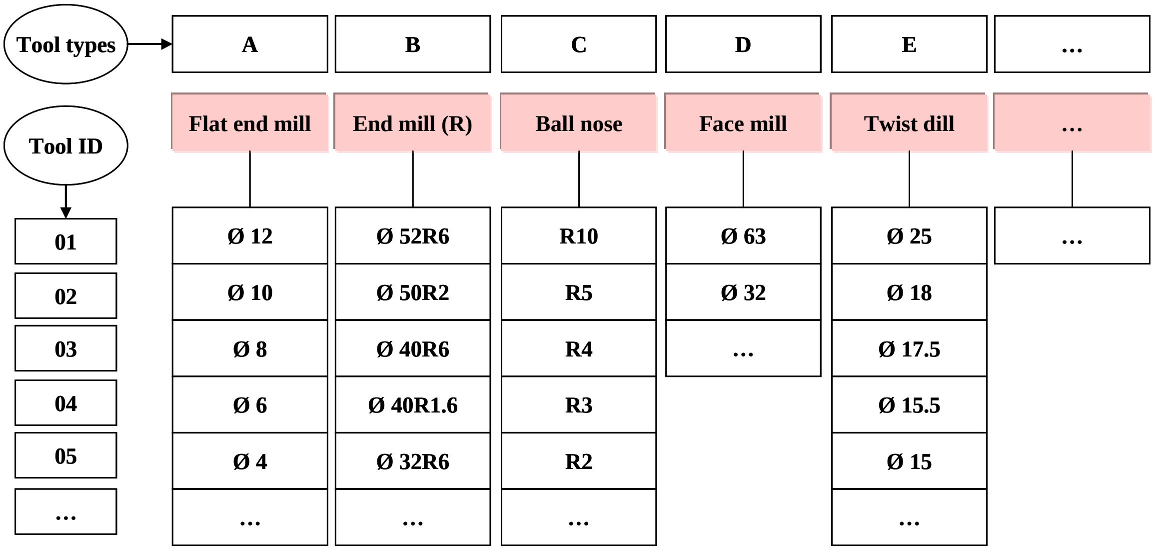
Appendix B

Structure of Machining Resource Database

Appendix B-1 Operation module

Operation ID	**Operation Type**	**Description**
A	End milling	…
B	Face milling	
C	Twist drilling	
D	Gun drilling	
E	Counter boring	
F	Reaming	
G	Tapping	
H	End milling_ELE	
I	Grinding	
J	EDM die-sinking	
K	EDM w/cut	
…	…	

Appendix B-2 Cutter module



Tool types	**A**	**B**	**C**	**D**	**E**	**…**
Tool ID	**Flat end mill**	**End mill (R)**	**Ball nose**	**Face mill**	**Twist dill**	**…**
01	**Ø 12**	**Ø 52R6**	**R10**	**Ø 63**	**Ø 25**	**…**
02	**Ø 10**	**Ø 50R2**	**R5**	**Ø 32**	**Ø 18**	
03	**Ø 8**	**Ø 40R6**	**R4**	**…**	**Ø 17.5**	
04	**Ø 6**	**Ø 40R1.6**	**R3**		**Ø 15.5**	
05	**Ø 4**	**Ø 32R6**	**R2**		**Ø 15**	
…	**…**	**…**	**…**		**…**	

Cutter Module--Cutter-type A (Flat end mill)

Cutter ID	**Diameter**	**Type**	**Length**	**Material**	**Coating**	**Remarks**
01	Ø 12	Solid	45	Carbide	TiN	
02	Ø 10	Solid	45	Carbide	TiN	
03	Ø 8	Solid	35	Carbide	TiN	
04	Ø 6	Solid	30	Carbide	TiN	
05	Ø 4	Solid	25	Carbide	TiN	Shank Ø6
06	Ø 3	Solid	25	Carbide	TiN	Shank Ø4
07	Ø 2	Solid	25	Carbide	TiN	Shank Ø4
08	Ø 1.5	Solid	25	Carbide	TiN	Shank Ø4
09	Ø 1	Solid	25	Carbide	TiN	Shank Ø4

Cutter Module--Cutter-type B (bullnose mill)

Cutter ID	**Diameter**	**Type**	**Length**	**Material**	**Coating**	**Remarks**
01	Ø 52R6	Inserted	80/150	Carbide	TiN	Roughing only
02	Ø 50R2	Inserted	80/150	Carbide	TiN	Roughing only
03	Ø 40R6	Inserted	70/120	Carbide	TiN	Roughing only
04	Ø 40R1.6	Inserted	70/140	Carbide	TiN	
05	Ø 32R6	Inserted	70/150	Carbide	TiN	Roughing only
06	Ø 32R2	Inserted	60/120	Carbide	TiN	Roughing only
07	Ø 32R1.6	Inserted	90/150	Carbide	TiN	
08	Ø 25R2	Inserted	60/115	Carbide	TiN	Roughing only
09	Ø 25R5	Inserted	60/100	Carbide	TiN	Roughing only
10	Ø 25R1.6	Inserted	80/120	Carbide	TiN	
11	Ø 25R0.8	Inserted	80/120	Carbide	TiN	
12	Ø 25R0.4	Inserted	80/120	Carbide	TiN	
13	Ø 20R1.6	Inserted	80/100	Carbide	TiN	
14	Ø 20R0.8	Inserted	80/100	Carbide	TiN	
15	Ø 20R0.4	Inserted	80/100	Carbide	TiN	
16	Ø 16R1.6	Inserted	80	Carbide	TiN	
17	Ø 16R0.8	Inserted	80	Carbide	TiN	
19	Ø 16R0.4	Inserted	80	Carbide	TiN	
20	Ø 12R0.5	Solid	45/35	Carbide	TiN	
21	Ø 10R0.5	Solid	45/65	Carbide	TiN	
22	Ø 8R0.5	Solid	35/45	Carbide	TiN	
23	Ø 6R0.5	Solid	30/40	Carbide	TiN	
24	Ø 4R0.5	Solid	10/20	Carbide	TiN	

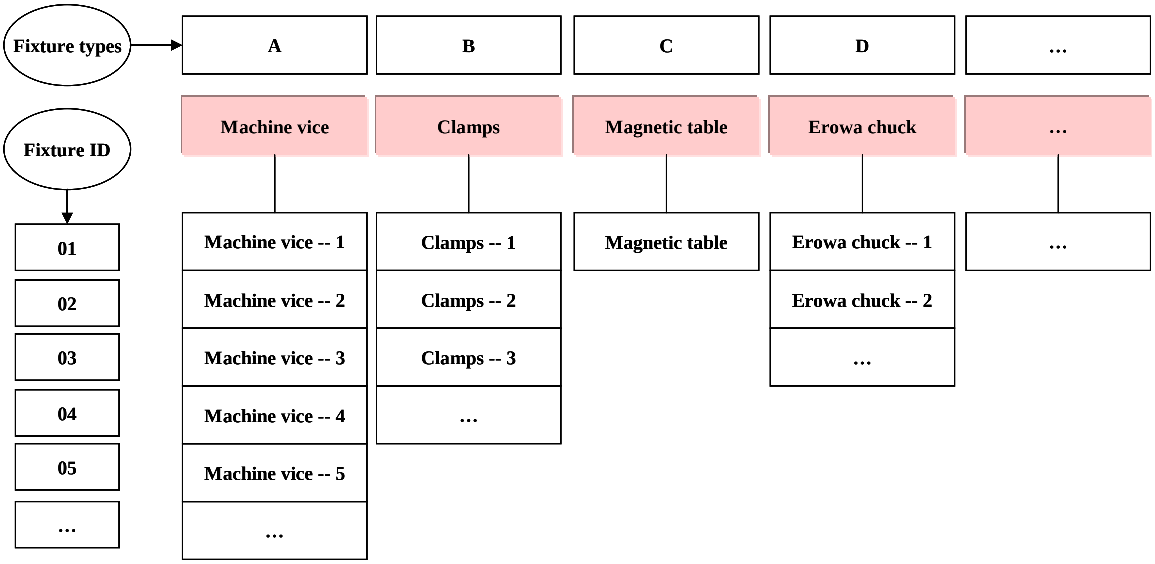
Cutter Module--Cutter-type C (Ballnose)

Cutter ID	Diameter	Type	Length	Material	Coating	Remarks
01	R10	Solid	80/120	Carbide	TiN	
02	R5	Solid	30/65	Carbide	TiN	
03	R4	Solid	40	Carbide	TiN	
04	R	Solid	35	Carbide	TiN	
05	R3	Solid	25	Carbide	TiN	
06	R2	Solid	20	Carbide	TiN	Shank Ø6
07	R1.5	Solid	20	Carbide	TiN	Shank Ø4
08	R1	Solid	20	Carbide	TiN	Shank Ø4
09	R0.75	Solid	20	Carbide	TiN	Shank Ø4
10	R0.5	Solid	20	Carbide	TiN	Shank Ø4

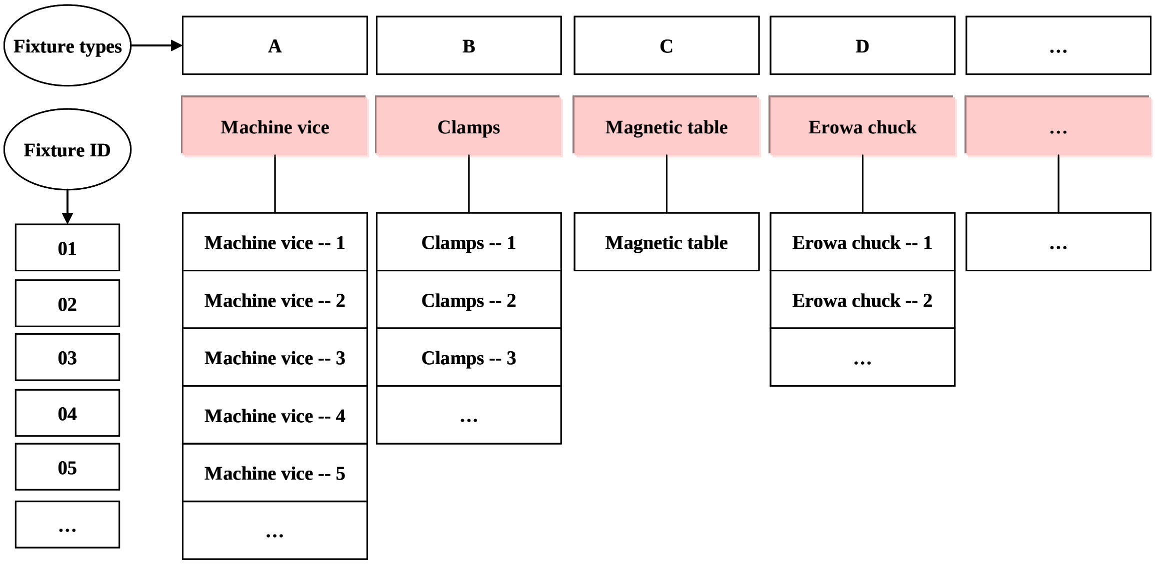
Cutter Module--Cutter-type D (Face mill)

Cutter ID	Diameter	No. of Insert	Material	Coating	Remarks
01	Ø25	4	Carbide	TiN	
02	Ø26	4	Carbide	TiN	
03	Ø32	4	Carbide	TiN	

Appendix B-3 Fixture module



Appendix B-4 Material module



Appendix C

Source Data of the Case Study of Chapter 5

Appendix C-1 Process Planning File of Injection Mould 4490

FU YU	**PROCESS PLANNING SHEET**			
Mold No. **4490**	**Part Name** **Main cavity**	**Part No.** **100**	**Engineered by**	**Date**

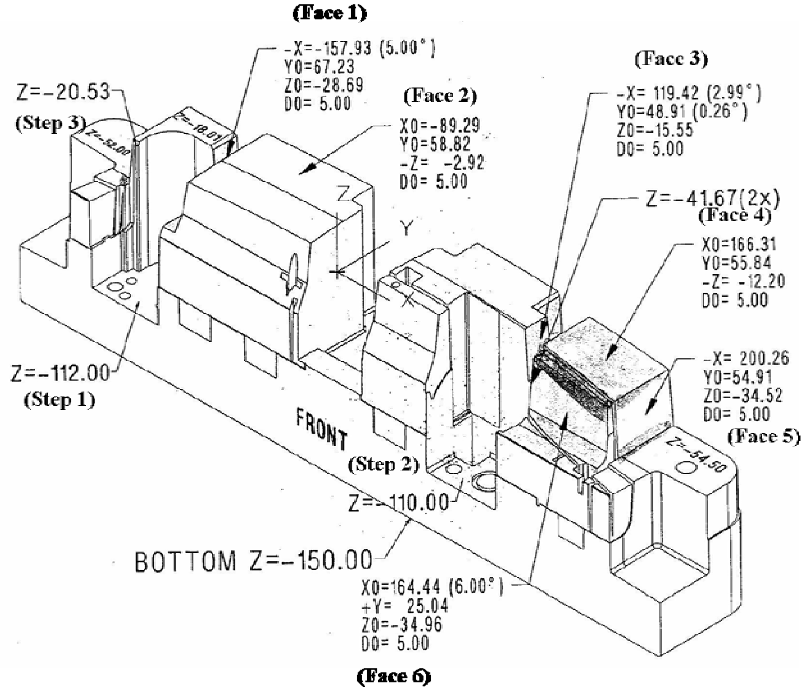
W/P SETTING
X: as shown
Y: as shown
Z: Top Z=-79.26
Machine: CNC

TOLERANCES	
X.XXX	**±0.02**
X.XX	**±0.05**
X.X	**±0.1**
UNLESS OTHERWISE SPECIFIED	

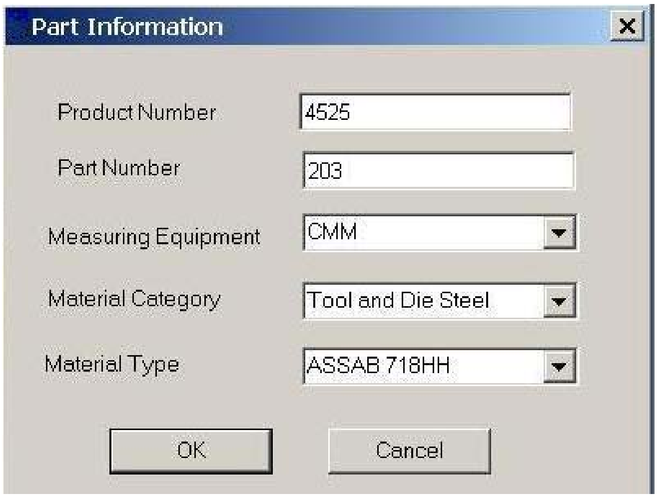
PROG DIR:
QTY:
NOTE:

Step	Feature	Operation	Machine type	Machine No.	Tool	Speed, m/min	Feed, mm/rev
1-4	All faces	Face milling	CNC_Roughing	Makino V55	Face mill Ø 20	60	0.48
5	All faces	Grinding	Grinding machines	Washino SE52VC	Ø 202	15/700	0.004
6	Face 1	End milling	CNC_Finishing	Moki Seiki SV-500	Ballnose R3	120	0.2
7	Slot 4	End milling	CNC_Finishing	Moki Seiki SV-500	End mill Ø 4	120	0.2
8	Chamfers on face 1	Chamfering	CNC_Finishing	Moki Seiki SV-500	End mill Ø 6	30	0.1
9	Face 2	End milling	CNC_Finishing	Moki Seiki SV-500	Ballnose R10	120	0.2
10-12	Screw holes	Reaming	CNC_Finishing	Moki Seiki SV-500	Reamer M4	25	0.01
13	Face 5	End milling	CNC_Finishing	Moki Seiki SV-500	End mill Ø 6R0.5	250	0.2
14-16	Face 6, 7, 8	End milling	CNC_Finishing	Moki Seiki SV-500	End mill Ø 6	120	0.2
17	Face 4	End milling	CNC_Finishing	Moki Seiki SV-500			
18-21	Chamfers on face 2, 6, 7, 8	Chamfering	CNC_Finishing	Moki Seiki SV-500	End mill Ø 6	30	0.1
22	Face 9	End milling	CNC_Finishing	Moki Seiki SV-500	End mill Ø 10	120	0.2
23	Slot 1, 2, 3	End milling	CNC_Finishing	Moki Seiki SV-500	End mill Ø 6	120	0.2

Appendix C-2 Sub-Core of Injection Mould 4525



Appendix C-3 Input Part Information of Injection Mould 4525



Product Number: 4525

Part Number: 203

Measuring Equipment: CMM

Material Category: Tool and Die Steel

Material Type: ASSAB 718HH

Appendix C-4 Abstracted Processing Information

Steps	Feature name	Operation type	Machine type	Machine used	Cutter type and diameter
Step 3	Face 5, step 3	End milling	CNC_Finishing	Moki Seiki SV-500	Flat End mill ϕ10
Step 7	Face 1, 3	End milling	CNC_Finishing	Moki Seiki SV-500	Flat End mill ϕ6
Step 11	Face 2	End milling	CNC_Finishing	Moki Seiki SV-500	Flat End mill ϕ12
Step 13	Face 4	End milling	CNC_Finishing	Moki Seiki SV-500	Flat End mill ϕ12
Step 21	Step 1	End milling	CNC_Finishing	Moki Seiki SV-500	Flat End mill ϕ12
Step 23	Step2	End milling	CNC_Finishing	Moki Seiki SV-500	Flat End mill ϕ12
Step 29	Face 6	End milling	CNC_Finishing	Moki Seiki SV-500	Flat End mill ϕ 10

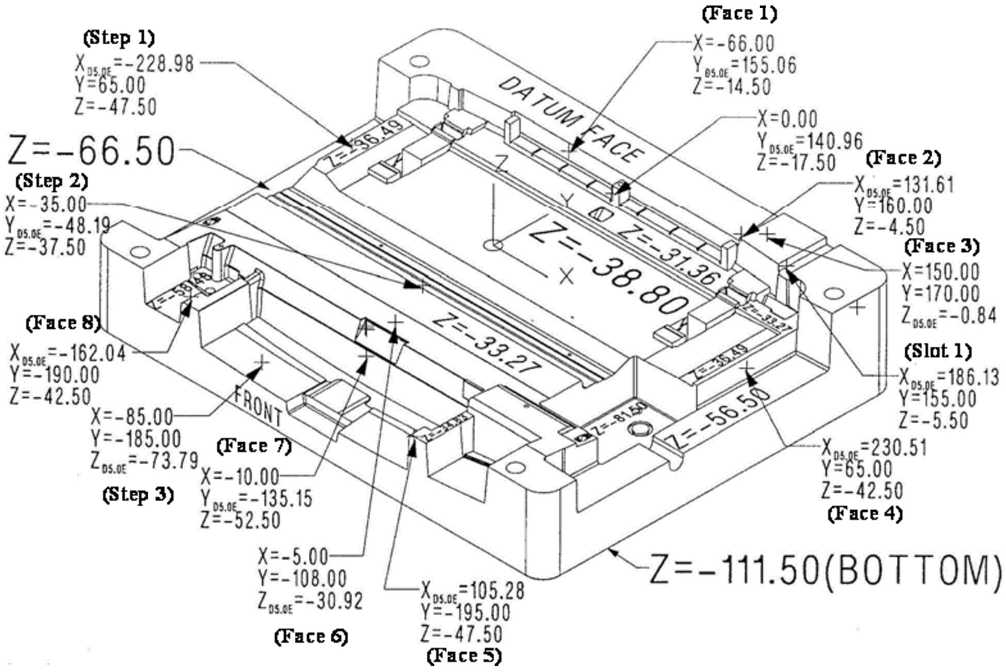
Appendix C-5 A Code of Each Feature

GTCC system for short-run SPC			**Step 3**	**Step 7**	**Step 11**	**Step 13**	**Step 21**	**Step 23**	**Step 29**
			Face 5, Step 3	Face 1, 3	Face 2	Face 4	Step 1	Step 2	Face 6
Primary code	D_1	Part class	6	6	6	6	6 (non-rotational)	6	6
	D_2	Part main shape	9	9	9	9	9 (all others)	9	9
	D_3	Rotational machining	2	2	2	2	2 (thread)	2	2
	D_4	Plane surface machining	9	9	9	9	9 (all others)	9	9
	D_5	Additional holes, teeth and forming	1	1	1	1	1 (axial, not on pitch circle diameter)	1	1
Supplementary code	D_6	Dimensions	1	1	1	1	1 (length/thickness: 2/1)	1	1
	D_7	Material category	A	A	A	A	A (tool and die steel)	A	A
	D_8	Original shape of raw material	1	1	1	1	1 (block)	1	1
	D_9	Accuracy	2	2	2	2	2 (0.02)	2	2
Secondary code	**D_{10}**	Measurement equipment	1	1	1	1	1 (CMM)	1	1
	D_{11}	Operation type	A	A	A	A	A (end milling)	A	A
	D_{12}	Machine group	C	C	C	C	C (Finishing group)	C	C
	$D_{13}D_{14}$	Machine sequential No.	01	01	01	01	01 (Moki Seiki SV-500)	01	01
	$D_{15}D_{16}$	Material type	01	01	01	01	01 (ASSAB718HH)	01	01
	D_{17}	Cutter type	A	A	A	A	A (flat end mill)	A	A
	$D_{18}D_{19}$	Cutter sequential No.	02, 04	01,01	01	01	01	01	02
	D_{20}~D_{23}	Product No.	4525	4525	4525	4525	4525	4525	4525
	D_{24}~D_{26}	Part No.	203	203	203	203	203	203	203
	D_{27}~D_{29}	Feature No.	003,004	008, 009	015	018	027	029	033

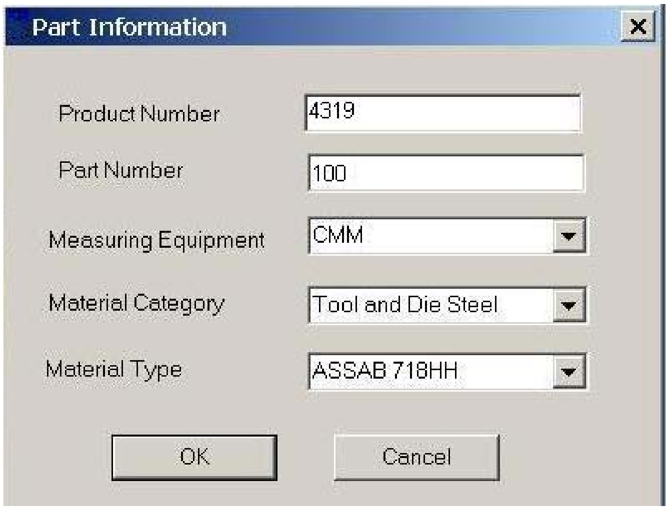
Appendix C-5 B Code of Each Feature

Feature Name	$D_7\_D_{10}\_D_{11}\_D_{12}D_{13}D_{14}\_D_{15}D_{16}\_D_{17}D_{18}D_{19}$	$D_{20}D_{21}D_{22}D_{23}\_D_{24}D_{25}D_{26}\_D_{27}D_{28}D_{29}$	Normal value
Face 5	A_1_A_C01_01_A02	4525_203_003	200.26
Step 3	A_1_A_C01_01_A04	4525_203_004	-20.53
Face 1	A_1_A_C01_01_A01	4525_203_008	-157.93
Face 3	A_1_A_C01_01_A01	4525_203_009	119.42
Face 2	A_1_A_C01_01_A01	4525_203_015	-2.92
Face 4	A_1_A_C01_01_A01	4525_203_018	-12.20
Step 1	A_1_A_C01_01_ A01	4525_203_027	-112.00
Step 2	A_1_A_C01_01_ A01	4525_203_029	-110.00
Face 6	A_1_A_C01_01_ A02	4525_203_033	25.04

Appendix C-6 Main Cavity of Injection Mould 4319



Appendix C-7 Input Part Information of Injection Mould 4319



Product Number: 4319

Part Number: 100

Measuring Equipment: CMM

Material Category: Tool and Die Steel

Material Type: ASSAB 718HH

Appendix C-8 Abstracted Processing Information

Steps	**Feature name**	**Operation type**	**Machine type**	**Machine used**	**Cutter type and diameter**
Step 4	Face 2, 3	End milling	CNC_Finishing	Moki NVD-5000(2)	Flat End mill ϕ12
Step 5	Slot 1	End milling	CNC_Finishing	Moki NVD-5000(2)	Flat End mill ϕ6
Step 9	Face 4, step 2	End milling	CNC_Finishing	Moki NVD-5000(2)	End mill ϕ12 R.5
Step 16	Face 6, 7	End milling	CNC_Finishing	Moki NVD-5000(2)	Flat End mill ϕ12
Step 18	Step 3	End milling	CNC_Finishing	Moki NVD-5000(2)	Flat End mill ϕ 8
Step 22	Face 5, 8	End milling	CNC_Finishing	Moki NVD-5000(2)	Flat End mill ϕ 10
Step 27	Face 1	End milling	CNC_Finishing	Moki NVD-5000(2)	Flat End mill ϕ 6
Step 33	Step 1	End milling	CNC_Finishing	Moki NVD-5000(2)	Flat End mill ϕ 8

Appendix C-9 A Code of Each Feature

GTCC system for short-run SPC			**Step 4**	**Step 5**	**Step 9**	**Step 16**	**Step 18**	**Step 22**	**Step 27**	**Step 33**
			Face 2,3	Slot 1	Face 4, step 2	Face 6,7	Step 3	Face 5,8	Face 1	Step 1
Primary code	D_1	Part class	6	6	6	6	6 (non-rotational)	6	6	6
	D_2	Part main shape	1	1	1	1	1 (step to one end & no shape elements)	1	1	1
	D_3	Rotational machining	2	2	2	2	2 (thread)	2	2	2
	D_4	Plane surface machining	9	9	9	9	9 (all others)	9	9	9
	D_5	Additional holes, teeth and forming	1	1	1	1	1 (axial, not on pitch circle diameter)	1	1	1
Supplementary code	D_6	Dimensions	9	9	9	9	9 (length/thickness: 10/1)	9	9	9
	D_7	Material category	A	A	A	A	A (tool and die steel)	A	A	A
	D_8	Original shape of raw material	1	1	1	1	1 (block)	1	1	1
	D_9	Accuracy	2	2	2	2	2 (0.02)	2	2	2
Secondary code	**D_{10}**	Measurement equipment	1	1	1	1	1 (CMM)	1	1	1
	D_{11}	Operation type	A	A	A	A	A (end milling)	A	A	A
	D_{12}	Machine group	C	C	C	C	C (Finishing group)	C	C	C
	$D_{13}D_{14}$	Machine sequential No.	03	03	03	03	03 (Moki NVD5000(2))	03	03	03
	$D_{15}D_{16}$	Material type	01	01	01	01	01 (ASSAB718HH)	01	01	01
	D_{17}	Cutter type	A	A	B (bullnose end mill)	A	A (flat end mill)	A	A	A
	$D_{18}D_{19}$	Cutter sequential No.	01,01	04	19,19	01,01	03	02,02	04	03
	D_{20}~D_{23}	Product No.	4319	4319	4319	4319	4319	4319	4319	4319
	D_{24}~D_{26}	Part No.	100	100	100	100	100		100	
	D_{27}~D_{29}	Feature No.	006	009	010	013	017 (Step 17*)	023,024,025**		

Appendix C-9 B Code of Each Feature

Feature Name	$D_7\_D_{10}\_D_{11}\_D_{12}D_{13}D_{14}\_D_{15}D_{16}\_D_{17}D_{18}D_{19}$	$D_{20}D_{21}D_{22}D_{23}\_D_{24}D_{25}D_{26}\_D_{27}D_{28}D_{29}$	Normal value
Face 2	A_1_A_C03_01_A01	4319_100_004	131.61
Face 3	A_1_A_C03_01_A01	4319_100_005	-0.84
Slot 1	A_1_A_C03_01_A04	4319_100_006	186.13
Face 4	A_1_A_C03_01_B19	4319_100_012	230.51
Step 2	A_1_A_C03_01_B19	4319_100_015	-66.50
Face 6	A_1_A_C03_01_A01	4319_100_023	-30.92
Face 7	A_1_A_C03_01_ A01	4319_100_024	-135.15
Step 3	A_1_A_C03_01_ A03	4319_100_028	-73.79
Face 5	A_1_A_C03_01_ A02	4319_100_030	105.28
Face 8	A_1_A_C03_01_ A02	4319_100_031	-162.04
Face 1	A_1_A_C03_01_ A04	4319_100_036	-155.06
Step 1	A_1_A_C03_01_ A03	4319_100_042	-228.95

Appendix C-10 Source data

Identification result							
Family ID	**Index code**	**Normal value (mm)**	**Measurements**				
			First pc.	**Second pc.**	**Third pc.**	**Forth pc.**	**Nth. Pc.**
1_C03_A01_A_1	4319_100_012	230.51	230.52	230.51	230.50	230.50	
	4319_100_015	-66.50	-66.49	-66.51	-66.50	-66.49	
1_C03_A01_A_2	4319_100_004	131.61	131.59	131.59	131.59	131.60	
	4319_100_005	-0.84	-0.82	-0.83	-0.83	-0.83	
	4319_100_005	-30.92	-30.89	-30.89	-30.90	-30.91	
	4319_100_023	-135.15	-135.12	-135.13	-135.14	-135.14	
	4319_100_024	105.28	105.25	105.26	105.26	105.27	
	4319_100_030	-162.04	-162.01	-162.02	-162.02	-162.03	
	4319_100_031	-73.79	-73.77	-73.77	-73.77	-73.78	
	4319_100_028	-228.95	-228.93	-228.94	-228.93	-228.94	
	4525_203_036	186.13	186.13	186.11			
	4525_203_042	-155.06	-155.05	-155.07			
1_C01_A01_A_1	4525_203_004	-157.93	-157.91	-157.94			
	4525_203_008	119.42	119.42	119.41			
	4525_203_009	-2.92	-2.92	-2.93			
	4525_203_015	-12.20	-12.19	-12.21			
	4525_203_018	-112.00	-112.01	-112.01			
	4525_203_027	-110.00	-110.01	-110.02			
	4525_203_029	200.26	200.25	200.26			
	4525_203_003	25.04	25.05	25.03			
	4525_203_033	116.20	116.21	116.20			
	4490_100_010	-20.53	-20.51	-20.51	-20.51	-20.53	
1_C01_A01_A_2	4490_100_013	-69.78	-69.77	-69.77	-69.78	-69.79	
	4490_100_017	-76.55	-76.55	-76.55	-76.56	-76.55	
	4490_100_023	-79.48	-79.47	-79.50	-79.48	-79.49	
	4490_100_024	78.43	78.42	78.44	78.44	78.43	
	4490_100_025	-44.98	-44.98	-44.99	-44.99	-44.98	

Family ID: 1_C03_A01_A_2

Data # in chart	Index code	Normal value (mm)	First measurement	Tolerance value	Transformed value
1	4319_100_004	131.61	131.59	0.02	-1
2	4319_100_005	-0.84	-0.82	0.02	-1
3	4319_100_023	-30.92	-30.89	0.02	-1.5
4	4319_100_024	-135.15	-135.12	0.02	-1.5
5	4319_100_030	105.28	105.25	0.02	-1.5
6	4319_100_031	-162.04	-162.01	0.02	-1.5
7	4319_100_028	-73.79	-73.77	0.02	-1
8	4319_100_042	-228.95	-228.93	0.02	-1
9	4319_100_006	186.13	186.13	0.02	-1
10	4525_203_036	-155.06	-155.05	0.02	-0.5
Data # in chart	**Index code**	**Normal value (mm)**	**Second measurement**	**Tolerance value**	**Transformed value**
11	4319_100_004	131.61	131.59	0.02	-1
12	4319_100_005	-0.84	-0.83	0.02	-1
13	4319_100_023	-30.92	-30.89	0.02	-1
14	4319_100_024	-135.15	-135.13	0.02	-1
15	4319_100_030	105.28	105.26	0.02	-1
16	4319_100_031	-162.04	-162.02	0.02	-0.5
17	4319_100_028	-73.79	-73.77	0.02	-1
18	4319_100_042	-228.95	-228.94	0.02	-0.5
19	4319_100_006	186.13	186.11	0.02	-1
20	4525_203_036	-155.06	-155.07	0.02	-0.5
Data # in chart	**Index code**	**Normal value (mm)**	**Third measurement**	**Tolerance value**	**Transformed value**
21	4319_100_004	131.61	131.59	0.02	-1
22	4319_100_005	-0.84	-0.83	0.02	-1
23	4319_100_023	-30.92	-30.90	0.02	-1
24	4319_100_024	-135.15	-135.14	0.02	-1
25	4319_100_030	105.28	105.26	0.02	0.5
26	4319_100_031	-162.04	-162.02	0.02	0.5
27	4319_100_028	-73.79	-73.77	0.02	0.5
28	4319_100_042	-228.95	-228.93	0.02	0.5
Data # in chart	**Index code**	**Normal value (mm)**	**Fourth measurement**	**Tolerance value**	**Transformed value**
29	4319_100_004	131.61	131.60	0.02	0.5
30	4319_100_005	-0.84	-0.83	0.02	0.5
31	4319_100_023	-30.92	-30.91	0.02	0.5
32	4319_100_024	-135.15	-135.14	0.02	0.5
33	4319_100_030	105.28	105.27	0.02	0
34	4319_100_031	-162.04	-162.03	0.02	0.5
35	4319_100_028	-73.79	-73.78	0.02	-1
36	4319_100_042	-228.95	-228.94	0.02	-0.4

Family ID: 1_C01_A01_A_1

Data # in chart	Index code	Normal value (mm)	First measurement	Tolerance value	Transformed value
1	4525_203_008	-157.93	-157.91	0.02	1
2	4525_203_009	119.42	119.42	0.02	0
3	4525_203_015	-2.92	-2.92	0.02	0
4	4525_203_018	-12.20	-12.19	0.02	0.5
5	4525_203_027	-112.00	-112.01	0.02	-0.5
6	4525_203_029	-110.00	-110.01	0.02	-0.5
7	4525_203_003	200.26	200.25	0.02	-0.5
8	4525_203_033	25.04	25.05	0.02	0.5
9	4490_100_010	116.20	116.21	0.02	0.5
10	4525_203_004	-20.53	-20.51	0.02	1
11	4490_100_023	-79.48	-79.47	0.02	0.5
12	4490_100_024	78.43	78.42	0.02	-0.5
13	4490_100_025	-44.98	-44.98	0.02	0
Data # in chart	**Index code**	**Normal value (mm)**	**Second measurement**	**Tolerance value**	**Transformed value**
14	4525_203_008	-157.93	-157.94	0.02	-0.5
15	4525_203_009	119.42	119.41	0.02	-0.5
16	4525_203_015	-2.92	-2.93	0.02	-0.5
17	4525_203_018	-12.20	-12.21	0.02	-0.5
18	4525_203_027	-112.00	-112.01	0.02	0.5
19	4525_203_029	-110.00	-110.02	0.02	-1
20	4525_203_003	200.26	200.26	0.02	0
21	4525_203_033	25.04	25.03	0.02	-0.5
22	4490_100_010	116.20	116.20	0.02	0
23	4525_203_004	-20.53	-20.51	0.02	1
24	4490_100_023	-79.48	-79.50	0.02	-1
25	4490_100_024	78.43	78.44	0.02	0.5
26	4490_100_025	-44.98	-44.99	0.02	0
Data # in chart	**Index code**	**Normal value (mm)**	**Third measurement**	**Tolerance value**	**Transformed value**
27	4490_100_010	116.20	116.22	0.02	1
28	4490_100_023	-79.48	-79.48	0.02	0
29	4490_100_024	78.43	78.44	0.02	0.5
30	4490_100_025	-44.98	-44.99	0.02	-0.5
Data # in chart	**Index code**	**Normal value (mm)**	**Fourth measurement**	**Tolerance value**	**Transformed value**
31	4490_100_010	116.20	116.20	0.02	0
32	4490_100_023	-79.48	-79.49	0.02	-0.5
33	4490_100_024	78.43	78.43	0.02	0
34	4490_100_025	-44.98	-44.98	0.02	0

Family ID: 1_C01_A01_A_2

Data # in chart	Index code	Normal value (mm)	First measurement	Tolerance value	Transformed value
1	4490_100_013	-69.78	-69.77	0.02	0.5
2	4490_100_017	-76.55	-76.55	0.02	0
Data # in chart	**Index code**	**Normal value (mm)**	**Second measurement**	**Tolerance value**	**Transformed value**
3	4490_100_013	-69.78	-69.77	0.02	0.5
4	4490_100_017	-76.55	-76.55	0.02	0
Data # in chart	**Index code**	**Normal value (mm)**	**Third measurement**	**Tolerance value**	**Transformed value**
5	4490_100_013	-69.78	-69.78	0.02	0
6	4490_100_017	-76.55	-76.56	0.02	-0.5
Data # in chart	**Index code**	**Normal value (mm)**	**Fourth measurement**	**Tolerance value**	**Transformed value**
7	4490_100_013	-69.78	-69.79	0.02	0.5
8	4490_100_017	-76.55	-76.55	0.02	0

Appendix D

3-way ANOVA Model

(Montgomery, D.C. and Runger, G. C., Applied statistics and probability for engineers, 2002)

Many experiments involve more than two factors, where there are a levels of factor A, b levels of factor B, c levels of factor c, and so on, arranged in a factorial experiment. In general, there will be abc … n total observations, if there are n replicates of the complete experiment. For example, consider the three-factor-factorial experiment, the observation in the *ijk*th cell for the *l*th replicates is denoted by Y_{ijkl} with underlying linear statistical model

$$Y_{ijkl} = \mu + \tau_i + \beta_j + \gamma_k + (\tau\beta)_{ij} + (\tau\gamma)_{ik} + (\beta\gamma)_{jk} + (\tau\beta\gamma)_{ijk} + \varepsilon_{ijkl} \begin{cases} i = 1,2,\ldots a \\ j = 1,2,\ldots b \\ k = 1,2,\ldots c \\ l = 1,2,\ldots n \end{cases}$$

Where μ is the overall mean effect, τ_i is the effect of the *i*th level of factor A, β_j is the effect of the *j*th level of factor B, γ_k is the effect of the *k*th level of factor C, $(\tau\beta)_{ij}$ is the effect of the interaction between A and B, $(\tau\gamma)_{ik}$ is the effect of the interaction between A and C, $(\beta\gamma)_{jk}$ is the effect of the interaction between B and C, $(\tau\beta\gamma)_{ijk}$ is the effect of the interaction between A, B, and C, and ε_{ijkl} is a random error component having a normal distribution with mean zero and variance σ^2. We are interested in testing the hypotheses of no main effect for factor A, no main effect for B, and C, and no interaction effects. The analysis of variance (ANOVA) will be used to test these hypotheses as shown in Table

Appendix C-1. Note that there must be at least two replicates (n≥2) to compute an error sum of squares. The F-test on main effects and interactions follows directly from the expected mean squares. These ratios follow F distribution under the respective null hypotheses.

Table Appendix C-1 ANOVA table for a three-factor factorial, fixed-effects model

Source of variation	**Sum of Squares**	**Degrees of freedom**	**Mean square**	**Expected mean squares**	**F_0**
A	SS_A	a-1	MS_A	$\sigma^2 + \frac{bcn\sum\tau_i^2}{a-1}$	$\frac{MS_A}{MS_E}$
B	SS_B	b-1	MS_B	$\sigma^2 + \frac{acn\sum\beta_j^2}{b-1}$	$\frac{MS_B}{MS_E}$
C	SS_C	c-1	MS_C	$\sigma^2 + \frac{abn\sum\gamma_k^2}{c-1}$	$\frac{MS_C}{MS_E}$
AB	SS_{AB}	(a-1)(b-1)	MS_{AB}	$\sigma^2 + \frac{cn\sum\sum(\tau\beta)_{ij}^2}{(a-1)(b-1)}$	$\frac{MS_{AB}}{MS_E}$
AC	SS_{AC}	(a-1)(c-1)	MS_{AC}	$\sigma^2 + \frac{bn\sum\sum(\tau\gamma)_{ik}^2}{(a-1)(c-1)}$	$\frac{MS_{AC}}{MS_E}$
BC	SS_{BC}	(b-1)(c-1)	MS_{BC}	$\sigma^2 + \frac{an\sum\sum(\beta\gamma)_{jk}^2}{(b-1)(c-1)}$	$\frac{MS_{BC}}{MS_E}$
ABC	SS_{ABC}	(a-1)(b-1)(c-1)	MS_{ABC}	$\sigma^2 + \frac{n\sum\sum\sum(\tau\beta\gamma)_{ijk}^2}{(a-1)(b-1)(c-1)}$	$\frac{MS_{ABC}}{MS_E}$
Error	SS_E	abc(n-1)	MS_E	σ^2	
Total	SS_T	abcn-1			

The analysis of variance assumes that the observations are normally and independently distributed with the same variance for each treatment or factor level. These assumptions should be checked by examining the residuals. A *residual* is the difference between an observation y_{ijkl} and its estimated (or fitted) value from the statistical model being studied, denoted as $\hat{y}_{ijkl}$. For the completely randomized design, $\hat{y}_{ijkl} = \bar{y}_{ijk\bullet}$ and each residual is $e_{ijkl} = y_{ijkl} - \bar{y}_{ijk\bullet}$, that is, the difference between an observation and the corresponding observed treatment mean.

The normality assumption can be checked by constructing a *normal probability plot* of residuals. To check the assumption of equal variance at each factor level, plot the residuals against the factor levels and compare the spread in the residuals. It is also useful to plot the residuals against $\bar{y}_{ijk\bullet}$ (sometimes called the fitted value); the variability in the residuals should not depend in any way on the value of $\bar{y}_{ijk\bullet}$. When a pattern appears in these plots, it usually suggests the need for a transformation, that is, analyzing the data in a different metric. For example, if the variability in the residuals increase with $\bar{y}_{ijk\bullet}$, a transformation such as $\log y$ or $\sqrt{y}$ should be considered.

The independence assumption can be checked by plotting the residuals against the time or run order in which the experiment was performed. A pattern in this plot, such as sequences of positive and negative residuals, may indicate that the observations are not independent. This suggests that time or run order is important or that variables that change over time are important and have not been included in the experiment design.

Most statistics software package will construct these plots on request.