Process Capability Studies in Theory and Practice

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by

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The work presented in this thesis is carried out at the Division of Quality Technology and Statistics, Luleå University, during 1995 and 1996. However, my interest in the concept of process capability studies started already in December 1992, when I joined the division. I want to thank the people who have made the research possible.

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ABSTRACT

The existence of variation has been a major problem within industry since the early days of the industrial revolution and perhaps even earlier. The fact that two parts not ever will be identical, forces every organisation to find a strategy for how to master variation. Process capability studies, a method designed to judge whether a process is capable or not, often plays an important part in such a strategy.

The concept of process capability studies has received both positive and negative criticism during the last decade. For instance, the supporters of process capability studies emphasise the importance of using the method to identify improvement priorities to be focused in the overall improvement process within an organisation.

However, as all methods, process capability studies has its limitations. Actually, it is not principally the method as such that has been criticised, but rather the measures of capability used when conducting process capability studies, the so called process capability indices. All existing process capability indices have some weaknesses, even the most sophisticated indices have relatively poor statistical properties which might lead the user to make incorrect decisions, even if most theoretical aspects of how to conduct process capability studies are known by the user. The use of process capability indices is for instance partly based on the assumption that the process output is normally distributed, a condition that is often not fulfilled in practice, where it is common that the process output is more or less skewed.

This thesis focuses on process capability studies in both theory and practice. In part 1 of the thesis some theoretical aspects of how to conduct process capability studies are identified and then the adherence to these aspects within Swedish industry is investigated. This study reveals that there are certain gaps between how process capability studies are supposed to be conducted according to theory and the way they actually are carried out in practice. The study also tries to explain why these gaps exist, by analysing common obstacles when implementing and conducting process capability studies.

In part 2, a simulation study focusing on the effects of skewness on estimates of some process capability indices belonging to the family of indices named $C_p(u,v)$ is presented. The effects of skewness are studied in three different cases, one incapable case, one case just capable and one very capable case. In all cases, four lognormal distributions with different skewness are used. The results from the simulation study indicate that the effect of skewness is relatively systematic, and therefore there are some hope that future investigations might use these results when formulating some practical solution to the problem of how to use process capability indices when the process monitored has a skewly distributed output.

Finally, the results are summarised and discussed and some suggestions for future research are given.

Keywords: Process capability studies; process capability analysis; process capability indices; variation; implementation; obstacles; non-normality; skewness.
# TABLE OF CONTENTS

Acknowledgement .......................................................... 1
Abstract ........................................................................... II

1 INTRODUCTION ........................................................................... 1
  1.1 Background .................................................................... 1
  1.2 Definitions of the concepts vital for the thesis ..................... 3
  1.3 Theoretical framework ...................................................... 7
    1.3.1 The importance of target values ................................. 11
    1.3.2 Setting of specifications based on Taguchi's loss function ..................................................... 17
    1.3.3 Process capability studies ........................................... 21
      1 Identify important characteristics, plan the study .......... 23
      2 Establish statistical control, gather data ....................... 23
      3 Assess the capability of the process ............................ 24
      4 Initiate improvement efforts ...................................... 25
    1.3.4 The history of process capability indices .................... 25
    1.3.5 Estimation of process capability indices .................... 29
    1.3.6 Using process capability indices for non-normal distributions ............................................... 31
  1.4 Identification of suitable research topics ........................... 33
  1.5 The objectives of the thesis .............................................. 34
    1.5.1 The structure of the thesis ....................................... 34

PART 1 Process capability studies — some theoretical and practical aspects

2 RESEARCH METHODOLOGY ......................................................... 37
  2.1 The research problem ...................................................... 37
  2.2 A description of the method used ...................................... 38
    2.2.1 Literature review .................................................... 39
    2.2.2 Interviews ................................................................ 40
    2.2.3 Questionnaire design .............................................. 41
      1 Specify the topics of interests ..................................... 42
      2 Construct a preliminary questionnaire ......................... 43
      3 Test the preliminary questionnaire ............................. 44
      4 Revise the questionnaire ............................................ 45
    2.2.4 Questionnaire survey 1 ............................................. 45
    2.2.5 Nonresponse analysis .............................................. 47
    2.2.6 Questionnaire survey 2 ............................................. 48
  2.3 Implications of the method used ........................................ 48
    2.3.1 Validity and reliability of the study using questionnaire 1 ...................................................... 49
    2.3.2 Validity and reliability of the study using questionnaire 2 ...................................................... 50
  2.4 Possible alternative methods ............................................ 51
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1.1</td>
<td>Use capable gauges</td>
<td>52</td>
</tr>
<tr>
<td>3.1.2</td>
<td>Establish statistical control</td>
<td>54</td>
</tr>
<tr>
<td>3.1.3</td>
<td>Conscious gathering of data</td>
<td>57</td>
</tr>
<tr>
<td>3.1.4</td>
<td>Check the distribution of the process output</td>
<td>63</td>
</tr>
<tr>
<td>3.1.5</td>
<td>Simultaneous use of several process capability indices</td>
<td>63</td>
</tr>
<tr>
<td>3.1.6</td>
<td>Use of confidence limits</td>
<td>69</td>
</tr>
<tr>
<td>3.2.1</td>
<td>Implementation aspects of process capability studies</td>
<td>71</td>
</tr>
<tr>
<td>3.2.2</td>
<td>Pressure between organisations to conduct process capability studies</td>
<td>72</td>
</tr>
<tr>
<td>3.2.3</td>
<td>Setting of specifications</td>
<td>73</td>
</tr>
<tr>
<td>3.2.4</td>
<td>Results achieved from using process capability studies</td>
<td>74</td>
</tr>
<tr>
<td>3.2.5</td>
<td>Advantages and disadvantages of conducting process capability studies</td>
<td>74</td>
</tr>
<tr>
<td>4.1.1</td>
<td>A short description of the respondents</td>
<td>75</td>
</tr>
<tr>
<td>4.1.2</td>
<td>Part 1, The respondents' organisations</td>
<td>76</td>
</tr>
<tr>
<td>4.1.3</td>
<td>Part 2, The implementation of process capability studies</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td>Definitions of the concept of capability</td>
<td>79</td>
</tr>
<tr>
<td></td>
<td>Educational efforts</td>
<td>80</td>
</tr>
<tr>
<td>4.1.4</td>
<td>Part 3, Measures of capability used within the respondents' organisations</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>Alternative measures of process capability</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td>Pressure between organisations to conduct process capability studies</td>
<td>86</td>
</tr>
<tr>
<td>4.1.5</td>
<td>Part 4, Setting of specifications</td>
<td>89</td>
</tr>
<tr>
<td>4.1.6</td>
<td>Part 5, Process capability studies within the respondents' organisations</td>
<td>92</td>
</tr>
<tr>
<td></td>
<td>Statistical control prior to the use of process capability studies</td>
<td>97</td>
</tr>
<tr>
<td></td>
<td>Handling of uncertainty</td>
<td>99</td>
</tr>
<tr>
<td></td>
<td>Use of capable gauges</td>
<td>101</td>
</tr>
<tr>
<td></td>
<td>Checking the distribution of the process output</td>
<td>103</td>
</tr>
<tr>
<td>4.1.7</td>
<td>Part 6, Achieved results from process capability studies</td>
<td>105</td>
</tr>
<tr>
<td></td>
<td>Different applications of the result from process capability studies</td>
<td>107</td>
</tr>
<tr>
<td>4.1.8</td>
<td>Part 7, Advantages and disadvantages of process capability studies</td>
<td>113</td>
</tr>
<tr>
<td>4.2</td>
<td>Nonresponse analysis</td>
<td>115</td>
</tr>
<tr>
<td>4.3</td>
<td>Conclusions</td>
<td>122</td>
</tr>
<tr>
<td>4.3.1</td>
<td>Theoretical aspects</td>
<td>122</td>
</tr>
<tr>
<td>4.3.2</td>
<td>Practical aspects</td>
<td>127</td>
</tr>
<tr>
<td>4.4</td>
<td>Generalisation of results</td>
<td>130</td>
</tr>
</tbody>
</table>
### 5 Obstacles when using process capability studies

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1 Questionnaire survey 2</td>
<td>132</td>
</tr>
<tr>
<td>5.1.1 Analysis of questionnaire 2, question 2</td>
<td>132</td>
</tr>
<tr>
<td>Management issues</td>
<td>134</td>
</tr>
<tr>
<td>Facts of reality</td>
<td>135</td>
</tr>
<tr>
<td>Traditional personal attitudes</td>
<td>136</td>
</tr>
<tr>
<td>Methodological aspects</td>
<td>136</td>
</tr>
<tr>
<td>5.1.2 Analysis of questionnaire 2, question 1</td>
<td>137</td>
</tr>
<tr>
<td>Management issues</td>
<td>138</td>
</tr>
<tr>
<td>Facts of reality</td>
<td>138</td>
</tr>
<tr>
<td>Traditional personal attitudes</td>
<td>138</td>
</tr>
<tr>
<td>Methodological aspects</td>
<td>139</td>
</tr>
<tr>
<td>5.1.3 Conclusions from questionnaire 2</td>
<td>139</td>
</tr>
</tbody>
</table>

### Part 2 The effect of skewness on some process capability indices

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 Process capability indices and non-normal distributions</td>
<td>143</td>
</tr>
<tr>
<td>6.1 The basic problem of non-normality</td>
<td>143</td>
</tr>
<tr>
<td>6.2 Effects of non-normality</td>
<td>144</td>
</tr>
<tr>
<td>6.3 Construction of process capability indices for non-normally</td>
<td>146</td>
</tr>
<tr>
<td>distributed characteristics</td>
<td>146</td>
</tr>
<tr>
<td>6.3.1 &quot;Distribution free&quot; process capability indices</td>
<td>147</td>
</tr>
<tr>
<td>6.3.2 Transformation of data</td>
<td>147</td>
</tr>
<tr>
<td>6.3.3 Clements' method</td>
<td>149</td>
</tr>
<tr>
<td>6.3.4 The Pearn-Kotz-Johnson method</td>
<td>151</td>
</tr>
<tr>
<td>6.3.5 Bootstrap methods</td>
<td>152</td>
</tr>
<tr>
<td>6.3.6 Flexible process capability indices</td>
<td>153</td>
</tr>
<tr>
<td>6.3.7 Wright's process capability index</td>
<td>154</td>
</tr>
<tr>
<td>6.4 A discussion on the methods developed for handling non-normal situations</td>
<td>155</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 The methodology of the simulation study</td>
<td>156</td>
</tr>
<tr>
<td>7.1 Research questions of interest</td>
<td>156</td>
</tr>
<tr>
<td>7.2 The method used</td>
<td>157</td>
</tr>
<tr>
<td>7.2.1 Base for comparison</td>
<td>157</td>
</tr>
<tr>
<td>7.2.2 Choice of simulation cases</td>
<td>158</td>
</tr>
<tr>
<td>7.2.3 Choice of process capability indices</td>
<td>160</td>
</tr>
<tr>
<td>7.2.4 The simulation routine</td>
<td>161</td>
</tr>
<tr>
<td>7.2.5 Validity and reliability of the simulation study</td>
<td>161</td>
</tr>
</tbody>
</table>
8 ANALYSIS AND RESULTS ........................................................................................................ 163
8.1 Base for analysis .................................................................................................................. 163
8.2 The effect of skewness on statistical properties of the estimated
process capability indices ........................................................................................................ 165
  8.2.1 Effects of skewness on the dispersion of estimates of
  process capability indices ....................................................................................................... 165
  8.2.2 Effects of skewness on the bias of estimates of
  process capability indices ....................................................................................................... 169
8.3 Suitable $u$- and $v$-values of $C_p(u,v)$ when the studied
characteristic is skewly distributed ......................................................................................... 172
8.4 The ability of $C_{p_{mk}}$ to differ capable processes from
non-capable processes ................................................................................................................ 175
8.5 Summary of results from the simulation study ..................................................................... 178
  8.5.1 Practical significance of the results ............................................................................. 179

PART 3 Discussion, conclusions and future research

9 DISCUSSION, CONCLUSIONS AND FUTURE RESEARCH .................................................................................... 183
  9.1 A discussion on the thesis’ results and conclusions ......................................................... 183
  9.2 Suggestions for future research ....................................................................................... 186

REFERENCES .......................................................................................................................................... 189

Enclosures  

<table>
<thead>
<tr>
<th>Enclosure</th>
<th>Number of pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enclosure 1: Design of questionnaire 1</td>
<td>1</td>
</tr>
<tr>
<td>Enclosure 2: Introductory letter to questionnaire 1</td>
<td>1</td>
</tr>
<tr>
<td>Enclosure 3a: Questionnaire 1</td>
<td>10</td>
</tr>
<tr>
<td>Enclosure 3b: Nonresponse questionnaire</td>
<td>1</td>
</tr>
<tr>
<td>Enclosure 4: Questionnaire 2</td>
<td>1</td>
</tr>
<tr>
<td>Enclosure 5: Analysis of questionnaire 2</td>
<td>2</td>
</tr>
<tr>
<td>Enclosure 6: Initial simulation parameters</td>
<td>2</td>
</tr>
<tr>
<td>Enclosure 7: Simulation routine</td>
<td>1</td>
</tr>
<tr>
<td>Enclosure 8: Bias and standard deviation in all simulation cases</td>
<td>3</td>
</tr>
<tr>
<td>Enclosure 9: The effect of skewness on some process capability indices</td>
<td>4</td>
</tr>
</tbody>
</table>
CHAPTER 1
INTRODUCTION

In this chapter the background of the thesis is given. Definitions of concepts, vital for the thesis, are presented together with a theoretical framework. Some problems concerning process capability studies are discussed together with the objectives of the thesis.

1.1 Background

No one really knows why variation exists, it is just a part of reality. Perhaps it has something to do with the second law of thermodynamics which basically says that everything spreads out. Wheeler & Chambers (1992) presents an axiom which has been apparent from the beginning of man’s efforts to make things, which reads as follows:

*No two things are alike.*

The existence of variation, however, can be both positive and negative. No person looks the same, and most of us find that positive. However, in industry, the word variation does not bring any positive ideas into peoples’ minds. Variation is often the main enemy, even if we do not always realise that. Often, the battle against variation is somewhat unfair. Even how hard we try to eliminate variation, it will always be there. No one has ever conquered and eliminated variation. We can only try to minimise variation, and the effects of it. The best plans possible, in the battle against variation, is either to minimise variation to be so insignificant that it does not in any way effect the performance of our product, or we can construct the product in such a way that it will be robust against any variation. The best strategy is perhaps to use both these plans simultaneously. Even if these plans sound simple enough, those who have tried to pursue them, have found how hard and difficult the struggle sometimes can be.

Even if two similar processes are controlled in the same way, their output will not be identical. One part will never be an identical copy of the other, which already has been implied by the axiom above. Tra-
Additionally, industry has tried to handle this problem by setting specification limits for important characteristics of a specific product. If a characteristic of a product is within these pre-set specification limits, then that specific product is claimed capable.

As time has passed, focus has moved from claiming a specific product capable, to claiming the actual production processes capable. Since the 1980’s a theoretical framework has been established to judge whether a process is capable or not. These studies are often called process capability studies or process capability analysis. Specific measures, called process capability indices, that compare the actual process output with the specification limits for a certain characteristic, have been developed.

The concept of process capability studies has received both positive and negative criticism during the last decade. The supporters of process capability studies emphasise for instance the importance of using the method for identifying improvement priorities to be focused in the overall improvement process. Other supporters point out the possibility of overall goal setting based on the concept of process capability studies. This has been utilised successfully within companies such as Motorola, IBM, ABB and SKF, see, e.g., Pena (1990), McFadden (1993) or Tadikamalla (1994). However, as all methods, process capability studies has its limitations. Actually, it is not mainly the method process capability studies as it is, that has been criticised, but rather the measures of capability used when conducting process capability studies, the so called process capability indices, see, e.g., Gunter (1989a-d), Dovich (1991a-b), Burke, Davis & Kaminski (1991) or Pignatiello & Ramberg (1993). All existing process capability indices have some weaknesses, even the most sophisticated indices have relatively poor statistical properties which might lead the user to make incorrect decisions, even if he or she is aware of most theoretical aspects of how to conduct process capability studies. The use of process capability indices is for instance partly based on the assumption that the process output is normally distributed, a condition that is often not fulfilled in practice. On the contrary, it is quite common that the process output is more or less skewly distributed.

This thesis will focus on both problems just described. First of all the theoretical aspects of how to conduct process capability studies will be identified and then the adherence to these aspects in practice will be checked. Finally, the thesis will focus on statistical properties of process capability indices in a study aimed at analysing the effects of skewness on estimates of the process capability indices most commonly used.
1.2 Definitions of the concepts vital for the thesis

In order to understand the contents of this thesis there are primarily two concepts that need to be defined. The first one is the concept of quality and the second one is the concept of capability. Since neither of these concepts have any universally accepted definition, the definitions used in each situation have to be carefully chosen. Let us first concentrate on a suitable definition of quality and then focus on a proper definition of capability and lastly try to see how these concepts fit together in this thesis.

The word "quality" is derived from Latin, and according to Ahlberg, Lundqvist & Sörbom (1966), it means "of what". However, the ancient meaning of the word cannot serve as a useful definition of quality today. The fact that the concept of quality is hard to define is proved by the abundance of definitions used. Garvin (1984) discusses the problem of finding a proper definition of the quality concept. According to him one reasonable explanation to all these definitions of the quality concept is that it has been considered in the four disciplines, philosophy, economics, marketing and operations management. However, each group has viewed it from a different vantage point. Philosophy has focused on definitional issues; economics on profit maximisation and market equilibrium; marketing on the determinants of buying behaviour and customer satisfaction; and operations management on engineering practices and management control. The result has been a host of competing perspectives, each based on a different analytical framework and each employing its own terminology. However, Garvin (1984) manages to find five approaches to define quality, which are described in figure 1.1.

Figure 1.1 Five different approaches to defining quality can be identified: 1 the transcendent approach of philosophy, 2 the product-based approach of economics, 3 the user-based approach of economics, marketing and operations management and 4 the manufacturing-based and 5 value-based approaches of operations management. Inspired by Garvin (1984).
Chapter 1, Introduction

The five approaches of defining quality in figure 1 are described below.

1 **The transcendent approach:** Proponents of this view claim that quality cannot be defined precisely, rather it is a simple unanalyzable property that we learn to recognise only through experience. According to Garvin (1984) this definition borrows heavily from Plato’s discussion of beauty. According to the transcendent approach quality can only be understood after one is exposed to a succession of objects that display its characteristics.

2 **The product-based approach:** Product-based definitions are quite different. They view quality as a precise and measurable variable. According to this view, differences in quality reflect differences in the quality of some ingredient or attribute possessed by a product. Product-based definitions of quality first appeared in the economics literature, where they were quickly incorporated into theoretical models. There are two obvious corollaries to this approach. Firstly, higher quality can only be obtained at a higher cost and, secondly, quality is viewed as an inherent characteristic of goods, rather than as something ascribed to them.

3 **The user-based approach:** User-based definitions start from the opposite premise that quality "lies in the eyes of the beholder". Individual consumers are assumed to have different wants or needs, and those goods that best satisfy their preferences are those that they regard as having the highest quality. By using this definition, two major problems will occur. The first one is practical – how to aggregate widely varying individual preferences so that they lead to meaningful definitions of quality at the market level. The second one is more fundamental – how to distinguish those product attributes that connote quality from those that simply maximise consumer satisfaction. The first problem is usually solved by some sort of market segmentation and the second problem by surveys of customer preferences within each segment.

4 **The manufacturing-based approach:** User-based definitions of quality incorporate subjective elements since they are rooted in customer preferences – the determinants of demand. In contrast, manufacturing-based definitions focus on the supply side of the equation, and are primary concerned with engineering and manufacturing practice. Virtually all manufacturing-based definitions identify quality as "conformance to requirements". Once a design or a specification has been
established, any deviation implies a reduction of quality. Excellence is equated with meeting specifications, and with "making it right the first time". In the manufacturing-based approach, quality is defined in a manner that simplifies engineering and production control. According to the manufacturing based approach, improvements in quality, which are equivalent to reduction in the number of deviations, lead to lower costs, since preventing defects is viewed as less expensive than repairing or reworking them.

5 The value-based approach: Value-based definitions define quality in terms of cost and price. According to this view, a quality product is one that provides performance at an acceptable price or conformance at an acceptable cost. The difficulty in employing this approach lies in its blending of two related but distinct concepts. Quality, which is a measure of excellence, is being equated with value, which is a measure of worth. According to Garvin (1984) the result is a hybrid – "affordable excellence" – that lacks well-defined limits and is difficult to apply in practice.

Garvin (1984) reaches an interesting conclusion when he states that a company cannot find a definition of quality suitable for the whole company. The approaches to quality need to shift as products move from design to market. The characteristics that connote quality must first be identified through market research, a user-based approach to quality, these characteristics must then be translated into identifiable product attributes, a product-based approach to quality, and the manufacturing processes must then be organised to ensure that products are made precisely according to these specifications, a manufacturing based approach to quality. A process that ignores any of these steps will not result in a quality product.

Since this thesis heavily emphasises the manufacturing side of a company, a manufacturing-based definition of quality is suitable. Gilmore (1974) gives the following manufacturing-based definition which is to be regarded as the definition of quality relevant for this thesis.

Quality is the degree to which a specific product conforms to a design or specification.

By using this definition, it is taken for granted that the preferences of the deliberately chosen customer segment have been identified and translated into identifiable product attributes, which then have been translated into exact specifications for each product attribute.
The argumentation above implies that finding a suitable definition of the quality concept is indeed very complicated since the concept has so many different meanings in different situations. When trying to establish a definition of the capability concept it has been just as difficult as for the concept of quality since definitions of the concept of capability are hard to come by. Therefore, a suitable definition of the concept of capability has been established during the study presented in this thesis. This definition is presented here:

*Capability is the ability of a process to produce products according to specified requirements.*

By looking at the definitions chosen it is clear that the definition of quality is product oriented while the definition of capability is process oriented. Therefore, the definitions of quality and capability do not become complete until some comment is made on what is meant by product and process.

In this thesis the term product has the same meaning as it has in SS-EN-ISO 8402:1994:

*A product is the result of activities or processes.*

This definition of a product implies that a product may include service, hardware, processed materials, software, or a combination thereof.

A suitable definition of process can also be found in SS-EN-ISO 8402:1994:

*A process is a set of interrelated resources and activities which transforms inputs into outputs.*

This is a very wide definition of a process which might lead us to picturing a process as for instance being every activity from ore-mining to the moment when a car leaves the factory. However, when reading this thesis it is wise to bear in mind that a process capability study only monitors a certain characteristic produced by a single machine forming a process of its own, if not multivariate process capability indices are used. Sometimes the monitored characteristic indirectly reflects the output of several machines before the one studied and sometimes the monitored characteristic only reflects the output of one single machine.

Another concept that deserves a closer definition in this thesis is the concept of Total Quality Management, usually denoted TQM. According to Bergman & Klefsjö (1995), Total Quality Management can be defined as:
Chapter 1, Introduction

A constantly changing system of values, tools, and methods aiming at increasing customer satisfaction. It is a never ending improvement process within all parts of an organisation, encouraging all employees to take part.

A strategy for how to master variation including methods such as process capability studies can be viewed as a part of Total Quality Management.

1.3 Theoretical framework

The existence of variation has been troublesome since man’s first efforts to make products. There has always been a need to have some strategy for handling variation. The need for such a strategy became even more important as the industrial revolution appeared.

Jaikumar (1988) studies the evolution of process control by performing a case study at Beretta which was founded in 1492 and has been engaged in the manufacture of firearms ever since. While the product has not changed much, the processes for making a rifle have. Thus, Jaikumar’s case study provides as close to a controlled experimental study of the evolution of process control as one could have. Jaikumar (1988) identifies six epochs of the development of process control at Beretta. These six epochs are:

1. The invention of machine tools and the English System of Manufacture (1800).
2. Special purpose tools and interchangeability of components in the American System of Manufacture (1850).
5. Information processing and the era of Numerical Control.

All six epochs were triggered by technology developed outside the firm. Therefore, the six epochs give a fair description of the world-wide development of process control.

One example of what this development has meant for industry can be described by studying the amount of rework as fraction of the total work during the stages of this development, see table 1.
Chapter 1, Introduction

Table 1.1 The development of process control can be divided into six epochs. The table describes the rework as fraction of total work experienced at Beretta during each one of these six epochs. From Jaikumar (1988).

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Rework as fraction of total work</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 English System</td>
<td>0.8</td>
</tr>
<tr>
<td>2 American System</td>
<td>0.5</td>
</tr>
<tr>
<td>3 Taylor Scientific Management</td>
<td>0.25</td>
</tr>
<tr>
<td>4 Statistical Process Control</td>
<td>0.08</td>
</tr>
<tr>
<td>5 Numerical Control Era</td>
<td>0.02</td>
</tr>
<tr>
<td>6 Computer Integrated Manufacturing</td>
<td>0.005</td>
</tr>
</tbody>
</table>

From reworking almost every detail in the 17th century the development of process control, together with the development of machine technologies, better materials and new managerial ideologies, has lead to that today, only a few parts per million of the products are reworked.

Since this thesis focuses on process capability studies, which is a method that combines statistical concepts, it is of importance to describe the role of statistics in the development of process control. Thereby, epoch number 4 in table 1, Statistical Process Control, is of special interest.

The first real attempt to master variation in a scientific way was made by Walter A. Shewhart in the early 1920's. Shewhart successfully brought together the disciplines of statistics, engineering and economics when he formed the concept of modern statistical process control. In his monumental work, Economic Control of Quality of Manufactured Product, see Shewhart (1931), he presented a strategy for how to deal with variation. Shewhart (1931) looked at variability as being either within limits set by chance, or outside those limits. If it was outside he believed that the source of variation could be identified. This viewpoint had its basis in his studies of the laws of variation in nature. According to Wheeler & Chambers (1992), Shewhart found that when he used statistics to describe variation in processes of nature he frequently reached the conclusion that there were some form of stability. When applying the same principles to manufactured data, he found that such data did not always behave the same way that natural data did. Out of this inconsistency he formulated a distinction which, according to Wheeler and Chambers (1992), can be phrased as follows:
While every process displays variation, some processes display controlled variation, while others display uncontrolled variation.

Controlled variation is characterised by a stable and consistent pattern of variation over time. Shewhart (1931) attributed such variation to "chance" causes. Uncontrolled variation is characterised by a pattern of variation that changes over time. Shewhart (1931) attributed these changes in the pattern of variation to "assignable" causes. In very few words Shewhart's strategy for handling variation is first of all based on identifying the assignable causes of variation and then eliminating them. Only when the assignable causes of variation are eliminated it is possible to make some predictions about the behaviour of the process within the near future. Shewhart (1931) noted that:

A phenomenon will be said to be controlled when, through the use of past experience, we can predict, at least within limits, how the phenomenon may be expected to vary in the future.

As long as a process displays uncontrolled variation planning, production and management will be filled with uncertainty. Therefore, the improvement process should start with eliminating assignable causes of variation. Only after this is achieved, efforts can be made to try to see some patterns in the chance causes, patterns that will lead to that chance causes by time will turn into assignable causes and thereby be possible to eliminate. Shewhart's strategy for handling variation implies that there is no end to the improvement process. There are always some chance causes left to be explained and thereby turned into assignable causes which can be eliminated. Thereby Shewhart already in the 1920's laid the very foundation of modern Total Quality Management, which is based on a philosophy of continuous improvements and a conviction that it is always possible to improve quality and at the same time reduce costs.

Shewhart did not only present a strategy for handling variation, but he also provided a powerful tool to use in the improvement process, the control chart, often referred to as the Shewhart control chart. The Shewhart control charts are based on a combination of probability and practical experience, and are effective at detecting the presence of uncontrolled variation in any process. Shewhart presented his first control chart in 1924. Unfortunately, his ideas were not widely known or used in industry since few managers and engineers at that time had any training in statistics. During the Second World War, control charts were used within the United State's industry and during the 1950's industries
in Japan started to use control charts on regular basis. Today the use of control charts is spread all over the world.

When looking at Shewhart’s definition of statistical control presented above it is obvious that the essence of statistical control is predictability. A process is predictable when it is in a state of statistical control, and it is unpredictable when it is not in a state of statistical control. Since the decision of whether a process is stable or unstable is to be based upon past experience, it follows that one will need to begin with data generated by the process in question. When a reasonable amount of these data has been accumulated they are used to calculate appropriate control limits. If the historical data fall within these limits, and if data collected after the limits have been calculated also stay within these historical limits, then it becomes reasonable to make a prediction regarding future observations. These limits are chosen in such a way that false alarms become rare. Usually the control limits are placed three sigma-units above and below the central line of the control chart, see figure 1.2. If we use three sigma-limits and the process characteristic monitored is normally distributed and in statistical control the risk of false alarm will be as low as 0.0027, which has been regarded as an acceptable risk. However, Wheeler & Chambers (1992) claim that Shewhart’s choice of using three-sigma limits was definitely not solely based upon probability theory. The strongest justification of the three-sigma limits is the empirical evidence that three sigma-limits work well in practice, that they provide effective action limits when applied to real world data.
Quality characteristic monitored

UCL

Three sigma-units

CL

Three sigma-units

LCL

Figure 1.2 The basic principles of Shewhart’s control charts. The characteristic monitored is controlled within an upper control limit (UCL) and a lower control limit (LCL). The distance between the central line (CL) and the lower and upper control limits is three sigma-units for the monitored quality characteristic. If all plotted points fall within these limits the monitored process is assumed stable, and if some point falls outside the control limits, then there is reason to believe that the process is unstable.

The most common control charts are the $\bar{x}$-R-diagrams. The $\bar{x}$-diagram is used for monitoring the location of the process while the $R$-diagram is used for monitoring the dispersion of the process. Today, there is a multitude of different control charts developed for all possible situations. However, the main purpose of these charts is to provide a tool which can help differentiate between stable and unstable processes and at the same time indicate how the process might be improved. Many books have been written on the subject of control charts and statistical process control, see, e.g., Shewhart (1931), Duncan (1986), Wadsworth, Stephens & Godfrey (1986) or Montgomery (1991).

1.3.1 The importance of target values

Variation always creates costs. The further upstream in the production process one works with reducing variation, the lower the cost of variation will be.
Let $X$ denote a performance characteristic for a particular product, and let the target value for $X$ be denoted by $T$. If the target value has been properly defined and if a particular unit of the product has a value of $X = T$, then there should be no problem with that unit. The problems appears when the product performance characteristic is not equal to $T$.

The traditional approach to the problem of product variation has been that of specifications. By using specification limits to define some neighbourhood of $T$, say $T \pm \Delta x$, manufacturers have hoped to place acceptable bounds upon the degradation in performance for the product. Note that the target value does not need to be symmetrically placed in the specification interval. To understand the specification approach and its shortcomings Wheeler & Chambers (1992) present the following example. Consider a stream of units produced and evaluated according to specifications of $T = 100$ and $\Delta x = 10$. The first unit has the value of 108 and is therefore deemed to be satisfactory. The next unit has a value of 102, and is also passed. The third unit has a values of 96 so it is passed. Say, the next unit has a value of 92. It is passed. The fifth unit has a value of 90, which is still within specifications, so it is passed and everything is still deemed to be satisfactory for the production process. However, when the sixth unit has a value of 89 the whole department is thrown into an uproar to find out why they suddenly are making a nonconforming product. Inspectors are sent to inspect all incoming products. Engineers are assigned to project teams to work on the process. Managers consider if a recall is needed and the workers adjust the process to increase the value of $X$. This sudden cascade of actions will of course greatly increase the costs associated with the production of this product. Everyone is so busy with temporary actions that no one discovers that the difference between the fifth unit (90) and the sixth unit (89) was less than any of the differences between earlier successive units, a fact that indicates that all actions taken when a product suddenly falls outside the lower specification limit might have been hasty.

Thus, specification limits are actually artificial boundaries used to make arbitrary decisions about what product to use. Wheeler & Chambers (1992) call them a naive attempt to deal with the problems created by the variation of product characteristics. All products are considered to be either good or bad and the dividing line between good stuff and bad stuff is seen to be a sharp cliff, as indicated by figure 1.3.
Chapter 1, Introduction

Figure 1.3 The loss function for conformance to specifications. The traditional specification concept of quality states that as long as a product is found to be within the specification range, that is the distance between the upper specification limit (USL) and the lower specification limit (LSL), then that product is considered not to increase the loss \( L(x) \). However, if the product is found to be either above or below the specification range, the product is directly thought of as causing a given loss. After Wheeler & Chambers (1992).

The view of how to deal with variation presented in figure 1.3 is still the world view. However, one should notice that this step function is created by a reaction on the part of management, rather than by any sudden and dramatic change in the product characteristic, \( X \). Therefore, the very nature of the specification approach fosters periods of neglect of the process broken by periods of intense process scrutiny. This indicates a need for a different approach to the problem of how to define a suitable loss function was needed.

An attempt to try to find this new approach was made by Genichi Taguchi 1960, see Taguchi (1986). His approach used a well-known mathematical construction in a new setting, and resulted in a powerful new perspective on the problem of variation in production. The heart of Taguchi’s approach is his definition of the concept of quality as the characteristic that avoids loss to society from the time the product is shipped. Loss is measured in terms of money and is linked to the hard technology of the product.
Taguchi’s approach uses the loss function $L(x)$ presented in figure 1.4. The loss function is generally assumed to be
1. non-negative for all values of $x$,
2. equal to zero when $x = T$ and
3. piecewise smooth near $T$.

Under these rather general conditions, one may use a Taylor series expansion to approximate $L(x)$ within some region close to $T$. When this is done the three terms of the approximation are

$$L(x) = L(T) + L'(T)(x - T) + L''(T)(x - T)^2/2.$$ \[(1.1)\]

Assumption (2) results in the first term on the right hand side of (1.1), $L(T)$, being zero. Assumptions (1) and (2) imply that the loss is minimal at $x = T$ and since the first derivative disappears at a minimum, $L'(T) = 0$ and the second term vanishes. Thus, the first non-zero term in the Taylor series expansion for $L(x)$ in the neighbourhood of $T$ is the term involving $(x - T)^2$. From this follows that the simplest form of $L(x)$ is the quadratic function

$$L(x) = K(x - T)^2.$$ \[(1.2)\]

By appropriate consideration of the cost associated with given deviations of $X$ from $T$, one may actually define the value of $K$ for a specific application. While $L(x)$ defines the loss associated with a particular value of $X$, it does not take into account the likelihood that a particular value of $X$ will occur. However, this problem can be solved by using the probability density function $f(x)$ for the studied characteristic. Then $f(x)$, will define the likelihood that $X$ will take on each value along the horizontal axis, while the loss function, $L(x)$ in (1.2), will define the loss for each value of $X$, which is illustrated in figure 1.4. Therefore, the average loss per unit of production will be found by integrating the product of $L(x)$ and $f(x)$. This integral is called the expected value of $L(x)$ and is given by

$$\mathbb{E}[L(x)] = \int_{0}^{\infty} L(x)f(x) \, dx = \int_{0}^{\infty} K(x - T)^2f(x) \, dx = K(\sigma^2 + (\mu - T)^2),$$ \[(1.3)\]
where $\sigma^2$ is the squared standard deviation, or variance, of the distribution of $X$, and $(\mu - T)^2$ is the square of the bias of the distribution of $X$. This result holds regardless of the form of the functional form of $X$.

![Figure 1.4 A quadratic loss function with a product distribution. The average loss per unit of production will be found by integrating the product of $L(x)$ and $f(x)$. After Wheeler & Chambers (1992).](image)

By analysing the equation given in (1.3) it is clear that the average loss due to product variation is seen to be proportional to the square of the process standard deviation and the square of the amount by which the process average deviates from the target value. This means that the average loss will always be minimised by operating on target with minimum variance. The failure to operate a process on target with minimum variance will inevitably result in dramatic increases in the average loss per unit of production. Such losses may be severe and are always unnecessary.

Taguchi (1986) presents his view of specification limits, customer costs and producer costs with the following example. A manufacturer of panes of glass used for greenhouses has found that panes with the thickness of $T$ minimises the customer costs in form of hailstone accidents and producer costs in form of used material at production, see figure 1.5. The thickness $T$ is thereby the target value for production. The specification limits have been chosen as $T \pm 0.20$ mm. If the capability of the process is improved, the producer could use this result for lowering manufacturing costs, in this case lower the use of material. However, instead of aiming at the target value $T$ the producer is aiming at $T - 0.18$ mm. Due to the very widely set specification limits the producer still experiences very little risk of producing defect panes.
According to figure 1.5 the producer receives a profit of \( \alpha \). But at the same time the customer experiences a loss of \( \beta \) which is substantially greater than the producer's profit. Taguchi calls this way of acting, worse that theft! In order to gain a few dollars in the production process the customer is caused a much greater loss. This way of acting is called "quality selection" and is according to Taguchi (1986) widely used among manufacturers.

![Figure 1.5](image.png)

**Figure 1.5** By choosing to set the actual process aim at \( T - 0.18 \) instead of at \( T \), the producer makes a profit of \( \alpha \). However, at the same time the customer makes a loss of \( \beta \) compared to the customer costs when the process is operation on the target value \( T \). Taguchi calls this way of acting "worse than theft!" From Bergman (1992).

Bendell, Disney & Pridemore (1989) present yet another example which emphasises the importance of target values. A couple of years ago a TV set was manufactured by Sony at two different locations. One factory was located in Japan and the other one in the USA. The TV sets were produced according to the same specifications. However, the definition of the TV sets manufactured in the american factory was much worse than on TV sets produced in Japan. When an analysis was performed to monitor the ability of both factories to produce within pre-set specification limits it was found that the TV sets from both factories were within specifications. However, as implied by figure 1.6, in the Japanese factory, most of the units had measurements very close to the target value. The distribution of measurements made on TV sets produced in the american factory shows that some sort of inspection probably had been carried out since the distribution has sharp edges close to
both the upper and lower specification limits. The moral from this example is that often it is not enough to have a very small number of nonconforming units. Often, it is also needed to achieve a very small variation among units produced and at the same time centred the process at the target value.

![Figure 1.6](image)

**Figure 1.6** A schematic illustration of the process output of two identical processes within Sony. One of the processes is from Sony in Japan and one is from Sony in the USA. It was found that the TV sets produced in Japan had much better definition than the ones produced in the USA. This could mainly be explained by the fact that the variation of the Japanese production process was much smaller compared to the American one. From Bendell, Disney & Pridemore (1989).

The Sony-example also points out another postulates of modern quality technology: quality cannot be achieved through inspection.

### 1.3.2 Setting of specifications based on Taguchi’s loss function

Every individual unit of a certain product is exposed to a number of disturbing factors during its entire life. According to Bergman & Klefsjö (1994), Taguchi divides the disturbing factors into the following groups:

- **outer disturbances**, like variations of temperature, voltage fluctuation and other environmental factors during usage

- **inner disturbances**, like wear, tear and deterioration within the individual unit, due to its operation
• *manufacturing variations*, i.e. deviations of the individual unit from the pre-set target value due to manufacturing. This gives variation between units manufactured under the same specification.

Typical for robust design is that even if an individual unit is exposed to disturbances of the above mentioned kinds its function will not be disturbed. In order to reach robust design the design process must be carried out carefully. Taguchi divides the design process into the three phases:

- system design
- parameter design
- specification design.

During system design the actual frame of the product is set. The final result of the system design is a prototype design which can satisfy the customer needs concerning the function, provided that it is not exposed to disturbances.

After the system design is finished target values are chosen for each characteristic of the product. The aim of the parameter design is to achieve the most robust design possible.

During manufacturing the aim is to control the manufacturing process to produce units as close to the target value as possible and with a minimum of variation. Since all production processes are exposed to different kinds of variation it is necessary to set a specification interval for each product characteristic. The Taguchi loss function described in equation (1.1) and (1.2) can be used for choosing proper specification limits. The Taguchi loss function can be written as

(1.4) \[ L(x) = L''(T)(x - T)^2/2. \]

In order to derive an exact loss function which satisfies that \( L(T) = 0 \) and \( L'(T) = 0 \), for a specific characteristic it is necessary to know \( L(x) \) for another point. Taguchi (1986) suggests that a deviation \( \Delta \) from the target value so that 50% of the customers would repair the unit, is suitable to use, see figure 1.7. Any customer who is repairing the unit must experience a loss which is greater than the cost of repair, here denoted by \( A \).
Chapter 1, Introduction

The probability density function for a randomly selected customer at a given deviation $\Delta$.

Figure 1.7 The value of the loss function for $x = T - \Delta$ is the expected cost of the loss that any randomly selected customer would experience at a given deviation of $\Delta$ from the target value $T$. After Bergman (1992).

By choosing the cost of repair equal to $A$ for a given deviation $\Delta$ from the target value we get

$$L(T - \Delta) = (T - \Delta - T)^2 L''(T)/2 = A$$

$$L(T - \Delta) = \Delta^2 L''(T)/2 = A$$

(1.5) \quad L''(T) = \frac{2A}{\Delta^2}.

By using the result from (1.5) in (1.4) we get

(1.6) \quad L(x) = \frac{2A(x - T)^2}{\Delta^2} = \frac{A}{\Delta^2} (x - T)^2.

Assume that a given measure $x$ can be adjusted to the target value $T$ at a given cost $B$. The adjustment is justified economically if

(1.7) \quad \frac{A}{\Delta^2} (x - T)^2 > B.

We shall adjust if
In this case we should use the specification limits $T \pm \delta$ where

$$\delta = \Delta \sqrt{\frac{B}{A}}.$$  

Taguchi’s idea for choosing specification limits is further illustrated in figure 1.8.

\[\text{Figure 1.8} \quad \text{This illustration shows how Taguchi suggests that the specification limits are to be chosen. First the loss function is calculated according to figure 1.6. Then the scrap cost } B \text{ is balanced against the customer loss. If the scrap cost is less than the loss to the customer we should scrap the unit. This strategy gives that the specification limits should be chosen as } T \pm \delta \text{ where } \delta = \Delta \sqrt{B/A}. \quad \text{From Bergman (1992).}\]

Traditionally, specifications are based either on experience of the engineer or on some standard for specification setting. Taguchi’s method however, provides a much more scientific approach to specification setting, which unfortunately is not yet widely used. According to Bendell, Disney & Pridemore (1989), the strength of Taguchi’s ideas is that it on a scientific basis brings customer expectations into the engineering process. The tools and techniques of Total Quality Management are directed towards the determination of optimum design parameters which become the target values for achievement and with minimal variation. The procedure cascades to cover all subsystems and components via a process of experimentation and process trials such that the
entire design, development, production and supply process focuses on a common purpose, that of meeting the customer requirements.

It is worth noticing that even though Wheeler & Chambers (1992) are against specification limits as such, they do not present any alternative strategy of how to determine acceptable bounds for variation. Taguchi (1986) also uses specification limits, even though he presents a strategy of how these can be set on a basis of customer demands. This leads to the conclusion that we will probably have to deal with the concept of specification limits even in the future.

1.3.3 Process capability studies

Can the process produce products that meet specifications, is the process capable? The question has been around as long as there have been specifications. Many procedures for answering this question have been proposed during the years. A theoretical framework has been established for how to assess the capability of processes. These analyses are often called process capability studies or process capability analyses. The objectives of using process capability studies is first of all to receive information about the process, information that can form a base for improvement efforts leading to a capable process, or perhaps an even more capable process. The information received during a process capability study is also useful in the overall improvement process within an organisation. Based on the information, correct priorities can be made of where to initiate most of the improvement efforts. It is important to know that it is not the process capability studies themselves that bring about improvements, but rather the actions taken, based on the result from the process capability studies.

It is important to notice that the work with achieving capable processes can never be finished. Even if a process at a given moment is considered as "capable enough", soon there will be another manufacturer that has a similar and even more capable process, making this manufacturer the market leader. The Sony-example presented in figure 1.6 stresses that the manufacturer with the largest part of the production process close to the target value will sooner or later be the market leader. The fact that theoretically, there is no end to how capable a process can become implies that there is no end to the improvement initiatives aimed at achieving more and more capable processes. There are obvious similarities between the cycle for solving problems in the continuous improvement work, for instance presented by Deming (1986, 1993), and the concept of process capability studies. Deming speaks of the PDSA-cycle where PDSA stands for "Plan-Do-Study-Act". Any
improvement effort should first of all be planned (Plan), then the improvement actions are followed thoroughly (Do), whereupon the result is studied (Study) and actions are taken upon the result of the improvement effort (Act). The PDSA-cycle first appeared in JUSE (1950) and is originally based on Shewhart’s ideas. Figure 1.9 shows the similarities between the PDSA-cycle and the way process capability studies are meant to be conducted.

Figure 1.9 A schematic illustration of how a process capability study should be conducted. First the characteristics of importance are identified and the study is planned, then statistical control is ensured and data is collected from the process. The capability of the process is then assessed and finally, actions are taken to further improve the process. The result from process capability studies helps co-workers making priorities on where the improvement efforts might be most effective. The improvement process starts all over again and theoretically, it will never end since there is no upper bound on how capable a process might become. This procedure has many similarities with Deming’s and Shewhart’s PDSA-cycle for improvements.

The four major steps in a process capability study presented in figure 1.9 are further described below. The description here is held short since a more thorough description of theoretical as well as practical aspects of how to conduct a process capability study is given in chapter 3.
Chapter 1, Introduction

1 Identify important characteristics, plan the study

Usually, customers just express some kind of function that they are expecting from a given product. Then it is up to the producer to identify what manufacturing characteristics that together accomplish this function. Since it is impossible for the producer to monitor every characteristic of a product, the most important characteristics for a given function are selected. Before the capability study is initiated it should be carefully planned. What is to be measured and how? What gauges are to be used and how should they be calibrated? These are some of the questions to be answered.

2 Establish statistical control, gather data

Before a process can be said to have a well defined capability, it must display a reasonable degree of statistical control. Therefore, the capability of a process depends upon both the conformity of the product and on the stability of the process. The importance of achieving a stable process before any process capability study is conducted is heavily emphasised by Wheeler & Chamber (1992). On the question of what can be said about the capability of an unstable process, they simply answer,

not much!

If a process is out of control, it has failed to display a reasonable degree of consistency in the past and it is illogical to expect that it will spontaneously begin to do so in the future. Therefore, a capability study monitoring an unstable process will only express the capability of the process at that very moment and nothing can be said about the capability of the process in the future. It is a good idea to use control charts for checking whether the process is in statistical control or not. As indicated it is indeed possible to conduct a process capability study whether the process is capable or not. However, the result from a capability study performed on an unstable process is of very little use. It is just a snapshot of the process and any action taken on the basis of such studies might just as well lead to deterioration instead of improvement.

When statistical control is established, the process data is collected so that the desired components of variation are reflected in the data. There are basically two types of process capability studies, *machine capability studies* where the inherent variations of the machine are monitored and *process capability studies* where all components of variations of the process are monitored. A more thorough description of these types of capability studies is given in chapter 3.
3 Assess the capability of the process

The simplest and easiest way to assess the capability of a stable process is to plot a histogram of the individual values directly from the control chart. The x-axis of the histogram can show the specification limits and the relationship between the histogram and these limits will portray the capability of a stable process, see figure 1.10.

![Histogram with Elbow Room](image)

**Figure 1.10** A simple way of describing the capability of the process is to plot the data in a histogram. The aim is to achieve as much "elbow room" as possible between the process output and the lower and upper specification limit and at the same time control the process so that every unit produced is as close as possible to the target value.

Figure 1.10 shows an easy way of assessing the capability of a process graphically. To receive an objective measure of the capability so called process capability indices have been developed. These indices compare the specification interval, i.e. the distance between the upper specification limit, USL, and the lower specification limit, LSL, with the actual process spread and provide a numerical measure of the capability of the process. The use of process capability studies often illuminates problems to be solved, problems to be viewed as improvement possibilities.

When deciding on what actions to take when further improving the process it is often wise to use several other improvement methods such as Design of Experiments (DOE), Failure Mode and Effect Analysis (FMEA), the seven Quality Control tools, the seven management tools or other improvement methods. A description of these and many other improvement tools is for instance given in Bergman & Klefsjö (1994, 1995).
4 Initiate improvement efforts

Finally, the improvement possibilities identified are initiated in order to achieve a more capable process than before.

1.3.4 The history of process capability indices

The idea of capability ratios or, as they are called today, process capability indices, was introduced by Juran (1974). Juran had identified a need in industry to somehow compare the specification interval with the actual process spread. Juran defined the first process capability index, $C_p$, as

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

where $USL$ is the upper specification limit, $LSL$ the lower specification limit and $\sigma$ denotes the standard deviation of the characteristic studied.

The multiplier "6" in the denominator is motivated by the same discussion that lead Shewhart (1931) to his choice of using three sigma-limits in his control charts. Shewhart (1931) noticed that three sigma-limits work well in practice and provide effective action limits.

The choice of using the multiplier "6" in the denominator of $C_p$ leads to the fact that if the distribution of the characteristic studied is normal and the expected value of that characteristic is equal to the midpoint of the specification interval, then the expected proportion of nonconforming items is $2\Phi(-d/\sigma)$, where $d = (USL - LSL)/2$. If for instance $C_p = 1$ then the proportion of nonconforming items is 0.27%, which often is regarded as "acceptably small". However, this requires that the process is centred at the midpoint of the specification interval.

The importance of a centred process is emphasised in figure 1.11. Since $C_p$ does not in any way reflect a shift in process mean of the studied characteristic it should only be viewed as an estimate of potential process capability.
Figure 1.11 Since both process I and II have the same value of $6\sigma$ and the same specification interval, they will also have the same $C_p$-value, even though it is obvious that process I is much more capable than process II. From Deleryd (1993).

Figure 1.11 shows that $C_p$ is not a good process capability index. It also shows that a good process capability index should react to changes both in spread and location of the studied characteristic.

The aim is not always to control a process between an upper and a lower specification limit. For some characteristics, only one specification limit is relevant. For instance when measuring the characteristic surface roughness it is only relevant to know that the measurements of surface roughness are lower than an upper specification limit. Another example could be measurements of tensile strength for a specific material. In most cases it is only of interest to know that these measurements exceed a certain lower specification limit. A graphical description of a process with only a lower specification limit is presented in figure 1.12.

Figure 1.12 A graphical description of a process where only a lower specification limit is relevant. From Deleryd (1993).
Chapter 1, Introduction

The process capability index \( C_p \) cannot handle situations where only one specification limit is relevant. To overcome this problem Kane (1986) presents a process capability index called \( C_{pl} \) which can handle the situation described in figure 1.12. He defined \( C_{pl} \) as

\[
C_{pl} = \frac{\mu - LSL}{3\sigma}.
\]

According to Kane (1986) the index \( C_{pl} \) was developed by some Japanese companies, trying to improve \( C_p \). In a similar manner to (1.11) the index for the upper specification limit is

\[
C_{pu} = \frac{USL - \mu}{3\sigma}.
\]

If the process capability indices \( C_{pl} \) and \( C_{pu} \) are combined, they form a process capability index for the case where both an upper and a lower specification limit are relevant. This index is called \( C_{pk} \) and was also introduced by Kane (1986), where \( C_{pk} \) is defined as

\[
C_{pk} = \frac{\min(USL - \mu, \mu - LSL)}{3\sigma}.
\]

The process capability index \( C_{pk} \) measures the distance between the expected value of the studied characteristic and the nearest specification limit and relates this distance to half the natural process spread, \( 3\sigma \), as described in figure 1.13.

![Figure 1.13](image)

**Figure 1.13** A graphical description of the process capability index \( C_{pk} \). When using \( C_{pk} \) the minimum value of either \((USL - \mu)/3\sigma\) or \((\mu - LSL)/3\sigma\) is used as a measure of process capability. From Deleryd (1993).
The process capability index $C_{pk}$ is more useful than $C_p$, from a practitioners point of view, since it can be used for characteristics where only one specification limit is relevant. Another advantage is that $C_{pk}$ reacts to changes in process spread as well as to changes in process location.

Even though the process capability index $C_{pk}$ is superior to $C_p$ it has one disadvantage since it does not account for characteristics with a pre-established target value, $T$. The importance of target values was discussed earlier in this chapter. To overcome this shortage of $C_{pk}$ the process capability index $C_{pm}$ was proposed independently by Hsiang & Taguchi (1985) and Chan, Cheng & Spiring (1988a). The process capability index $C_{pm}$ is defined as

$$C_{pm} = \frac{USL - LSL}{6\sigma^{'}}$$

where $\sigma^{'}$ is defined in (1.16).

Hsiang & Taguchi (1985) use the idea that the quality of a product, or rather lack of quality, is the loss to society caused by the product after delivery. The loss to society can be expressed by a loss function, earlier described in (1.1) and (1.2), according to

$$L(x) = K(x - T)^2.$$  

Since $K$ in (1.15) is a positive constant every deviation from the target value causes a loss to the customer or the society. The square error loss from the target value and can be expressed as

$$\sigma^{'} = \sqrt{E((x - T)^2)}.$$  

The formula (1.16) can be viewed as a special case of (1.5) where $K = 1$. Since $\sigma^{'} = \sqrt{E((x - \mu)^2) + (\mu - T)^2}$ and $\sigma^2 = E((x - \mu)^2)$ then $C_{pm}$ can be expressed as

$$C_{pm} = \frac{USL - LSL}{6\sqrt{\sigma^2 + (\mu - T)^2}}.$$  

Chan, Cheng & Spiring (1988a) also introduce a process capability index $C_{pm}^{*}$ which can be used for specifications where the target value is not centred between the upper and the lower specification limit. The process capability index $C_{pm}^{*}$ is defined as
Another version of $C_{pm}$ which is based on the same idea as the development of $C_{pk}$ from $C_p$ is introduced by Pearn, Kotz & Johnson (1992). This process capability index is called $C_{pmk}$ and is defined as

$$C_{pmk} = \frac{\text{Min}(USL - \mu, \mu - LSL)}{3\sqrt{\sigma^2} + (\mu - T)^2}.$$  

An interesting contribution to the field of process capability indices was made when the process capability index $C_p(u,v)$ was introduced by Vännman (1995). The process capability index $C_p(u,v)$ can actually be viewed as a class of indices which, for instance, includes the indices $C_p$, $C_{pk}$, $C_{pm}$ and $C_{pmk}$. The process capability index $C_p(u,v)$ is depending on the two non-negative characteristics, $u$ and $v$ and is defined as

$$C_p(u,v) = \frac{d - u|\mu - M|}{3\sqrt{\sigma^2} + v(\mu - T)^2},$$

where $d = (USL - LSL)/2$, is half the length of the specification interval. In (1.20), $M$ stands for the midpoint of the specification interval, which is given by $M = (USL + LSL)/2$.

The indices $C_p$, $C_{pk}$, $C_{pm}$ and $C_{pmk}$ can all be viewed as special cases of $C_p(u,v)$ and are obtained by letting $u = 0$ or 1 and $v = 0$ or 1 according to the following combinations

$$C_p(0,0) = C_p, C_p(1,0) = C_{pk}, C_p(0,1) = C_{pm} \text{ and } C_p(1,1) = C_{pmk}.$$  

**Multivariate process capability indices**

In general the customer is interested in a given function of a product, e.g., the car starts when the key is turned. This function often depends on a number of different characteristics of the product and in order to achieve the function articulated by the customer all these characteristics must meet pre-set specifications. This leads to a multivariate scenario. To make the scenario even more complex, the desired function often depends on the combined effect of these characteristics, rather than on their individual values.

Recently, several multivariate process capability indices have been presented in literature. However, as indicated by Kotz & Johnson (1993), the intrinsic difficulties arising from the use of a single index as a
quality measure are increased when the single index has to summarise measurements on several characteristics rather than just one. This has lead to a very limited practical interest in multivariate process capability indices so far. Kotz & Johnson (1993) claim that, as far as they know, multivariate process capability indices are used very rarely, if at all, within industry. Due to the limited use of multivariate process capability indices in practice, the concept is not further described in this thesis.


1.3.5 Estimation of process capability indices

When conducting process capability studies, data from the process has to be gathered in a systematic way. Usually, one or several of the capability indices described above are then calculated on the basis of the data. When estimating the value of a process capability index, it is common to estimate $\mu$ and $\sigma$ according to

\begin{align}
\hat{\mu} &= \bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i \\
\hat{\sigma} &= s = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2}.
\end{align}

Since the data gathered consists of random measures from the process, the estimated process capability indices themselves will be stochastic variables. This means that it is natural to receive somewhat different values of an estimated process capability index, calculated from two successively conducted process capability studies on a single stable process. Of course, the estimates of process capability indices will be more accurate, the more data gathered. If the estimates of process capability indices are based on a small number of observations, the uncertainty can be quite substantial. If for instance the true capability is known to be $C_{pk} = 1.33$ and the number of observations used for each estimate is $n = 50$, the probability is about 18% of getting an estimate smaller than 1.20 and about 5% of getting an estimate smaller than 1.10, as indicated by figure 1.14. A lucid discussion of uncertainties in
estimates of different capability indices can be found in Pignatiello & Ramberg (1993).

Figure 1.14 The result of 1000 simulated estimates of $C_{pk}$, denoted by $\hat{C}_{pk}$, each one based on 50 observations for a process output normally distributed with parameters $N(49.5, 1.0)$. The target value is assumed to be 50.0, and $C_{pk} = 1.33$. From Bergman & Klefsjö (1994).

The example in figure 1.14 clearly indicates that the variability of estimated process capability indices can be quite substantial and possibly leading to erroneous decisions. Therefore, it is of utmost importance to be able to handle the uncertainty in the estimated process capability indices by using confidence limits or some other method. The use of confidence limits for estimates of process capability indices will be discussed in chapter 3.

1.3.6 Using process capability indices for non-normal distributions

Many of the theoretical aspects of process capability studies assume that the process output is normally distributed. However, in reality, it is quite common that the process output is non-normally distributed. The most common type of non-normality, experienced in practice, is a skewly distributed process output, see Gunter (1989b). The difference between a normally distributed process output and a skewly distributed process output is shown in figure 1.15.

For some characteristics it is quite natural to receive a skew output rather than a normally distributed one. For instance, it is quite common
that characteristics which are delimited by a lower specification limit equal to zero, a so called "natural zero", are skewly distributed. One example is the characteristic surface roughness where it is desired that the surface roughness is as small as possible. When measuring surface roughness the distribution of the process output has often an even heavier tail to the right than the skew distribution in figure 1.15.

![Normal Distribution vs. Skew Distribution](image)

*Figure 1.15* The difference between the forms of a normally distributed process output and a skewly distributed output is illustrated by the corresponding probability density functions.

When the process output is skewly distributed a problem appears when estimating any process capability index. Basically, this problem is focused on the percentage of nonconforming items, as illustrated in figure 1.16.

![Normal Distribution vs. Weibull Distribution](image)

*Figure 1.16* An illustration of a probability density function from a Weibull distribution (2) with $\gamma = 8.63$, $\alpha = 1.5$ and $\beta = 1.36$ and a probability density function from a normal distribution (1) with $\mu = 10$ and $\sigma = 1$. The upper specification limit (USL) is 14 and the lower specification limit (LSL) is 6. When calculating $C_{pk}$ for both these processes it tells us that $C_{pk} = 4/3$ for both these processes, i.e. they are equally capable. However, when focusing on the percentage of nonconforming items it is found that the normal distribution is more capable than the Weibull distribution. From Grönlund (1990).
When calculating the percentage of nonconforming items for both distributions in figure 1.16, the percentage of nonconforming items for the Weibull distribution is 0.3442% and the percentage of nonconforming items for the normal distribution is 0.0067%. The fraction of nonconforming items is more than 50 times larger for the Weibull distribution compared to the normal distribution in this example, despite that the true value of $C_{pk}$ indicated that both outputs should be equally capable.

The fact that the basic process capability indices lack the ability to establish fair measures of capability for differently distributed characteristics have been discussed in many articles, see, e.g., Gunter (1989b), Clements (1989), Chan, Cheng & Spiring (1988a) or Pearn, Kotz & Johnson (1992). However, even though many solutions to this problem have been presented, none of them have been broadly accepted as a final solution to the problem. A more thorough description of the problem of conducting process capability studies for skewly distributed characteristics is given in chapter 6.

1.4 Identification of suitable research topics

The literature review has indicated some problems concerning the concept of process capability studies and hopefully given all details necessary to understand this thesis in its initial stages. The following two topics have been selected as suitable research areas to be handled in this thesis.

1 When reading literature on the concept of process capability studies, some authors indicate that the method is often used wrongly, see, e.g. Gunter (1989a-d), Dovich (1991a-b), Burke, Davis & Kaminski (1991) or Pignatiello & Ramberg (1993). Their point of view is often based on their own experience and no scientific study has yet been performed in order to see, first of all if and how and then why, the concept is misused. It would also be of interest to see how process capability studies actually are being conducted in practice.

2 Since no final solution has been found to the problem of how to handle process capability studies for non-normal distributions, the area is still an interesting research topic. The study presented in this thesis will not solve this problem, but rather try to give an understanding of it. Hopefully, some of the results reached in this thesis will help solving the problem of how to conduct process capability studies for non-normally distributed characteristics. Since this problem mainly is due to the inability of process capability indices to handle these situa-
tions, the study will be focused on these measures of capability and their properties. The most common non-normally distributed characteristics, experienced in practice, are skewly distributed, see Gunter (1989b). Therefore, the study will focus on this type of non-normality.

The two identified research topics have been specified in the objectives of this thesis.

1.5 The objectives of the thesis

The objectives of the thesis are to

1. examine the differences, if any, between how process capability studies theoretically should be conducted and how they actually are being conducted. If the gap between theory and practice is real, then efforts will be made to explain the existence of this gap.

2. study the effect of skewness on estimates of the most commonly used process capability indices. The aim is not to solve the problem of how to conduct process capability studies for skewly distributed characteristics but to give an understanding of the problem.

1.5.1 The structure of the thesis

Since the thesis consists of two quite different objectives it has been written in two main parts. Part 1, Process capability studies—some theoretical and practical aspects, tries to meet objective 1, and part 2 The effect of skewness on some process capability indices, tries to meet the second objective. In both part 1 and part 2, more thorough descriptions of the theoretical concepts are presented. Also the methodology used in the different parts are described separately.

Finally, the results from part 1 and 2 are discussed in part 3, where some directions for future research also are given.

So far, the material found in chapter five of this thesis has been accepted for publication, see Deleryd (1996).
Part 1

Process capability studies—some theoretical and practical aspects
CHAPTER 2
RESEARCH METHODOLOGY

In this chapter we will discuss the research methodology and the implications of the methods used in connection to the studies presented in part 1. A possible alternative method will also be discussed.

2.1 The research problem

All scientific efforts are in one way or another performed in order to reach reasonable explanations to different phenomena or questions. Finally, when the researcher has reached broadly accepted explanations and answers to these phenomena or questions, they are added to a base of knowledge, where other researchers can use the findings to build upon in their own research. In this way, all scientific research becomes cumulative. The practice of careful examination of research findings has been used in science for centuries and proved very effective.

In order to facilitate for another researcher, it is of utmost importance to carefully describe the methodology used in your own research. Therefore, the methodology of the studies presented in part 1 is explained in this chapter in order to make it possible for other researchers to determine its credibility.

The research project, of which methodology is described in this chapter and which is aimed at meeting the first of the objectives of the thesis, has been carried out in order to try to find answers to the following two questions:

Research question number 1: Are there any differences between how process capability studies are conducted in Swedish industry today, compared to how process capability studies are supposed to be conducted according to theory?

and; if such differences exist:

Research question number 2: How can the existence of these differences be explained?
As implied by research question number 1 the study has been delimited to only study differences between theory and practice within Swedish industry. When choosing between deeper studies within a few organisations and a wide study of how process capability studies are conducted all over the world, it seemed reasonable to delimit the study to a questionnaire study among Swedish organisations. If gaps between theory and practice are found in Swedish industry it is likely that the same differences are to be found in other industrial countries as well.

Research question number 1 implies that some sort of comparison between theory and practice has to be made. It is obvious that first of all the important parts of process capability studies have to be identified in theory, whereupon the adherence to these parts within Swedish industry, is to be checked. If the result of this comparison is that no differences exist between the theoretical and the practical aspects of process capability studies, then the research project can be regarded as finished. However, if differences seem to exist, then efforts will be made in order to try to explain the origin of their existence.

2.2 A description of the method used

The comparison between theory and practice of process capability studies within Swedish industry has been performed by the author during 1995. However, as implied by the methodological description below, several other persons, both academics and practitioners, have been actively consulted in order to ensure and improve the output of the study. The different parts of the study are described in figure 2.1.
Figure 2.1 The comparison between theory and practice of process capability studies has been made by conducting the following parts: 1. Literature review, 2. Interviews, 3. Questionnaire design, 4. Questionnaire survey 1 and 5. Nonresponse analysis. In order to fully describe the method used, it must at this early point of the thesis be revealed that indeed, large discrepancies between theory and practice have been found and therefore another questionnaire survey, marked Questionnaire survey 2 in the figure, has been conducted in order to explain the origin of these discrepancies.

The different parts of the methodology used are described in detail below. First the method used in order to try to answer research question number 1 is presented, whereupon the method used for answering research question number 2 follows.

2.2.1 Literature review

As discussed in chapter 1, the concept of process capability studies has been present in academic press since the 1980’s and since the start of the
author’s interest in the concept, in 1993, well over 200 articles, relevant to the concept of process capability studies, have been collected. The literature review is indirectly based on most of these articles and has been focused on identifying the most important factors, influencing the reliability of the results from process capability studies. Altogether, six important aspects influencing the reliability of the results from process capability studies have been found and are discussed in chapter 3. These are,

- capable gauges
- statistical control
- conscious gathering of data
- use of confidence limits
- simultaneous use of several process capability indices
- checking the distribution of the process output.

In order to find out if any similar study had been performed elsewhere, letters were sent to prominent academics within the field of process capability studies. These academics are known to have focused especially on practical aspects of process capability studies in their own research. Letters were sent to Dr. Chan, Hong Kong, Dr. Chou, USA, Dr. Evans, USA, Dr. Gunter, USA, Dr. Kane, USA and finally Dr. Porter, UK. Upon receiving all their answers, it was clear that none of them had ever heard of such a study, as presented here. However, most of them endorsed the study and believed the outcome to be fruitful.

2.2.2 Interviews

The literature review focused on identifying theoretical aspects of how to conduct process capability studies. However, in order to investigate how process capability studies actually are conducted, some practical aspects must also be included in the survey. Therefore, a reference group which supported the initial stages of the study, was formed. The reference group consisted of Peter Fabricius at SKF Sweden AB, Anna Sjödahl at Scania Trucks & Buses, Hans Wassén at AB Sandvik Coromant and Magnus Wächter at Hägglunds Vehicle AB. The reason for choosing these people was that they all have a thorough knowledge of statistical process control and process capability studies combined
Part 1: *Chapter 2, Research Methodology*

with practical experience from implementing and using these methods. Interviews were held with each one of them in order to find out:

1 If the important factors influencing the reliability of the result from process capability studies, identified by the literature review, were relevant.

2 What practical aspects of how to implement and conduct process capability studies that are of importance.

During these interviews, which lasted between one and two hours each, and were held freely, it became clear that the important parts identified in the literature review were indeed relevant. Also several practical aspects of how to implement and conduct process capability studies were identified. The practical aspects which were identified are,

- implementation aspects of process capability studies
- pressure between organisations to conduct process capability studies
- setting of specifications
- achieved results from using process capability studies
- advantages and disadvantages of conducting process capability studies.

These aspects were also included in the study together with the theoretical aspects identified by the literature review. The practical aspects are also described in detail in chapter 3.

2.2.3 Questionnaire design

Research question number 1 of interest in this study involves measuring the correspondence between how process capability studies are conducted in Swedish industry today and how process capability studies are meant to be conducted according to theory. It was decided that this question should be answered by using a questionnaire, since the obedience to the different aspects of process capability studies, relatively easy can be operationalised into questions that are concrete enough to be included in a questionnaire.

Designing a good questionnaire is an intricate problem where several aspects have to be considered. According to Sudman & Bradburn (1989), there is no such thing as a perfect questionnaire. However, it is important to allocate appropriate resources to the design process of the questionnaire. If the questionnaire does not include, relevant questions,
introduced in a logical order and with understandable wordings, then
the result from the study will suffer or worse, be worthless. Any imper-
fection in the questionnaire and in its completion will directly result in
irrelevant data.

A great deal of research has been done on the design of question-
naires and questions and on the task of completion of the questionnaire.
The basic design process of a questionnaire is described thoroughly in
Sudman & Bradburn (1989) and according to them it consists of four
important parts, shown in figure, 2.2.

![Figure 2.2](image)

**Figure 2.2** The design process of a questionnaire consists of four parts, 1 Specify the topics of interest, 2 Construct a preliminary ques-
tionnaire, 3 Test the questionnaire and finally, 4 Revise the ques-

The design process of questionnaire 1, reflecting research question
number 1, has followed all four steps in figure 2.2 and is carefully
described below.

1 **Specify the topics of interest**

The first step when designing a questionnaire is to specify the topics of
interest and to operationalise these topics into questions, which all
reflect the main topics, in one way or another. In questionnaire 1 the
topic of interest is to study the obedience, within Swedish industry, to
the different aspects of process capability studies. This main topic has
already been discussed thoroughly above, and it has been indicated
how this topic should be operationalised.

The literature review resulted in six theoretical aspects influencing
the reliability of the results from process capability studies. If an organi-
sation is using process capability studies according to theory, then these
aspects would be fulfilled. This obviously qualifies these aspects to be
operationalised and included in the questionnaire. The interviews on
the other hand, resulted in some practical aspects which would be rele-
vant to operationalise and include in the questionnaire. It is worth noticing that these practical aspects were not vital for meeting the first objective of the thesis. However, by including these practical aspects a deeper understanding of how process capability studies are conducted in Swedish industry has been gained. The operationalisation of theoretical as well as practical aspects of how process capability studies are conducted, is specified more clearly in chapter 3 and in enclosure 1.

2 Construct a preliminary questionnaire

Every researcher who uses questionnaires is anxious that the response rate will be satisfactory, in order to insure the reliability of the results. When designing a questionnaire, there are many factors to consider, which influence the response rate. For instance, the size of the questionnaire, the types of questions asked, the order of the questions, the layout of the questionnaire, the wording used and the degree of confidentiality are some of the most important factors to consider. Below, a discussion is given of how these factors have been handled when designing questionnaire 1.

When looking at all identified aspects to be covered by the questionnaire, see enclosure 1, it is obvious that the questionnaire will be relatively large. However, it was decided that in order to establish a good measuring apparatus that really would describe how process capability studies are conducted within Swedish industry today, the questionnaire has deliberately been made rather comprehensive.

It was also decided to frequently use open questions in order to really see if and how process capability studies were conducted within the surveyed organisations. However, where possible, closed questions have been used.

All questions were sorted and presented under separate headings in an order which was believed to make sense to the respondents. Almost all existing literature on questionnaire design, see, e.g., Kalton & Schuman (1982), Jolliffe (1986) or Holme & Solvang (1991), mentions that it is wise to start the questionnaire with some easy to fill in questions which do not in any way include any controversial aspects that might make the respondent throw the questionnaire away. Therefore, first of all some demographical facts about the respondent's organisation were asked in the questionnaire. The more sensitive questions concerning how the organisation really conducts process capability studies, were deliberately placed in the middle of the questionnaire. Towards the end of the questionnaire, the questions again became more neutral.
Lots of efforts were allocated to the design process of the questionnaire, in order to make it pleasant for the respondents to fill it in. All questions were numbered and a frame was allocated to each question in order to clearly separate them from each other. Enough writing space was given to all the open questions and so on.

The wording used in the questionnaire has been made as clear and uncomplicated as possible. Since the term process capability studies, has two accepted expressions in Swedish, "kapabilitetsstudier" and "duglighetsstudier", both of these expressions were used in parallel in the start of the questionnaire in order to make it clear what concept that was intended to be covered by the survey.

It was guaranteed that the questionnaire was to be analysed so that no one ever would be able to reveal which organisations that participated in the survey. However, as the first task of all in the questionnaire, the respondents were asked to give information about their address, telephone number and so on. There were three reasons for asking for this information. First of all it was considered vital to be able to contact these organisations if research question number 2 was to become relevant and to check directly with them if their answers in questionnaire number 1, in some way would be difficult to interpret. Secondly, by looking at the name of the organisations it would be possible to see if there, for some reason, were several persons within the same organisation, each one sending in a filled in questionnaire, and by doing so causing a bias in the result. Finally, the respondent’s address was asked for in order to be able to return the final result to every one participating actively in the survey. As guaranteed, at the start of the questionnaire, the information concerning the respondent’s address and organisation has remained secret to all others but the author.

3 Test the preliminary questionnaire

The preliminary questionnaire was tested in two separate ways. First of all a test was made at the Division of Quality Technology and Statistics at Luleå University, where several of the author’s colleagues read the questionnaire and helped to improve it.

After this internal test, an external test run was performed within the reference group which also participated in the initial interviews of the study. They tried to fill in the preliminary questionnaire with respect to their own organisation.

Both the internal and the external test runs resulted in several suggestions on how to improve the questionnaire.
4 Revise the questionnaire

The internal and external test runs resulted in some improvements of the questionnaire. For instance the formulations of some questions were revised in order to avoid misinterpretations. Also a large part of the preliminary questionnaire was heavily re-designed in the final questionnaire. This part concerned educational aspects in connection to the implementation of process capability studies and was far too comprehensive in the preliminary questionnaire.

Since it is of importance to reach as many organisations as possible within Swedish industry that conduct process capability studies one question was added. In this question the respondents are invited to suggest other persons that they know of, and who are working in organisations where process capability studies are conducted, and to whom it would be fruitful to send a questionnaire. Later on, the decision to include question number 26 turned out to be a success. Approximately 25% of the filled in questionnaires came as a direct result from question number 26.

The final version of the questionnaire is given in Swedish in enclosure 3a.

2.2.4 Questionnaire survey 1

When conducting surveys it is sometimes necessary to distinguish between the target population and the study population which is the population sampled, see Jolliffe (1986). The target population, is the population towards which the survey is aimed. However, sometimes the target population is not easily identified. Then the survey has to aim at one or several study populations which hopefully, to a large extent, coincides with the target population. In every survey, there is also a need to be able to decide if a respondent within the study population really is a part of the target population or not.

The aim of the study is not to investigate how large part of all organisations within Swedish industry that are conducting process capability studies, but to see how organisations that do conduct process capability studies actually act. The target population in this survey consists of those organisations within Swedish industry where process capability studies are conducted. In order to reach these organisations, two study populations have been used. The first study population includes all members of the Swedish Association for Quality, belonging to the section of Statistical Methods, SFK-StaM. The second study population consists of persons who have participated in courses on Total Quality
Management, given by the Association of Swedish Engineering Industries, VI, during 1992 - 1995. These two study populations were chosen since they were likely to coincide with the target population.

Due to the introduction of question number 26 in the questionnaire, see enclosure 3, a third study population has been identified. Since this population consists of persons belonging to organisations that by members of study population one and two, are known to conduct process capability studies, this study population was almost completely a part of the target population.

The concepts of study populations and target population, in connection to this survey, are further illustrated in figure 2.3.

**Figure 2.3** In order to reach as many organisations as possible within the target population, three study populations have been selected. The study populations have been chosen so that as large part as possible of them coincides with the target population, i.e. as many organisations as possible within the study populations are actually conducting process capability studies.
A total number of 764 questionnaires were sent out to the study populations, 359 questionnaires to members of study population 1, 329 questionnaires to study population 2 and 76 questionnaires to study population 3. The envelopes were addressed directly to the respondents. An introductory letter, explaining the purpose of the survey and clarifying where their address had been found, was sent together with the questionnaire. The introductory letter is presented in enclosure 2. Also a brochure, describing the work at the Division of Quality Technology and Statistics at Luleå University, was included in order to certify that the study is endorsed by a university, an act which hopefully had some positive effect on the response rate.

Since the study populations had been relatively loosely picked, it was decided that no letter was to be sent out in order to remind the respondents to answer. However later on, a nonresponse analysis has been performed, which is described in the next section.

2.2.5 Nonresponse analysis

As mentioned above 764 questionnaires were sent out and when the survey was finished, 205 questionnaires had been filled in and returned. This leaves 559 questionnaires, that by some reasons, never were filled in and returned. In order to find out why these questionnaires were left unanswered, a nonresponse analysis was performed.

There were two main purposes with the nonresponse survey. First of all it was considered important to find out why these organisations did not answer questionnaire 1. Secondly, it was of interest to see if there were some differences between those organisations that answered questionnaire 1 and those that did not. If such differences exist they too would probably add some natural explanations to why some organisations did not answer questionnaire 1.

A nonresponse questionnaire was designed to cover the two main purposes just described. This nonresponse questionnaire, which is given in enclosure 3b, covered four questions to be answered.

The nonresponse analysis was performed among 250 randomly chosen organisations within the group of 559 organisations, where no reply had been made on questionnaire 1. There were 163 of these 250 nonresponse questionnaires that were filled in properly and returned. The result from the nonresponse questionnaire is presented in section 4.2.
2.2.6 Questionnaire survey 2

As a result from questionnaire 1 it was obvious that many aspects of how process capability studies shall be conducted, were not considered within the organisations that actually are conducting process capability studies. This discovery obviously leads to the question, of how the discrepancies between theory and practice can be explained?

I order to establish some answers to this question a new questionnaire was designed. It was also decided that this questionnaire should be sent to all 205 respondents of questionnaire 1 and also to 53 of the respondents identified through the nonresponse analysis, who had shown interest in the result from questionnaire 1. There were two reasons for choosing these two groups. First of all these 258 persons, had shown interest in receiving the result from questionnaire 1 and secondly, they were indeed very likely to be aware of what the concept of process capability studies really means.

It was decided that questionnaire number 2, which focused on identifying reasons why the discrepancies between theory and practice exists, should only contain two questions. The first of these questions asked whether the respondent belongs to an organisation in which process capability studies are conducted or not. The second question plainly asked for the respondent’s opinion of why it sometimes is hard to implement and conduct process capability studies according to all theoretical aspects, independently of whether the organisation is conducting process capability studies or not. This second question was made open in order not to influence the respondent’s answers. The second questionnaire is given in enclosure 4.

A research report, including the result from questionnaire 1 and the nonresponse survey, see Deleryd (1995), was sent together with questionnaire 2 to the 258 persons described above. Altogether 60 of these respondents filled in and returned questionnaire 2, which gives a response rate of 23%. The analysis of questionnaire 2 is presented in chapter 5.

2.3 Implications of the method used

When discussing the implications of the methods used it is worthwhile to look back at how the two research problems of interest in this research project were formulated. The first question focused on enlightening possible differences between theory and practice of how process capability studies are conducted within Swedish industry today. The
other question focused on explaining the origin of these differences between theory and practice, if they were existing. Since differences actually were found, research question number 2 became relevant.

Both research questions have been answered by using questionnaires, even if other methods were used during the development of questionnaire 1.

When evaluating the result from a research project, there are mainly two different aspects of the research project that are of interest, the validity and the reliability of the research project. A relatively simplified description of the two concepts is that validity is a measure of how well the research objective has been operationalised and the reliability is a measurement of the reproducibility of the study leading to the same results and conclusions. The validity and the reliability of the different parts of this research project are discussed in the next two sections.

2.3.1 Validity and reliability of the study using questionnaire 1

A lot of efforts were made in order to first of all identify all practical and theoretical aspects of process capability studies, see the description of the literature review, the letters to prominent academics within the field of process capability studies and the interviews with practitioners within Swedish industry, discussed above. The theoretical and practical aspects were then operationalised into appropriate questions enhancing the validity of questionnaire 1. This procedure is described in more detail in chapter 3 and in enclosure 1.

By including question number 26 it was ensured that a large part of the target population has been reached. The frequent use of open questions in questionnaire 1 made it easy to sort out questionnaires coming from respondents claiming that process capability studies are conducted within their organisation, even though it was obvious that they did not know what process capability studies are.

The nonresponse analysis showed that at least 38 of the respondents, who did not answer questionnaire 1 worked in organisations where process capability studies actually were conducted. These facts indicate both one negative and one positive aspect of the validity of the method used in the survey. It clearly shows that the study populations were properly chosen since there were more organisations than those answering that actually conduct process capability studies. However, it also indicates that the questionnaire might have been too comprehensive, leading to left out answers.

Since all questionnaires exist and all the respondents addresses are available there would be no problem at all to repeat the study. The
question is if a repeated study would give the same results and conclusions.

All open questions in the questionnaire have resulted in a variety of answers that have been categorised by the author. It is possible that another researcher might do this categorisation in another way and for that reason reach slightly different results. However, the discrepancies between how process capability studies are conducted compared to how they theoretically should be conducted were found to be so large that any researcher using the same method would undoubtedly reach the same conclusion.

2.3.2 Validity and reliability of the study using questionnaire 2

Questionnaire 2 was constructed in order to find out, why it sometimes is so hard to implement and conduct process capability studies. It was immediately realised that this question is very delicate since the respondent might interpret it as an unjust accusation, implying that process capability studies are conducted erroneously within the respondent’s organisation. Therefore, it was decided to use an open question and just plainly ask for the respondent’s opinion without making any connection to the respondent’s own organisation. Researchers who have studied the effects of validity in connection to sensitive questions recommend using simple open questions asking for the respondent’s opinion without any association to the respondent in person, see, e.g., Sudman & Bradburn (1989). By formulating the question in this way, the validity when using questionnaire 2 is enhanced since the respondent without reflecting, answers the question based on own experiences from the work with process capability studies within the own organisation.

There would be no problem to repeat the study using questionnaire 2. However, a repeated study made by another researcher would probably not lead to exactly the same result. Since an open question was used, the author has categorised all answers into several reasons why it sometimes is so hard to implement and conduct process capability studies. Another researcher might perform the categorisation in another way, leading to somewhat different results. The Ishikawa-diagram presented in figure 5.1 would probably not look exactly the same if another researcher performed the study.
2.4 Possible alternative methods

Both research questions have been studied by using questionnaires. Research question number 1 is quite suitable to be answered by using a questionnaire since the theoretical and practical aspects of process capability studies relatively easy can be operationalised within a questionnaire. A questionnaire survey also has the advantage that it is easy to reach a large part of the target population with relatively limited resources.

However, research question number 2 is not ideal to operationalise within a questionnaire, and if it is to be done it should be done with an open question without any connection to the respondent in person, just as it has been done in questionnaire 2. Another possible method, leading to a deeper understanding of difficulties when implementing process capability studies, would be to use case studies, both within organisations that have succeeded and failed with the implementation of process capability studies. The reason for choosing a questionnaire for answering research question number 2, is mainly to give an idea of what obstacles there might be when implementing process capability studies and it was also chosen in order to give suggestions of how to focus future research projects within the area. Hopefully, the author will be given the chance to return to this question within the near future, but using several case studies to study implementation effects.
CHAPTER 3

THEORETICAL AND PRACTICAL ASPECTS

In order to understand the study of how process capability studies are conducted, which is presented in chapter 4, a description of some theoretical and practical aspects covered in the study, are given in this chapter. First the theoretical aspects included in the survey are described. The theoretical aspects are then followed by a similar description of some practical aspects. In connection to both the theoretical and practical aspects some suitable topics to be covered by questions in a questionnaire are presented.

3.1 Theoretical aspects

The theoretical aspects all reflect the reliability of the results from the process capability studies in one way or another. In order to truly trust the results and make correct decisions, all six theoretical aspects presented below would have to be considered. All the theoretical aspects are derived from relevant and relatively recent research.

3.1.1 Use capable gauges

To ensure that the gauges used in a process capability study are capable is perhaps one of the most important aspects of all. If the gauge is not accurately chosen the whole study becomes worthless.

The basic idea of using a gauge is to establish an estimate of the so-called true value of a given property. There are many aspects to consider when making this estimate. The first problem is perhaps that there is no such thing as a true value. We will never know the true value, we can only try to calibrate our gauges so that they produce measurements as close as possible to the ones produced by the most accurate gauge existing.

The total errors produced when using a gauge can be explained by the five concepts, accuracy, repeatability, reproducibility, stability and linearity, see Ford (1980). These concepts are defined below.
• **Accuracy** is the difference between the true value and the average of a number of measurements. The easiest way of estimating the accuracy is to estimate the true value with the best gauge available, and then compare this value with the average of a number of measurements made with the studied gauge on one single unit.

• **Repeatability** describes the inherent variation of a gauge which is apparent when a single operator is using the gauge. An estimate of the repeatability is given by making an estimate of the variation of a number of measurements performed by a single operator on a single unit.

• **Reproducibility** is a measure of the variation among measurements that appears when different operators are using the same gauge. An estimate of the reproducibility is given by studying the variation among averages of measurements produced by different operators using the same gauge on the same unit.

• **Stability** is the difference between two runs of measurements on the same details performed at different times.

• **Linearity** describes the inherent variation, the repeatability, within the given interval of measurements covered by the gauge.

When performing a process capability study it is important to choose a gauge that first of all is intended to be used to measure the monitored characteristic. This gauge must also be calibrated, i.e. the accuracy of the gauge must be acceptably small. The inherent variation of the gauge, the repeatability, must be small enough, compared to the specification interval. When performing process capability studies there are often different operators using the same gauge, a fact that also makes the concept reproducibility an important factor to consider. The organisation must have appropriate routines for handling these concepts, otherwise the measurements produced in a process capability study might become too uncertain. A process capability study based on uncertain measurements might lead to erroneous decisions.

The two concepts repeatability and reproducibility have been combined in what is called Repeatability- and Reproducibility-studies, usually denoted R&R-studies. A thorough description of the two concepts repeatability and reproducibility is given in Mandel (1972).
When it comes to the use of capable gauges it would be fruitful to include some questions concerning the following topics:

- If and how the capability of the gauges used is monitored and secured.
- It would also be interesting to see if and how the inherent dispersion, the repeatability, is considered when choosing a specific gauge for measuring a specific characteristic with given specifications.

### 3.1.2 Establish statistical control

The fact that the process must be in statistical control before conducting a process capability study has already been enlightened in chapter 1. Wheeler & Chambers (1992) clearly describes the importance of establishing statistical control before any real improvements of the process can be achieved. They describe the improvement process of any process in four different states, the state of chaos, the brink of chaos, the threshold state and the ideal state, see figure 3.1.

A manufacturer whose process is in the state of chaos usually knows that a problem exists but has no idea of how to correct it. No matter what they try nothing works for long, because the process is always changing. As a result, they finally despair of ever operating their process rationally. The only way to make any progress in moving a process out of the state of chaos is to first eliminate the assignable causes. This will be facilitated by using control charts.

For periods of time the manufacturer operating in a state of chaos will perhaps experience that the process is producing 100% of conforming products. However, if there are some assignable causes left the conformance can change in a moment. The assignable causes determine what is produced by the process. The only way to make any progress in moving a process out of the brink of chaos is to eliminate all assignable causes. This will require the use of control charts.

The only way out of the state of chaos or the brink of chaos is to establish statistical control. According to Wheeler & Chambers (1992) most managers of today are unaware of this fact, they call these managers "chaos managers".
Figure 3.1  The aim of the improvement process is to achieve a process in control and with 100% of conforming products. The improvement process of reaching this state can be in any of the four squares, the state of chaos, the brink of chaos, the threshold state or the ideal state. In order to reach the ideal state the process must be brought into statistical control. Constantly, efforts have to be put into the improvement process. Otherwise, the effect of entropy will eventually bring the process into a state of chaos. Based on ideas from Wheeler & Chambers (1992).
If the manufacturer succeeds to bring the process into statistical control, the threshold state is reached. The fact that the process displays statistical control means that the variation in the product stream is consistent over time. When a manufacturer has reached this state there are tremendous opportunities to improve the process since all changes can be based on reliable data. The real solution is to stop making non-conforming products. To do this with a process that is in the threshold state, the producer will have to modify the process, because the process is already operating as consistently as possible. When a process is brought into the threshold state the use of process capability studies becomes relevant. By conducting process capability studies and using other improvement methods simultaneously it is possible to improve the process so that it will enter the ideal state.

A process operating in the ideal state will produce 100% conforming products, all the time. Once a process is in the ideal state, the continued use of control charts will naturally result in continuing process improvement. This will lead to even more uniform products, which will yield lower costs and greater productivity. A manufacturer with all processes in the ideal state and who is applying control charts to further improve all processes will increase the chances of climbing the ladder of competition faster than the competitors.

The improvement process can never end. Even if a process has been brought into the ideal state, there is nothing to assure it will stay that way. It is possible for a process to move from one state to another. In fact there is a universal force acting on every process that will cause it to move in a certain direction. That force is entropy. It continually acts upon all processes to cause deterioration and decay, wear and tear, breakdowns and failures. Entropy is relentless. Every process will naturally and inevitably migrate toward the state of chaos. The only way this migration can be overcome is by continually repairing the effect of entropy.

When it comes to establishing statistical control it would be fruitful to include a question concerning the following topic:

- Since the central tool for establishing or verifying statistical control is the use of control charts it would do to quite simply ask the respondents if they are using control charts or not. If they do then it would be suitable to ask them to describe their view of how control charts and process capability studies fit together in their organisation.
3.1.3 Conscious gathering of data

Even if we have tried to eliminate all assignable causes of variation, the average value of the process may vary with time. This can, for instance, depend on variations between various shifts, different machines or different material suppliers. We can then regard the variation of the average value of the process as a random variable, whose dispersion it is possible to estimate.

According to Bergman & Klefsjö (1994), the dispersion in every process can be viewed as consisting of two components, a variation from unit to unit and a variation that is due to the usually slower variation of the average value. If we only take the first mentioned variation into account, the variation from unit to unit, we would be dealing with a machine capability study, whereas a process capability study monitors both dispersion components.

When conducting a capability study it is of utmost importance to be sure of what components of variation that are desired to be reflected in the data gathered. To estimate the machine capability we thus need a homogeneous set of data, for instance taken from the same material, the same set-up and the same shift. However, to estimate the process capability we need to study the process during a longer period of time and to pay extra attention to how we estimate the dispersion. An estimate of process capability cannot, for example, be based on \(R\)-values of a number of samples, taken during an extended period of time since we can have constant variation within the groups but a considerable variation of the average value over the same period of time, see figure 3.2.

A capability index for a machine capability study is usually indicated by "\(m\)", for example \(C_m\) and \(C_{mk}\), in a similar way as \(C_p\) and \(C_{pk}\) refer to the capability index for the process.

Sometimes the terms machine capability and process capability are misunderstood in practice. It would be quite natural to believe that the concept of machine capability tell us the capability of a given machine in the workshop and that the concept of process capability tell us the capability of a series of machines, forming a process, or a line, in the workshop. However, this conception is not correct. Both concepts focus on the ability of a process to meet specified requirements. This process could be just a single operation in a single machine meeting a given specification. However, it is possible that the characteristic formed in this process indirectly is reflected by the behaviour in previous machines. Machine capability only focuses on the short-term variability of the process while the process capability focuses on the long-term variability of the same process.
Figure 3.2 Viewed over a longer period of time the average value of the process varies. Even if the dispersion from unit to unit is relatively constant, the dispersion of the whole process over a longer period of time will be larger because of the variation of the average value of the process. From Bergman & Klefsjö (1994).

Today, in literature the term *machine capability* is more often replaced by *short-term capability* and the term *process capability* is replaced by *long-term capability*, see, e.g., Barnett (1990) or Runger (1993). The terms, short-term capability and long-term capability, are much more appropriate than machine capability and process capability since they are associated directly with what is actually measured in the two kinds of process capability studies.

It should be noted that of the two concepts short-term capability and long-term capability, the long-term capability is of most interest from a customer's point of view since it measures the performance of the process over a longer period of time. The short-term capability can however provide useful information to be used in the improvement process within the organisation.

In order to monitor the desired components of variation, data has to be consciously gathered. If it is the short-term capability that is desired, then the measurements are to be made on units produced directly after each other while all outer disturbances are held as constant as possible.
If the long-term capability is desired, measurements are to be made on randomly selected units over a longer period of time, making it possible for all disturbances usually involved in the process, to be reflected in the data. However, the problem is not just as simple as how to select units to measure, the question of how many measurements that are needed is directly apparent. The answer is of course that the more measurements used the more correct the estimate of any process capability index will be. On the other hand, the more measurements made the more the study will cost. To derive a recommendation which takes both theoretical and practical aspects into consideration it is worth studying the probability distribution function of a given process capability index for different values of $n$, where $n$ denotes the number of measurements used in each estimate, see figure 3.3.

Figure 3.3 indicates that from both a theoretical and practical point of view, it is often accurate enough to use 50 measurements when making an estimate of a process capability index. For instance, the gain in accuracy when making 100 measurements compared to 50 measurements, is from a practical point of view not of interest, since it doubles the measurement cost while the gain in reduced variability of the estimated index is relatively small. The recommendation of using 50 measurements when estimating a process capability index holds regardless of what index used.

Everyone that is conducting process capability studies sooner or later comes to a point where it has to be decided what level is to be regarded as capable enough. What level of any process capability index is to be considered as good enough? To shed some light on the problem table 3.1 has been constructed.
Figure 3.3 The probability distribution function for estimates of the process capability index $C_{pk}$ is given for different numbers of measurements, $n$, used in each estimate of $C_{pk}$. The variability of the probability density function is becoming smaller as $n$ increases. From a practical point of view it is often good enough to use 50 measurements when estimating a process capability index. All eight plots in the figure are derived from a normally distributed characteristic which has a true capability of $C_{pk} = 1.0$. The calculations are based on results from Vännman & Kotz (1995a).
Table 3.1 The table shows the conformance between the value of $C_p$ and the defect rate, or the rate of nonconforming items. The example is based on a normally distributed process which is perfectly centred. To give a more realistic picture of what these defect rates actually mean, two examples, duration of power outages per month and the number of misspelled words, are given. After McFadden (1993).

<table>
<thead>
<tr>
<th>$C_p$</th>
<th>Defect rate (ppm)</th>
<th>Duration of power outages per month</th>
<th>Number of misspelled words</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.33</td>
<td>317400</td>
<td>228.5 hours</td>
<td>159 per page</td>
</tr>
<tr>
<td>0.67</td>
<td>45600</td>
<td>32.8 hours</td>
<td>23 per page</td>
</tr>
<tr>
<td>1.00</td>
<td>2700</td>
<td>1.94 hours</td>
<td>1.35 per page</td>
</tr>
<tr>
<td>1.33</td>
<td>63</td>
<td>2.72 minutes</td>
<td>1 per 31 pages</td>
</tr>
<tr>
<td>1.67</td>
<td>0.57</td>
<td>1.48 seconds</td>
<td>1 per several pages</td>
</tr>
<tr>
<td>2.0</td>
<td>0.002</td>
<td>0.005 seconds</td>
<td>1 per small library</td>
</tr>
<tr>
<td>2.33</td>
<td>0.000003</td>
<td>0.00001 seconds</td>
<td>1 per large library</td>
</tr>
</tbody>
</table>

When deciding on what level of any process capability index to be considered as capable enough it is indeed important to base this decision on customer demands. Take for instance the two examples in table 3.1. If there is even one second of power outage per month, we directly react and get disappointed, just think about all the timers that have to be reset. On the other hand if we find one misspelled word in a book we are reading, it does not disturb us in the same way. Therefore, the power company and the publisher would probably find themselves on a different level on the "defect rate ladder".

If the customer demand is the basic level of what defect rate to fulfil, then there are basically two strategies for how to set goals for an improvement process aiming at even further reducing the defect rate. The first strategy is to successively increase the goal as the process is improved. The other strategy is to do as Motorola, and other companies after them, have done. Motorola clearly stated that all its processes should meet a defect rate of 0.002 ppm, which corresponds to $C_p = 2.0$. The basic idea of Motorola’s six-sigma program, as they call it, is presented in figure 3.4.
Figure 3.4 The basic concept of Motorola’s six-sigma program. The principal goal of every process within Motorola is to establish a process that is centred between the upper and lower specification level and where the distance from the centre of the specification interval to any of the specification limits is equal to six sigma for the studied process. Thereby the name six-sigma program. By achieving a process with these characteristics it is possible for the process to shift as much as 1.5 sigma in any direction without more than 3.4 ppm of the produced products would be nonconforming. From McFadden (1993), who built on Harry (1988) and Billington & Ahmadian (1990).

By setting the level for claiming a process capable this high, Motorola has established a certain security level for sudden changes. Changes that are almost certain to appear sooner or later. Motorola’s six-sigma program has proven very effective and many companies, both small and large, have copied their program, see, e.g., Pena (1990), McFadden (1993), Tadikamalla (1994) or Harry (1994).
When it comes to conscious gathering of data it would be fruitful to include some questions concerning the following topics:

- First of all it would be of interest to see if the studied organisations make any difference, what so ever, between machine capability studies and process capability studies.

- In order to see if the respondents' organisation really are making a difference between machine capability studies and process capability studies it would be suitable to ask the respondents to describe how the units measured are selected.

- It would also be of interest to see what levels of estimated process capability indices are considered to be the limit for claiming that a specific process is capable within different organisations.

3.1.4 Check the distribution of the process output

The inability of process capability indices to handle skewly distributed characteristics has already been discussed in section 1.3.6 and it will further be discussed in chapter 6. Therefore, no further presentation is made here. However, it is obvious that two processes with the same estimate of a given process capability index can correspond to a different percentage of nonconforming items, see figure 1.16.

When it comes to checking the distribution of the process output it would be fruitful to include some questions concerning the following topics:

- First of all it would be interesting to see if the distribution of the process output is checked or not.

- If the distribution of the output is checked it would be of interest to see what methods are used for this purpose.

- Perhaps the most interesting thing of all when it comes to checking the distribution of the process output is to see what actions are taken if the output is found to be skewly distributed.

3.1.5 Simultaneous use of several process capability indices

In chapter 1 the history of process capability indices has been carefully described. Today, there is an abundance of indices proposed. The development of these indices has all the time aimed at receiving a mea-
Part 1: Chapter 3, Theoretical and practical aspects

sure of capability that in the best possible way monitors changes both in process location and in the dispersion of the process, while still having as good statistical properties as possible.

Here some attempts are made to visualise the ability of different process capability indices to react to changes in location and dispersion of the monitored process.

According to the formulas of different process capability indices described in chapter 1 it is clear that all of them react to changes in dispersion of the monitored process. It is, however, not as clear how well the process capability indices react to changes in location of the monitored process. Figure 3.5 describes how the most common indices react to changes in process location. By looking at figure 3.5 it is obvious that $C_p$ does not at all react to changes in location, which is obvious from its definition and it has been indicated earlier in figure 1.11. Another interesting fact is that all process capability indices have the same value when the process is on target, given symmetrical specifications. It is also apparent that $C_{pm}$ reacts more rapidly than $C_{pk}$ to changes in location, but that $C_{pmt}$ reacts even more rapidly than both $C_{pk}$ and $C_{pm}$. The process capability indices $C_{pm}$ and $C_{pm^*}$ react in the same way since the target value $T$ is placed at the midpoint of the specification interval.
### Part 1: Chapter 3, Theoretical and practical aspects

#### Figure 3.5

A description of how some of the most common process capability indices react to a sudden change in location of the process output. In the example the standard deviation equals 2/3 and the target value $T$ is symmetrically placed within the specification interval. The indices $C_p$ to $C_{pm^*}$ are defined in equations (1.10) - (1.19). From Spiring (1991) and Deleryd (1993).

<table>
<thead>
<tr>
<th>Case</th>
<th>$\mu$</th>
<th>$C_p$</th>
<th>$C_{pu}$</th>
<th>$C_{pjk}$</th>
<th>$C_{pk}$</th>
<th>$C_{pm}$</th>
<th>$C_{pmk}$</th>
<th>$C_{pm^*}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13</td>
<td>2</td>
<td>1.5</td>
<td>2.5</td>
<td>1.5</td>
<td>1.11</td>
<td>0.83</td>
<td>1.11</td>
</tr>
<tr>
<td>2</td>
<td>14</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>2</td>
<td>2.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.11</td>
<td>0.83</td>
<td>1.11</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>0.63</td>
<td>0.32</td>
<td>0.63</td>
</tr>
<tr>
<td>5</td>
<td>17</td>
<td>2</td>
<td>3.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.43</td>
<td>0.11</td>
<td>0.43</td>
</tr>
</tbody>
</table>

![Diagram](image-url)
In figure 3.5 the comparison is based on the assumption that the target value is placed in the middle of the specification interval. In a similar way, an attempt to describe the ability of the same indices to react to changes in location of the process when the target value is not placed in the middle of the specification interval is given in figure 3.6. In figure 3.6 the target value is placed at the midpoint of the specification interval.

Figure 3.6 tells us once again that $C_p$ only measures potential capability, i.e. the capability if the process is perfectly centred between the specification limits, which is not the same thing as centred at the target value. Any user of $C_p$ should by now have realised $C_p$’s inappropriate-ness as a measure of capability.

The process capability indices $C_{pu}$, $C_{pl}$ and $C_{pk}$ do not consider that the target value is unsymmetrically placed in the specification interval since they as well as $C_p$ do not include the target value in the formula. There are versions of $C_{pk}$ presented in Kane (1986) that exchange $\mu$ for $T$ and therefore would consider an unsymmetrically placed target value, but these indices are not presented here.

The process capability index $C_{pm}$ does not seem to work very well in this case either. This can be realised by comparing case 3 and case 5 in figure 3.6. According to $C_{pm}$ these two cases are equally capable even though it is obvious that the percentage of nonconforming items is much larger in case 5, compared to case 3.

However, it is interesting to notice that $C_{pmk}$ and $C_{pm}$ seem to be able to handle situations where the target value is unsymmetrically, as well as symmetrically placed, within the specification interval.

Another way of visualising the ability of different process capability indices to react to changes in process location and at the same time even show their reaction to changes in process dispersion is to draw three-dimensional plots, see figure 3.7. On the $x$-axis a measure of dispersion is given according to $a = \sigma /((USL - LSL)/2)$ and on the $y$-axis a measure of deviation of the process location from the target value $T$ is given according to $|\mu - T|/d = |\mu - T|/(USL - LSL)/2$. On the $z$-axis the value of the process capability index is given. Since it is quite common to say that a process is capable if the process capability index exceeds 1.33, this limit has been chosen as an upper limit on the $z$-axis.
Figure 3.6  A description of how some of the most common process capability indices react to a sudden change in location of the process output. In the example the standard deviation equals 2/3 and the target value T is unsymmetrically placed within the specification interval. The indices $C_p$ to $C_{pm}^*$ are defined in equations (1.10) - (1.19). From Spiring (1991) and Deleryd (1993).
Part 1: Chapter 3, Theoretical and practical aspects

Figure 3.7  The ability of the process capability indices $C_p$, $C_{pk}$, $C_{pm}$ and $C_{pmk}$ to react to changes in dispersion and location of the monitored process is described by the three-dimensional plots. On the $x$-axis a measure of dispersion is given according to $\sigma/d = \sigma/((USL - LSL)/2)$ and on the $y$-axis a measure of deviation of the process location from the target value $T$ is given according to $|\mu - T|/d = |\mu - T|/((USL - LSL)/2)$. On the $z$-axis the value of the process capability index is given. Since it is quite common to say that a process is capable if the process capability index exceeds 1.33, this limit has been chosen as an upper limit on the $z$-axis. From Deleryd (1993).

From figure 3.7 it is once again clear that $C_p$ does only react to changes in process dispersion and not to changes of process location. The process capability index $C_{pk}$ reacts somewhat stronger to changes in process dispersion compared to $C_p$, while it also reacts to changes in
process location. The process capability indices $C_{pm}$ and $C_{pmk}$ react strongly to changes both in process dispersion and process location. By looking at the slope of the three-dimensional plots of $C_{pm}$ and $C_{pmk}$ it is clear that $C_{pmk}$ reacts somewhat stronger than $C_{pm}$. The steeper the slope the more sensitive the index is to changes in process dispersion and process location.

Since all indices have somewhat different characteristics it is often a good idea to use several of the indices simultaneously.

When it comes to the use of several process capability indices simultaneously it would be fruitful to include some questions concerning the following topics:

- First of all it would be suitable to ask if they use process capability indices at all. If process capability indices are used it would be of interest to see what indices are used in each organisation. If process capability indices are not used when conducting process capability studies, it would be of interest to know the reason why.

- It would also be of interest to see if any organisation uses alternative measures of capability.

### 3.1.6 Use of confidence limits

Any estimate of a given process capability index is based on a limited number of measurements made on units produced by the process. Therefore, even if two process capability studies are performed on the same stable process directly after each other, it is indeed natural to receive somewhat different estimates of the same process capability index in each study. This has been indicated in figure 1.14 and 3.3 and will be further illustrated and discussed in part 2.

Due to the fact that estimates of any process capability indices indeed are stochastic and not true values, it makes the decision of whether the process is capable or not somewhat complicated. One study might give the result $\hat{C}_{pk} = 1.28$ and the next study on the same stable process might give the value $\hat{C}_{pk} = 1.41$. If the limit for claiming a specific process capable has been chosen as $\hat{C}_{pk} \geq 1.33$, how is the practitioner supposed to handle this situation? One way of solving the problem would be to somehow calculate a level somewhat higher than 1.33. If this level is reached it guarantees, with some kind of certainty, that the estimated process capability index actually is larger than 1.33. Statistical theory provides such a method, it is called confidence intervals, or
confidence limits. The basic principle for how to use confidence limits for estimates of process capability indices is indicated by figure 3.8.

Figure 3.8 The 95% single-sided confidence limit for $\hat{C}_p$ is presented for $C_p = 1.33$. From the figure it is clear that the uncertainty of an estimated process capability index decreases as $n$ increases, where $n$ denotes the number of measurements used in each estimate. The figure assumes a normally distributed characteristic. As $n$ increases the confidence limit will approach a value of 1.33. The figure tells us that if our estimate of $C_p$ is based on 50 measurements and we want to be 95% confident that our estimate is larger than 1.33, the received estimate will have to be $\hat{C}_p \geq 1.60$. Figure 3.8 is derived by using formulas for confidence limits for $\hat{C}_p$, presented in Chou, Owen & Borrego (1990).

Due to the complexity of many process capability indices it is not easy to derive these confidence limits. Most of the calculations made are based on the assumption that the process characteristic is normally distributed. Kane (1986) has constructed confidence limits for $C_p$. For the more complex process capability indices $C_{pk}$ and $C_{pm}$, approximate confidence limits are derived by Marcucci & Beazely (1988), Chou, Owen & Borrego (1990), Bissell (1990), Boyles (1991) and Guirguis & Rodriguez (1992). Confidence limits for $C_{p_{mk}}$ and other process capability indices have not yet been established, as far as the author knows. The reason for the abundance of articles focusing on confidence limits for estimates of process capability indices is, as mentioned, that the confidence limits cannot be derived exactly. Therefore, different approximations are used by different researchers. Several resampling methods to create confi-
Part 1: Chapter 3, Theoretical and practical aspects

dence limits for $C_{pk}$ for various underlying distributions, is presented by Franklin & Wasserman (1992a-c). Brown (1994) uses a simulation study to derive confidence limits for $C_{pk}$ for skewly distributed characteristics.

When it comes to the use of confidence limits it would be fruitful to include some questions concerning the following topics:

- First of all it is of interest to see if practitioners make some efforts at all to somehow compensate for the uncertainty inherent in an estimate of a given process capability index.

- If practitioners in some way compensate for this uncertainty it would be interesting to see if they are using confidence limits or some other method.

3.2 Practical aspects

The practical aspects briefly discussed below have been identified during interviews with the reference group within Swedish industry. These practical aspects are of interest to include in the survey since they help to provide a more thorough picture of how process capability studies are conducted within the respondents organisations. The presentation of these practical aspects are not thoroughly based on existing research, but rather on the discussions between the author and the reference group.

3.2.1 Implementation aspects of process capability studies

Since the concept of process capability studies involves the use of some rather complicated statistical measures and at the same time includes some philosophical aspects of continuous improvements, a proper implementation of process capability studies would have to include some sort of introductory education and training.
When it comes to the introduction of process capability studies it would be fruitful to include some questions concerning the following topics:

- When the introduction was started. This result will help in the analysis.
- If there is a broadly accepted definition of capability within an organisation the introduction has probably been more thorough than otherwise. By giving their formulation of a definition the respondents would at the same time present their view of the concept of process capability studies.
- It would be suitable to include questions covering educational efforts within the respondents organisations. Educational efforts where the concept of process capability studies has been included.

3.2.2 Pressure between organisations to conduct process capability studies

A common scenario occurs in today’s industrial world when a company that has been successful with using statistical process control and process capability studies, asks its suppliers to do likewise. Often the company formally requests its suppliers to become certified as preferred suppliers by demonstrating that their processes are both in control and capable. This scenario has lead to the fact that the use of process capability studies has spread rapidly during the last decade. The key issue is the long-term capability of the supplier’s process.

However, according to Schneider and Pruett (1995), small suppliers typically do not have the resources or knowledge to fully apply statistical process control and process capability studies. Frequently, even large suppliers have this problem. Hence, the uncritical application of statistical process control and process capability studies that follows can lead to a misjudgement of the supplier’s long-term capability.
When it comes to pressure between organisations to conduct process capability studies it would be fruitful to include some questions concerning the following topics:

- Has the surveyed organisation experienced that some of its customers have articulated some wish or requirement that the organisation ought to be conducting process capability studies? One measure of the extent of these demands would be to measure how many customers that have articulated such demands. Of course, it would also be of interest to see how these demands have been formulated.

- It would also be of interest to see how common it is that the surveyed organisation themselves articulates these kind of demands towards their suppliers.

### 3.2.3 Setting of specifications

Specifications have been around since the industrial revolution, and perhaps even earlier, see, e.g., Jaikumar (1988). Previously in this thesis it has been shown how Taguchi suggests a strategy for setting specifications based on a scientific reasoning. However, the author’s experience is that in most cases the setting of specifications is based on past experience and in some cases based on no fact at all.

Since specifications is an important part of process capability studies it would be fruitful to include some questions concerning the following topics:

- How common is it that specifications are set, based on external customer demands or expectations?

- Since single-sided specifications effect what process capability indices to use it would be of interest to see how common they are.

- The importance of target values has earlier been emphasised in the thesis. Therefore, it would be interesting to see how common the use of target values is. The presence or absence of target values also effect what process capability indices to use.
3.2.4 Results achieved from using process capability studies
One of the most interesting questions is if the use of process capability
studies actually contributes to any improvements at all.

When it comes to results achieved from using process capability studies it would
be fruitful to include some questions concerning the following topics:

- To receive some measures of how large part of the processes within an organ-
  isation that was capable when they implemented process capability studies. Then
  this measure is to be compared with a similar measure of how large part of the
  processes that is capable today.

- Another interesting aspect is to see when the different organisations estimate
to have reached the goal when every process within the organisation will be
capable. As indicated both by figure 1.9 and 3.1 there is no upper limit of how
capable a process can become, but it would nevertheless be interesting to see
the practitioner's view of how long it takes from the implementation of pro-
cess capability studies until every process is acceptably capable.

- In would be interesting to see how the result from process capability studies are
  used and by whom.

3.2.5 Advantages and disadvantages of conducting process capability
studies

Every method has its advantages and disadvantages. When implement-
ing a new method it is extremely important to be aware of the advan-
tages and disadvantages with a certain method. By knowing these it
will be more likely that proper resources are allocated and that proper
education is provided.

When it comes to advantages and disadvantages from using process capability
studies it would be fruitful to include a question concerning the following topic:

- Quite simply ask the respondents to give their view of the advantages and
disadvantages associated with using process capability studies.
CHAPTER 4

PROCESS CAPABILITY STUDIES WITHIN SWEDISH INDUSTRY

In this chapter the result from questionnaire 1 will be presented and discussed. In order to make the presentation clear and easy to understand the questions have been translated and pasted in. The analysis is presented in the same order as the questions were asked in questionnaire 1. The result from the nonresponse analysis performed in connection to questionnaire 1 is presented and finally, the result from the questionnaire is summarised and a comparison between process capability studies in theory and practice is made.

4.1 Results from questionnaire 1

Questionnaire 1, which is presented in enclosure 3a was sent out to a total number of 764 organisations within Swedish industry. Of the respondents within these 764 organisations 205 answered the questionnaire and of these 205 respondents there were 101 who claimed that they were working in organisations where process capability studies are conducted and 104 who claimed that they did not.

When the questionnaires, answered by the respondents within the 101 organisations where process capability studies were conducted, were analysed more closely, it was obvious that four of these organisations did actually not conduct process capability studies since the respondents’ answers focused on implementations of other improvement methods. This leaves 97 questionnaires, filled in properly by respondents working within organisations where process capability studies are really conducted, to form a base for analysis. It was also found that a small number of the 97 respondents worked within the same large organisation. However, they worked at different locations in Sweden and the process capability studies were not identically conducted at these places. Therefore, it was considered important to use all
these filled in questionnaires in the analysis. By looking at their answers of question number 2 it was clear that they had filled in the question-naire based on experiences from their own part of the organisation.

Therefore, the fact that three large organisations within Swedish industry are represented by 2 respondents each in this study does not cause any large bias, if any, in the final results.

All the results presented below are based on the filled in questionnaires from the 97 respondents who worked in organisations where process capability studies are conducted. When suitable, the number of respondents who answered a specific question has been added to the figure texts.

4.1.1 A short description of the respondents

Of the 97 respondents, 73 worked in some sort of quality function within their own organisation. The other 24 respondents worked as top managers, production managers, sales personnel or statisticians.

4.1.2 Part 1, The respondents’ organisations

In order to describe the organisations, questions were asked about the number of employees and what line of business the organisations belonged to, see question number 3 and 4.
Based on the answers from the 97 respondents it is obvious that process capability studies are mainly conducted within large organisations, measured by the number of employees. Most of the 97 organisations have more than 100 employees, as seen in figure 4.1.

![Figure 4.1](image)

**Figure 4.1** The number of employees within the organisations where process capability studies actually are conducted. It is obvious that most of these organisations are fairly large, measured by the number of employees \((n = 97)\).

The answers to question number 4, concerning what lines of business the respondents' organisations were operating in, are summarised in figure 4.2.
The result from figure 4.2 is not very surprising since process capability studies is by tradition mainly a method used within manufacturing industries, i.e. the four categories at the top of figure 4.2, heavy manufacturing industry, precision-tool industry, processing industry and motor industry. The large number of organisations belonging to the motor industry is explained by the fact that suppliers to the motor industry are included in this category. Even if it is most common that process capability studies are conducted within manufacturing industries, figure 4.2 indicates that the concept of process capability studies also is applicable within other lines of businesses, which is implied by the lower seven categories in figure 4.2.
4.1.3 Part 2, The implementation of process capability studies

In order to establish an estimate of how long it takes from the implementation of process capability studies within an organisation until the moment when every process within that organisation is capable, questions number 5 and 21 were asked. The result from these questions are presented in figure 4.3.

5. When did you start conducting process capability studies and estimate process capability indices or other types of capability measures within your organisation?

21. When do you estimate that all processes within your organisation will be capable? Year:

![Figure 4.3](image)

*Figure 4.3 The figure illustrates when process capability studies were implemented within the respondents' organisations and when it is estimated that all processes within these organisations will be capable. For introduction year, n = 94, for finishing year n = 52.*

It is obvious that most organisations in this study have started the implementation of process capability studies after 1985 and most of the organisations estimate that all their processes will be capable before 2000. It must be remembered that the results in figure 4.3 indeed are estimates and can only be viewed as approximate figures. For instance, the definition of what is regarded as a capable process differs between organisations. One interesting remark is that six of the respondents claim that they never will experience the moment when every process is capable, since they believe that the definition of what is regarded as capable processes will automatically be changed as the processes become better. Since 52 of the respondents stated an introduction year as well as an estimated finishing year for the work with achieving
capable processes, it is possible to calculate the distribution of how long the respondents estimate that it will take from the implementation of process capability studies until every process within the organisation is capable. This distribution is shown in figure 4.4.

![Figure 4.4](image)

**Figure 4.4** The distribution of how long the respondents estimate that it will take from the implementation of process capability studies until every process within the organisation is capable ($n = 52$).

The distribution of how long it usually takes before all processes are capable within an organisation shows that this is a very lengthy process. Figure 4.4 shows that time spans of 5 to 20 years are quite common. A deeper analysis, based on the respondents' answers, was performed in order to see if it takes longer time to reach the goal with all processes capable within larger organisations compared to smaller ones. However, an effect like that could not be supported, based on the answers from the 97 respondents.

**Definitions of the concept of capability**

In order to see how the concept of capability is defined within Swedish industry, the respondents were asked if their organisations used any definition of capability. If the respondents organisation used a definition, these respondents were then asked to reproduce their definition, see question number 6. It was also possible for every respondent to give their own definition of capability, if their own organisation lacked one.
6. Do you have a formulated definition of capability within your organisation?

- Yes  - No

(If yes) 6a. Please reproduce the definition of capability used within your organisation.

(If no) 6b. If an accepted definition of the concept of capability is not existing within your organisation. How would you define your own definition of capability? Start for instance like this: When we talk about capability within our organisation we mean..................

There were 29 of the 97 respondents working in organisations where a definition of the capability concept existed. This leaves 68 organisations where process capability studies are conducted even though they lack an accepted definition of the capability concept. Of these 68 respondents there were 39 who tried to give their own definition of the concept of capability. Instead of giving every respondent’s definition of capability in this thesis, a summarised definition has been made by the author, based on all existing definitions which were expressed in the answers of the questionnaires. This definition is presented here:

*Capability is the ability of a process to produce products according to specified requirements.*

**Educational efforts**

Since the concept of process capability studies involves some statistical concepts, usually apprehended as rather difficult to perceive, the implementation of process capability studies would probably benefit from a proper education- and training-programme. In order to see if any education and training had been given in connection to the implementation of the process capability studies within the respondents’ organisations, question number 7 was asked.
7. Have any education efforts been carried out within your organisation, where questions concerning process capability have been included?

☐ Yes  ☐ No

(If yes) 7a. Please, describe the different parts of these education efforts shortly.

(If yes) 7b. Mark the categories of personnel who have received proper training and education concerning the concept of capability within your organisation.

☐ Managers
☐ "Middle managers"
☐ Constructors
☐ Production planners
☐ Production personnel
☐ Others: _________________________
☐ Others:

Since the respondents, in question number 7a, also were asked to quantify the contents of the training and education which had been given within their own organisation it could easily be judged whether the education had been relevant or not. If the training and education within a specific organisation included some basic statistical concepts combined with the theory of process capability studies it was considered that proper training and education had been given, within that specific organisation. It was found that in 71 of the 97 studied organisations, proper education and training had been given.

The distribution of which types of personnel that received this training and education, when implementing process capability studies within the respondents' organisations, is given in figure 4.5.

It is clear that it is mainly personnel directly involved in the actual manufacturing parts of the organisations, who first of all have been given proper training and education.
It is worth noticing that the top managers within these organisations have not received very much education and training concerning process capability studies. Only within 27 of the 97 examined organisations top managers have been given proper education. This fact may constitute a major problem since a prerequisite for making the management allocating the resources necessary in the implementation process is that they are aware of the different parts of the concept of process capability studies.

4.1.4 Part 3, Measures of capability used within the respondents’ organisations

Process capability indices are often used to measure the capability of processes. However, there are also other kinds of measures available. In the questionnaire, question number 8 was asked in order to give a picture of what type of process capability indices that are used within Swedish industry today.
8. Are any process capability indices used within your organisation?

☐ Yes  ☐ No

(If yes) 8a. Are any of the following indices used within your organisation?

The notations in the formulas of the indices have the following notations:

USL = The upper specification limit
LSL = The lower specification limit
μ = The expected value of the process output
σ = The standard deviation of the process output
T = The target value

\[ Cp = \frac{USL - LSL}{6\sigma} \]  ☐ Yes  ☐ No

\[ Cpk = \frac{\text{Min}(USL - \mu, \mu - LSL)}{3\sigma} \]  ☐ Yes  ☐ No

\[ Cpm = \frac{USL - LSL}{6\sqrt{\sigma^2 + (\mu - T)^2}} \]  ☐ Yes  ☐ No

(If no) 8b. Why is none of the indices presented above used within your organisation?

There were 85 of the 97 respondents who claimed that process capability indices were used within their respective organisations. The most frequently used process capability indices are presented in figure 4.6.

![Figure 4.6](image)

**Figure 4.6** The figure shows the process capability indices most frequently used within the respondents' organisations.
By looking at figure 4.6 it is obvious that the process capability indices $C_p$ and $C_{pk}$ are most popular. The process capability index $C_{pm}$ is only used in 17 of the 97 organisations. One interesting aspect, which is not shown by figure 4.6, is that 64 of the organisations use both $C_p$ and $C_{pk}$ and that 15 of the organisations use $C_p$, $C_{pk}$ and $C_{pm}$ in their process capability studies. One explanation to the relatively limited use of $C_{pm}$ is that only few of the organisations have started to use target values. Since these indices have quite different characteristics it is often a good idea to use several process capability indices in the same study. By looking at the respondents' answers it is clear that an organisation often starts by using the process capability index $C_p$, and then moves towards a more frequent use of $C_{pk}$ when they realise that $C_p$ only expresses potential capability. When the work with process capability studies matures within an organisation and they start to address target values to each specification, it becomes more natural to use the process capability index $C_{pm}$.

In order to identify the reasons why some organisations do not use process capability indices, question number 8b, was asked. The answers to this question have been categorised into the following three categories:

- some of the organisations had just recently started with process capability studies and not yet been able to decide what index/indices to use.

- a number of respondents mentioned that they never had heard of the process capability indices $C_{pk}$ or $C_{pm}$.

- some of the respondents claimed that their organisations had no intentions to use process capability indices. These organisations mainly focused on measures of process variation as measures of process capability.

It is worth noticing that indices like $C_{pmk}$ and $C_p(u,v)$ are not used at all within the respondents' organisations. A natural explanation is perhaps that these indices are quite new and have not yet been focused by industry. Another explanation is that these indices can be apprehended as quite complicated and therefore difficult to use.
Alternative measures of process capability

Question number 9 was asked to see what type of measurements of capability are used, besides the process capability indices $C_p$, $C_{pk}$ and $C_{pm}$.

9. Are there any alternative measures of capability, different from the traditional process capability indices, used within your organisation?
   
   ☐ Yes  ☐ No

   (If yes) 9a. How do you define these alternative measures of capability? (Please, enclose some more information concerning these measures, together with the questionnaire in the response envelope.)

There were 21 of the 97 respondents who mentioned different measures of process capability. Their answers have been categorised into the following categories.

- Number of complaints, precision of delivery.
- Target centring, measured by $CM = \frac{2|T-\mu|}{USL-LSL}$.
- The fraction of measurements observed within the specification limits, measured in percent.
- The fraction of measurements observed outside the specification limits, measured in parts per million, ppm.
- Different measures of process variation, mainly focused on 6σ-programmes.
- The fraction of measurements observed within the central 70% of the specification interval.

Pressure between organisations to conduct process capability studies

One possible reason why an organisation starts conducting process capability studies is that the customers of the organisations require it. In order to estimate how common it is that customers require that process capability studies should be conducted within the suppliers organisations, question number 10 was asked.
As a result, it was found that 52 of the 97 respondents had experienced some sort of requirement from their customers, that their own organisations was expected to be conducting process capability studies. This is a very interesting figure since it is possible that the implementation of process capability studies is not made with the same enthusiasm as if the implementation had been more voluntary. A natural result from a customer-forced implementation of process capability studies is that it is made because the organisation has to and not because the organisation sees the possible benefits from such an implementation.

By question number 10a it was found that 249 external customers constitute the requirement that these 52 organisations should conduct process capability studies.

In order to clarify how these customers have formulated their requirements, question number 10b was asked. It was found that the 249 external customers could be divided into the following two categories:

- External customers who simply require that their supplier shall conduct process capability studies, without any specific demands on what process capability indices to use or what levels to reach. It was 20 of the 52 organisations that had customers belonging to this first category.

- External customers who had precisely specified the process capability indices that should be used and what levels that were expected to be reached. In this second category it was very common that one or more of the following requirements had been stated; $C_{pk} \geq 1.33$, $C_{pk} \geq 1.5$ or $C_{pk} \geq 2.0$. Also this category consisted of 20 organisations.

It seems to be a fact that it is exclusively the process capability index $C_{pk}$ that is used when some organisation requires that their supplier shall be conducting process capability studies. Only one respondent has
stated that one of their customers has required that they shall distinguish between process capability studies and machine capability studies. No respondent claims to have been given any customer-instructions on how many measurements to make in each study, or how the measurements should be made.

It is also interesting to study how common it is that the respondents, who claim that process capability studies are conducted within their own organisation, also require that their own suppliers shall do the same. This topic was covered by question number 11.

11. Does your organisation require that your suppliers shall be conducting process capability studies and that process capability indices shall be used as measures of capability within their organisations?

☐ Yes ☐ No

(If yes) 11a. Please, give an estimate of how many of your suppliers to whom you have addressed such demands.

(If yes) 11b. Please, give an example of how these requirements have been formulated.

It was found that 43 of the 97 respondents actually spread such requirements to a total number of 486 suppliers. It is worth noticing that this figure seems to have been doubled compared to how many of the respondents who had customers who required that the respondents’ organisations should conduct process capability studies, see question number 10 a.

It was 19 of the respondents’ organisations where they only required that their suppliers should conduct process capability studies, without specifying demands on what process capability indices to use or what levels to reach.

It was 19 organisations where the respondents’ organisations had gone further and gave specific instructions on what process capability indices to use and on what levels to reach. These requirements were usually formulated as $C_{pk} \geq 1.33$, $C_{pk} \geq 1.5$ or $C_{pk} \geq 2.0$.

In order to see in what lines of businesses it is most common to state requirements towards suppliers that they should conduct process capability studies, figure number 4.7 was developed.
Figure 4.7 The figure shows how many of the respondents’ organisations within different lines of businesses that expect their suppliers to be conducting process capability studies ($n = 43$).

As indicated by figure 4.7 it is obvious that it is mostly organisations within heavy manufacturing industry, motor industry and precision-tool industry that expect their suppliers to be conducting process capability studies.

4.1.5 Part 4, Setting of specifications

The way specifications are set directly effects the results from process capability studies. If the specification interval is large, it clearly enhances the chances of claiming that a specific process is to be capable. By this fact, question number 12 was asked about how specifications are set within Swedish industry.
12a. Please, give an estimate of how large part of the specifications within your organisation that are set on the basis of demands articulated by external customers. Approximately ____%. 

12b. Please, give an estimate of how large part of the specifications within your organisation that are single-sided. Approximately ____%. 

12c. Please, give an estimate of how large part of the specifications within your organisation that incorporates a target value, i.e. a value within the specification range that the operator should aim at. Approximately ____%. 

The result from question number 12a, where the respondents were asked to estimate the percentage of specifications set, that are based on external customers’ needs or expectations, is presented in figure 8.

![Figure 4.8 The distribution of the percentage of specifications set, which are based on external customer demands (n = 83).](image)

The shape of the distribution in figure 4.8 is rather interesting. It seems as if the voice of the customer is either present or not present within the respondents’ organisations. In some organisations almost all specifications are in one way or another based on external customer demands. On the other hand, in some organisations the specifications are set only on internal basis.

The result from question number 12b, where the respondents were asked to estimate the percentage of single-sided specifications within their own organisation, is presented in figure 4.9.
It is clear that single-sided specifications are quite common within the respondents' organisations. This fact indicates that a useful process capability index should be able to handle single-sided distributions. This might be one reason why the process capability index $C_{pk}$ is relatively popular.

The result from question number 12c, where the respondents were asked to estimate the percentage of specifications that are complemented with a target value, is presented in figure 4.10.
From figure 4.10 it is clear that the concept of using target values seems to be either present or not present within the respondents' organisations.

4.1.6 Part 5, Process capability studies within the respondents' organisations

In order to find out how process capability studies actually are conducted within Swedish industries, question number 13 was asked. Indirectly, these questions tell us how data are gathered when the respondents' organisations are conducting process capability studies.

<table>
<thead>
<tr>
<th>13.</th>
<th>Do you make any distinction between machine capability studies and process capability studies within your organisation?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>□ Yes □ No (If No, go on to question 13e.)</td>
</tr>
<tr>
<td>(If yes) 13a.</td>
<td>How are the measured units selected when you are conducting a <strong>machine capability study</strong> within your own organisation and <strong>how many</strong> units are usually used in each study?</td>
</tr>
<tr>
<td>(If yes) 13b.</td>
<td>If process capability indices are used when you are conducting <strong>machine capability studies</strong>: What lower level of these estimated process capability indices is used for claiming a specific process capable?</td>
</tr>
<tr>
<td>(If yes) 13c.</td>
<td>How are the measured units selected when you are conducting a <strong>process capability study</strong> within your own organisation and <strong>how many</strong> units are usually used in each study?</td>
</tr>
<tr>
<td>(If yes) 13d.</td>
<td>If process capability indices are used when you are conducting <strong>process capability studies</strong>: What lower level of these estimated process capability indices is used for claiming a specific process capable?</td>
</tr>
<tr>
<td>(If no) 13e.</td>
<td>How are the measured units selected when you are conducting a <strong>capability study</strong> within your own organisation and <strong>how many</strong> units are usually used in each study?</td>
</tr>
<tr>
<td>(If no) 13f.</td>
<td>If process capability indices are used when you are conducting <strong>capability studies</strong>: What lower level of these estimated process capability indices is used for claiming a specific process capable?</td>
</tr>
</tbody>
</table>
When analysing the result from question number 13 it is clear that 46 of the respondents claimed that a distinction is made between process capability studies and machine capability studies within their own organisation.

The results from question number 13 are presented in figure 4.11 - 4.15.

![Figure 4.11](image)

Figure 4.11  The distribution of how many measurements that are made in each machine capability study within the respondents' organisations where a difference is made between process capability studies and machine capability studies (n = 44).

Those respondents who claimed that machine capability studies were conducted within their own organisations also made it clear that the measurements then were made on units produced straight after each other, which indicates that they really are conducting machine capability studies. It was most common to make 50 such measurements.
Figure 4.12 The distribution of how many measurements made in each process capability study within the respondents' organisations where a difference is made between process capability studies and machine capability studies. One respondent claimed that they perform 1000 measurements. This respondent has been left out in the figure in order to make it more clear (n = 42).

The respondents within organisations where a difference is made between process capability studies and machine capability studies claimed that when process capability studies are conducted, the measurements are made on randomly selected units produced during a longer time span, in order to include all components of variation within the process. This procedure indicates that they are really conducting process capability studies. As in the case of machine capability studies, it was most common to make 50 measurements. Some of the respondents mentioned that when they are conducting process capability studies, measurements are used, which in the first place were produced when drawing control charts. It seems to be quite common to use 25 subgroups of 5 measurements each, as a base for an individual process capability study.

The results from questions number 13b and 13d, which focused on the levels of different process capability indices that were considered as minimum levels for claiming the machine or process capable, are compiled in figure 4.13. When analysing the result from questions number 13b and 13d it was clear that the process capability indices $C_{mk}$ and $C_{pk}$ were used exclusively. In figure 4.13, the "*" indicates that it is an estimated value.
Part 1: Chapter 4, Process capability studies within Swedish industry

Figure 4.13 The figure shows the levels of estimated process capability indices that are used within the respondents’ organisations in order to judge whether processes are capable, when conducting machine capability studies and process capability studies.

It is obvious that the levels for claiming processes capable are slightly higher for machine capability studies compared to process capability studies, which is quite natural since less components of variation are included in the machine capability study. From figure 4.13 it is clear that when conducting process capability studies it is common to set the level for claiming the process capable at $C_{pk}^* \geq 1.33$. When conducting machine capability studies the levels for claiming the process capable are more fluctuating, but it is quite common that the level is set at $C_{mk}^* \geq 1.67$.

There are 22 of the respondents who worked within organisations where no difference was made between machine capability studies and process capability studies. These respondents filled in questions 13e and 13f, and the analysis of these questions is presented below.
Figure 4.14 The distribution of how many measurements made in each capability study within the organisations where no difference is made between machine capability studies and process capability studies ($n = 22$).

The organisations where no difference between how machine capability studies and process capability studies are conducted, are simply referred to as organisations that only conduct capability studies, in order to make the text easier to read.

By looking at figure 4.14 it is clear that even among the organisations that only are conducting capability studies it is quite common to use 50 measurements in each study. These 22 respondents could not describe if these measurements were made on units produced straight after each other or not, which clearly indicates that the difference between machine- and process capability studies was not known.

Upon analysing the result from questions number 13a, 13c and 13e, i.e. the questions related to the number of measurements used in machine capability studies (13a), process capability studies (13c) and those organisations that are only conducting capability studies (13e), it is clear that the lowest number of measurements is used within the category of organisations that only are conducting capability studies, see figure 4.15.
Part 1: *Chapter 4, Process capability studies within Swedish industry*

Figure 4.15  A comparison of how many measurements that are used in each study within organisations that are conducting machine capability studies (13a), process capability studies (13c) and those organisations that only are conducting capability studies (13e). In the box-plots, the upper and lower 10%-percentiles of each distribution are cut off to make it more understandable.

Another aspect, indicated by figure 4.15, is that the largest amount of measurements are made when process capability studies are conducted, which is a quite natural result since these studies should include all components of variation of the process monitored.

**Statistical control prior to the use of process capability studies**

Another important aspect when conducting process capability studies is that the process ought to be in statistical control before the study is conducted. A process capability study focusing a process which is not in statistical control only tells us if the process is capable right now, and nothing can be predicted about the behaviour of the process in the near future. One possible way to judge whether a process is in statistical control or not is to actively use control charts. In order to find out to what extent the respondents’ organisations use control charts in connection to their process capability studies, question number 14 was asked.
14. Are the process capability studies conducted within your organisation somehow connected to some form of process control where control charts are used?

☐ Yes ☐ No

(If yes) 14a. Please, give a short description of how the use of control charts is linked to the process capability studies conducted within your organisation.

When analysing the result from question 14 it was clear that of the 97 respondents who, in question number 1, claimed to be working in organisations where process capability studies are conducted, there were 41 who mentioned that control charts are used in connection to their process capability studies. By looking at their written comments in question number 14a, it was clear that these 41 respondents could be divided into the following two groups:

1 Respondents working in organisations where control charts are used before process capability studies are conducted, in order to verify if the process is in statistical control or not.

2 Respondents working in organisations where it is clearly stated that the process must be capable before control charts are applied.

Since a prerequisite for conducting process capability studies properly is to establish statistical control within the process, it is quite surprising to see that some organisations clearly state that the process must be capable before control charts are applied. The distribution of these two categories is illustrated in figure 4.16.
Figure 4.16 The figure shows the connection between the use of control charts and process capability studies within some of the respondents' organisations. From a theoretical point of view, a SPC-programme where control charts are used actively in order to verify if the process is in statistical control, should precede a process capability study if an estimate of the capability of the process within the near future is desired. In the figure the abbreviation PCS stands for process capability studies (n = 41).

Handling of uncertainty

When conducting process capability studies, some units produced in the process monitored are selected and measured. Based on these measurements, the process is then claimed to be either capable or not capable. Of course, the confidence of this procedure is clearly affected by the number of measurements made. The more measurements used in each study, the more confident the result will be. Since the estimates of the process capability indices is based on measurements performed on randomly selected units from the process, the indices themselves will vary, even if the process is in statistical control. In order to find out how the uncertainty of the estimated process capability indices is handled within Swedish industry, question number 15 was asked. The result from question number 15 is presented in figure 4.17.
15. What alternative does best describe the way you are handling the uncertainty of the received estimates of process capability indices when you are conducting process capability studies within your organisation.

- We do not at all consider the uncertainty that can be involved in the estimated process capability indices.
- We use confidence limits to assure, with a given certainty, that the received estimates of the process capability indices are larger than a certain value.
- Other alternative:

Figure 4.17 The figure shows that within 78 of the respondents' organisations, no consideration is made to the uncertainty of the estimated values of the process capability indices. Confidence limits are only used within 10 of the respondents’ organisations (n = 88).

In figure 4.17, one of the most interesting findings in this study is presented. Within as much as 80% (78/97) of the respondents’ organisations, no consideration is made to the uncertainty of the estimated values of the process capability indices. The importance of making such considerations becomes even more relevant, since it is shown from figure 4.15 that it is quite common that process capability studies are based on a relatively small number of measurements.

The respondents who had chosen to make comments in the open part of question number 15, gave comments which revealed that they did not really understand why estimated process capability indices include a certain amount of uncertainty.
Use of capable gauges

It is of importance to verify that the process monitored in a process capability study is in statistical control before the study is initiated and of course it is also important to know how to handle the uncertainty within the estimated values of the process capability indices. But it is even more important to be fully aware of the capability of the measurement equipment, the gauges, used in the process capability studies. If the measurements are made with inappropriately calibrated gauges it is of course not at all possible to trust the results from that process capability study. Based on these facts, question number 16 was asked. The result from question number 16 is presented in figure 4.18.

16. Do you study the capability of the gauges used when you are conducting process capability studies within your own organisation?

☐ Yes   ☐ No

(If yes) 16a. Please, give a short description of how the capability of the gauges used when you are conducting process capability studies, is insured.

Figure 4.18 A description of how the capability of the gauges used in process capability studies is insured, or not insured (n = 97).
There were 30 of the respondents who claimed that the capability of the gauges used when conducting process capability studies were insured by performing, repeatability and reproducibility studies, so called R&R-studies. When testing repeatability, a given unit is measured several times with the same gauge using the same operator under constant temperature etc. The aim is to establish a measure of the inherent spread of the gauge. When conducting a reproducibility test, the same gauge is used, but all operators working with a specific gauge are involved. The aim of this study is to monitor the spread between operators.

There were 16 of the respondents who claimed that the average value of the gauges was calibrated against a measuring-rod, but they did not at all focus on the inherent spread of the gauges or on the spread between operators in some form of R&R-study.

As much as 53% (51/97) of the respondents claimed that the capability of the gauges within their organisations was not checked. This result seems rather strange. It simply cannot be true that so many organisations do not calibrate their gauges. However, if looking at the formulation of question number 16 it is not obvious that the respondents should mention something about calibrating gauges since the question focuses on measuring the capability of gauges.

It is of importance to use capable gauges when conducting process capability studies but it is also important to choose a gauge which has an inherent spread which is neglectable in comparison with the specification interval of the studied characteristic. In order to get a picture of how this problem is handled in Swedish industry, question number 17 was asked.

17. Are there any articulated requirements within your organisation of how large the inherent dispersion of the gauges used might be compared to the specification range for the characteristic measured?

☐ Yes    ☐ No

(If yes) 17a. Please represent the requirements used within your organisation, for how large the inherent dispersion of the gauges used might be compared to the specification range for the characteristic measured?

When analysing the result from question number 17 it was clear that within 38 of the respondents’ organisations, specific routines existed which controlled what gauge to use when measuring a specific characteristic. A majority of these 38 respondents claimed that the inherent
spread of the gauge must not exceed 10% of the specification interval of the characteristic studied.

**Checking the distribution of the process output**

Some theoretical aspects of the concept of process capability studies relies on the assumption that the process output is normally distributed. For instance, if it is of interest to compare the capability of two processes it is important to check if the output from both these processes can be described with the same distribution, usually with a normal distribution. In order to see how the respondents' organisations check whether the process output is normally distributed or not, question number 18 was asked.

18. Do you check the distribution of the process output, when you are conducting process capability studies within your organisation, to see if it is normally distributed or not?

- Yes  - No

(If yes) 18a. Please, mark the methods used to check if the process output is normally distributed or not.

- Histogram
- Probability plotting paper for the normal distribution
- A statistical test, namely: ____________________________
- Other method: ____________________________

(If yes) 18b. Please, describe how you act if you find that the process output is skewly distributed rather than normally distributed, when you are conducting process capability studies?

Of all 97 surveyed organisations, there were 77 organisations that regularly check whether the process output is normally distributed or not. The methods used when checking the process output are described in figure 4.19.
Figure 4.19  The different methods used when determining whether the process output is normally distributed or not.

Histograms and use of probability plotting paper for the normal distribution are the two most widely used methods for determining whether the process output is normally distributed or not. What is not shown in figure 4.19 is that within 36 of the respondents' organisations, both histograms and probability plotting paper for the normal distribution were used when determining the distribution of the output. The two respondents who mentioned some sort of statistical test, mentioned the Chi-square-test. There were eight of the respondents who used computer facilities when determining whether the process output is normally distributed or not.

Figure 4.19 shows that within a large number of the respondents' organisations the shape of the process output is checked. But checking whether the process output is normally distributed or not is only one side of the problem. It is perhaps even more important to know how to act if the process output is found to be skewly distributed. In order to find out how the respondents' organisations handle skewly distributed process outputs, question number 18b was asked.

A very interesting finding was discovered when analysing the results from question 18b. It seems as if some respondents believe that if the process output is not normally distributed, there is some systematic cause which gives a skewly distributed output and if this systematic cause is identified and eliminated, then the process output will automatically become normally distributed. Few of the respondents have indicated that they are aware of the fact that a skewly distributed out-
put sometimes can be just as natural as one normally distributed. Only 10 of the respondents seem to have some sort of strategy for conducting process capability studies when the process output is skewly distributed. The most commonly used strategy is Clements’ method, see Clements (1989). On the other hand, it seems as if other respondents just make another sample when they find that the first one was skewly distributed, and hope that this second sample will be more normally distributed, which of course is a rather questionable strategy. Another strategy which seems quite common is simply to stop the process capability studies when it is found that the process output is skewly distributed, which is very unfortunate since the study can give so much valuable information. However, it is not very surprising that different strategies for conducting process capability studies when the process output is skewly distributed have appeared, since a well established and at the same time theoretically sound strategy does not exist today.

4.1.7 Part 6, Achieved results from process capability studies

To get a picture of how far the respondents’ organisations have come in the process of achieving all processes within the organisation capable, the respondents were asked to estimate the percentage of capable processes when they started to conduct process capability studies and the percentage of capable processes today, see questions number 19 and 20.

<table>
<thead>
<tr>
<th>Question</th>
<th>Description</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.</td>
<td>Please, give an estimate of the percentage of capable processes within your own organisation when you started monitoring the capability of your processes.</td>
<td>Approximately %</td>
</tr>
<tr>
<td>20.</td>
<td>Please, give an estimate of the percentage of processes within your own organisation that are capable today according to the requirements that you have set up for a capable process.</td>
<td>Approximately %</td>
</tr>
</tbody>
</table>

The result from these questions are shown in figure 4.20 and 4.21. First of all the distribution of the percentage of capable processes when starting to conduct process capability studies (question number 19) and the distribution of the percentage of capable processes today (question number 20), is shown in figure 4.20.
Figure 4.20  It is clear that the percentage of capable processes has increased quite dramatically since process capability studies were implemented within the respondents' organisations. In the box-plots, the upper and lower 10%-percentiles of each distribution are cut of.

Figure 4.20 indicates that the percentage of capable processes definitely has increased within the respondents' organisations.

There were 66 respondents who gave both an estimate of the percentage of capable processes when implementing process capability studies and an estimate of the percentage of capable processes today. In order to further analyse the increase of capable processes, the differences between these estimates given, are illustrated in figure 4.21.
Figure 4.21 The distribution of the increase of capable processes, measured in percentage units \((n = 66)\).

It is of interest to notice that some of these organisations have improved as much as 50 percentage units or more. These organisations have most certainly experienced a large drop in the number of defective units produced. All organisations but one have experienced an increase in the percentage of capable processes. This organisation has been left out in figure 4.21. The reason for a decrease within one organisation is that during the process of achieving capable processes, the definition of what is to be considered as a capable process has been augmented within this specific organisation.

**Different applications of the result from the process capability studies**

It is more and more common to conduct process capability studies within Swedish industry, which for instance is indicated by figure 4.3. How the organisations that conduct process capability studies use the results from these studies has been reflected in question number 22.

22. Please, give a short summary of how the result from the process capability studies conducted within your organisation is used.

All respondents' answers have been categorised into 16 different ways of using the result from the process capability studies. There are 13 of these ways of using the result that are illustrated in figure 4.22.
Each one of the 13 different ways of using the result from the process capability studies, conducted within the respondents’ organisations are described more in detail below.

A. **A basis in the improvement process.** Using the result from process capability studies in the improvement process was the most common way of using the result. The respondents who mentioned this application claimed that process capability studies constituted a part of the overarching improvement process.

B. **Alarm clock.** The respondents who mentioned that the results from process capability studies were used as an alarm clock if a specific process suddenly changed for the worse, did not express the same proactive attitude as the respondents of category A, who mentioned that the result formed a base in the improvement process.

C. **Specifications for investments.** By looking at the result from the process capability studies the organisations know the capability of
their processes. This way the organisations know what capability must be expected from newly purchased machines. By giving specifications for levels of process capability indices, expected to be reached by new machines, the purchasing process is facilitated. Surprisingly, this way of using the result from the process capability studies, came as high as in "third place".

D. Certificate for customers. In order to make it easier for customers to trust that the purchased products are capable, the supplier is able to attach the result from the process capability studies conducted when the actual products were produced, with the delivery. Based on this knowledge, the customer knows if it is possible to use these products directly or if some sort of inspection must be performed.

E. A basis for new constructions. Within 10 of the respondents' organisations the result from the process capability studies are used actively in the construction process. By knowing the capability of the production processes the designer knows how to set reasonable specifications in order to make the products producable. If there is a need for more narrow specifications than the own processes are able to meet, then decisions have to be made on either improvements of present machines or acquisition of new ones.

F. Control of maintenance efforts. By continuously conducting process capability studies it is possible to see if some machines gradually are deteriorating. In this way maintenance efforts can be planned.

G. Specifications for introducing new products. Some of the respondents' organisations demand that prior to the market release, the processes producing that specific product must be capable in order to avoid problems and complaints.

H. Reasonableness of customer demands. By conducting process capability studies the organisations are well aware of how capable their own processes are. By knowing the capability of all processes, it is possible to directly inform customers whether it is possible to produce the product they are asking for or not. Thereby, future misunderstandings are avoided at an early stage.

I. Motivation of co-workers. There were six of the respondents who mentioned that the result from the process capability studies were used for motivating co-workers. By making it possible for all co-
workers to follow the progress of the improvement process, aiming at achieving capable processes, everyone was encouraged and when they experienced that many earlier problems suddenly disappeared, motivation had clearly increased.

J. Priorities in the improvement process. The resources allocated for investments are often limited. Then the result from the process capability studies can help to identify the processes where the need for new machines is impending, in order to optimise the whole chain of production processes. If an incapable machine constitutes a bottleneck, improvement efforts should of course first of all be directed to this machine.

K. Base for inspection activities. Based on the result from the process capability studies, it is possible to determine how much the process output from an incapable process has to be inspected. Within some of the respondents' organisations all units produced in an incapable process are inspected.

L. Receipt for improvements. If the capability of the processes are monitored constantly, then the results of improvement efforts initiated ought to be reflected in the results of the process capability studies.

M. Quality improvement programmes. Only three of the respondents mentioned that process capability studies form a base in the improvement programmes within these organisations. These programs can for instance be compared with Motorola’s six-sigma programme. It is somewhat surprising that only three of the respondents' organisations have realised the advantages of using such a strategy.

The areas of using the result from the process capability studies described above were mentioned by three or more of the respondents. However, the following applications were mentioned by single respondents.

- The right operator at the right machine. This organisation placed more experienced operators in machines that were incapable and hard to control.

- Certificate usable at audits. When ISO 9000 audits were conducted, the result from the process capability studies came in handy.
A part of the bonus system. One organisation had made a connection between the progress of the improvement process focused on achieving all processes capable, and the bonus system.

It is worth noticing that 20 of the respondents did not answer question number 22. Maybe, it was found too hard to answer or perhaps they did not know why they were conducting process capability studies.

The different fields of application of the result from the process capability studies have been described above. By asking question number 23, it was investigated what categories of personnel who actually have an interest in the result from the process capability studies. The result from question number 23 is presented in figure 4.23.

23. What categories of personnel are most interested in the result from the process capability studies conducted? Mark the category most interested with a number 1, and the second most interested category with a number 2 and so on.

- Managers
- "Middle managers"
- Constructors
- Production planners
- Production personnel
- Others: _____________________________
- Others: _____________________________
Middle managers
Production personnel
Top managers
Production planners
Constructors
Quality related personnel
Sales personnel
Maintenance personnel

Average value

Figure 4.23 The figure describes what categories of personnel within the respondents' organisations that actually have an interest in the results from the process capability studies. The analysis of question number 23 has been made by transforming the respondents' answers. If a respondent had mentioned that a specific category of personnel first of all used the result, then this category has been given the highest rank 5, on a scale from 0 to 5, where 0 means that this specific category of personnel never uses the result from the process capability studies conducted within that specific organisation. Then the average of all respondents' answers for a specific category of personnel has been calculated and these average values are presented in the figure.

It is clear that the result from the process capability studies conducted are mainly used by categories of personnel working close to the actual production processes. It is interesting to see that top managers frequently seem to be quite interested in the result from the process capability studies.
4.1.8 Part 7, Advantages and disadvantages of process capability studies

There are advantages and disadvantages connected to most methods. In order to investigate the respondents' views of the advantages and disadvantages of the concept of process capability studies, questions number 24 and 25 were asked.

24. Please, describe the three major advantages of conducting process capability studies, experienced within your organisation.

25. Please, describe the three major disadvantages of conducting process capability studies, experienced within your organisation.

The advantages of conducting process capability studies could be categorised according to figure 4.24.

![Advantages Chart]

Figure 4.24 The respondents' views of the advantages of conducting process capability studies.
First of all it is obvious that by conducting process capability studies knowledge about the processes is gathered which makes it easy to base decisions on facts. Improvement priorities are identified and the result is very rewarding, better products, more satisfied customers and also a higher level of motivation among co-workers.

The mentioned disadvantages of the concept of process capability studies are presented in figure 4.25.

<table>
<thead>
<tr>
<th>Disadvantages</th>
<th>Number of respondents</th>
</tr>
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<tbody>
<tr>
<td>Resource consuming</td>
<td></td>
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<tr>
<td>Difficult theory</td>
<td></td>
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<tr>
<td>Hard to motivate co-workers</td>
<td></td>
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<tr>
<td>No quick results</td>
<td></td>
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<tr>
<td>Difficult analysis</td>
<td></td>
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<tr>
<td>Extensive education efforts needed</td>
<td></td>
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<tr>
<td>Hard to determine what to measure</td>
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<tr>
<td>Not suitable for short runs</td>
<td></td>
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<tr>
<td>Different indices give different results</td>
<td></td>
</tr>
<tr>
<td>How to handle skew distributions?</td>
<td></td>
</tr>
<tr>
<td>Difficult to apply for attribute data</td>
<td></td>
</tr>
<tr>
<td>Difficult to apply for service industries</td>
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</tbody>
</table>

Figure 4.25 The respondents’ views of the disadvantages of conducting process capability studies.

In order to conduct process capability studies properly, appropriate resources have to be allocated. First of all it is a matter of time and money. Since the theory of process capability studies often is apprehended as difficult to conceive the importance of proper education efforts is endorsed. The fact that the method does not give any quick results, also indicated by figure 4.4, emphasises the importance of enough resources allocated in order to achieve capable processes. The difficulty of the theoretical aspects of process capability studies, combined with the fact that the method does not give any quick results
might make it hard to motivate co-workers. However, despite these dis-
advantages figure 4.20 proves that the percentage of capable processes
increase when an organisation actively work with process capability
studies.

When looking closer at the advantages and disadvantages of
conducting process capability studies, presented in figure 4.24 and 4.25,
it is interesting to see that some respondents believe that process capa-
bility studies increases co-worker motivation while others experiences
that it is hard to motivate co-workers.

4.2 Nonresponse analysis

Questionnaire number 1, presented in enclosure 3a, was sent out to 764
organisations. Of these organisations there were 205 that answered.
This leaves 559 organisations that for some reason did not answer
questionnaire 1. In order to find out why they did not answer, a nonre-
sponse analysis has been performed. Since all respondents of ques-
tionnaire 1 gave their name and address together with their filled in
questionnaire, it was possible to identify all 559 organisations that did
not answer questionnaire 1. Altogether there were 163 respondents who
filled in the nonresponse questionnaire, presented in enclosure 3b. This
gives a response rate of 65% (163/250) within the nonresponse survey.

The fist question asked within the nonresponse questionnaire, see
enclosure 3b, focused on the size of the organisations, measured by the
number of employees that for some reason did not deliver an answer of
questionnaire 1. In figure 4.26, the size of the organisations in the non-
response survey is compared with the size of the organisations that did
answer questionnaire 1 and also were conducting process capability
studies. The latter category has been described earlier in figure 4.1.

Just a short glance at figure 4.26 tells us that the organisations that
did not answer questionnaire 1, i.e. the organisations represented in the
nonresponse survey, seem to be organisations that are smaller com-
pared to those organisations that answered questionnaire 1 and actually
are conducting process capability studies. This supports the conclusion
from figure 4.1, that it is most of all relatively large organisations, mea-
sured by the number of employees, that are conducting process capa-
bility studies.
Figure 4.26 A comparison of organisation size, measured by the number of employees, between the 163 organisations represented in the nonresponse survey and the 97 organisations that answered questionnaire 1 and actually are conducting process capability studies. In the box-plots, the upper and lower 10%-percentiles of each distribution are cut off.

The second question in the nonresponse survey focused on the different professions of the respondents. In figure 4.27 the professions of the 97 respondents of questionnaire 1 is compared with the professions of the respondents of the nonresponse questionnaire.
Figure 4.27 A comparison of the different professions of the 163 respondents represented in the nonresponse survey and the professions of the 97 respondents that answered questionnaire 1.

There seems to be relatively small differences between the percentage of respondents with the same profession within the two groups. However, there are some differences worth commenting on. First of all it is clear that an overwhelming part, 76%, of the respondents of questionnaire 1 worked in some sort of quality function within their organisation, either as quality managers or as some sort of quality coordinators. This category has been named quality related personnel in figure
4.27. However, among the respondents of the nonresponse questionnaire there were only 40% of the respondents belonging to this profession. Another, more general difference, between the two groups is that the respondents of questionnaire 1 only belonged to five different professions, quality related personnel, top managers, production managers, sales personnel and statisticians, while the respondents within the nonresponse survey belonged to a large variety of professions, indicated by figure 4.27. The variety of professions among the respondents in the nonresponse survey indicates that it is possible that some questionnaires have been directed to persons working in organisations where process capability studies are conducted even though the receiver was not aware of this fact.

Question number 3 in the nonresponse survey, see enclosure 3b, was asked to be able to tell if there are any large discrepancies between different lines of businesses within the two categories, organisations from questionnaire 1 and organisations from the nonresponse survey. The analysis of different lines of businesses within these two categories is presented in figure 4.28.
Figure 4.28: A comparison of the different lines of businesses of the 163 organisations represented in the nonresponse survey and the lines of businesses of the 97 organisations identified as conductors of process capability studies through questionnaire 1.

Figure 4.28 indicates that actually there are no large discrepancies between the different lines of businesses within the two groups. Most businesses are equally represented but there are some differences worth
noticing. First of all, the concept of process capability studies is developed for manufacturing industries and not primarily for industries such as for instance, the service industry. This fact is reflected in figure 4.28 since the percentage of organisations within the service industry is larger in the group of organisations represented in the nonresponse survey. The higher percentage of consultants within the nonresponse survey is quite natural since they represent small organisations where the need for process capability studies is indeed limited. A rather surprising result is that the percentage of processing industries seems so be twice as large among organisations from questionnaire 1.

The last question in the nonresponse questionnaire, see enclosure 3b, tried to capture the different reasons why questionnaire 1 was not answered. All respondents’ answers have been categorised into 10 different reasons for not answering, presented in figure 4.29.

Figure 4.29 Ten different reasons for not answering questionnaire 1. The abbreviation PCS stands for process capability studies.
All ten reasons for not answering questionnaire 1 are commented below.

- The most common reason for not answering questionnaire 1 is that the organisations do not conduct process capability studies.

- The second largest reason was that the respondents worked in organisations where process capability studies actually are conducted, but that they could not find the time to fill in the questionnaire, which of course can be an effect of either two things. First of all their schedule might be so tight that no questionnaire, even how small it was, could be filled in, or they found the questionnaire too comprehensive.

- There were 16 of the respondents who claimed that it had not been relevant for them to fill in questionnaire 1 since they were either unemployed, ill for a longer period of time or they had retired.

- Some of the respondents claimed that the reason for not answering was that they did not have time. These respondents work in organisations where process capability studies are not conducted.

- There were 13 of the respondents who did not remember receiving questionnaire 1.

- Some of the respondents mentioned that they did not know what process capability studies are and this was the reason for not answering.

- Another reason for not answering, mentioned by six respondents, was that they passed the questionnaire on within their own organisation since they believed that another colleague was more suitable to fill it in.

- There were only three of the respondents who explicitly expressed that they had found the questionnaire too comprehensive. However, as mentioned above, this reason might be common among the respondents who mentioned that they are conducting process capability studies and could not find the time to fill it in.

- There were two of the respondents who mentioned that they were not at all interested and therefore they had not answered.

- There were also two of the respondents who mentioned that on grounds of principle, they never answer questionnaires.
By summarising the result from the nonresponse survey it is clear that the organisations that did not answer questionnaire 1 were smaller compared to the organisations that answered. The nonresponse survey also indicated that a natural explanation for some missed answers is that some copies of questionnaire 1 were sent to service industries and consultants, both representing lines of businesses where it is relatively uncommon to find organisations that are conducting process capability studies. Finally it was found that the most common reason for not answering questionnaire 1 was that process capability studies were not conducted within the surveyed organisations. The second most common reason for not answering the questionnaire was that the respondents had no time to fill in the questionnaire even though they actually were working within an organisation where process capability studies are conducted. This last finding indicates that several presumptive respondents might have been missed because they found the questionnaire too comprehensive. On the other hand it also indicates that the study populations were appropriately chosen since there were many more organisations than those that answered questionnaire 1 that actually conducted process capability studies.

4.3 Conclusions

Many interesting results can be found from the study presented in this chapter. Just by taking a short glance at the results presented it is obvious that many of the theoretical aspects of how to conduct process capability studies are quite often violated. Of course, it cannot be expected that every organisation conducts process capability studies according to all theoretical findings and recommendations, especially since many presentations of how to conduct process capability studies, are not only inconsistent but also stained with errors. The study has also produced some results which are of more practical interest.

The most interesting results are summarised below. First of all some theoretical aspects are discussed which then are followed by results of more practical nature.

4.3.1 Theoretical aspects

The results concerning theoretical aspects are discussed in accordance with the six vital aspects, all effecting the reliability of the results from the process capability studies, identified in the literature review which is presented in chapter 3. These aspects are capable gauges, statistical
Part 1: Chapter 4, Process capability studies within Swedish industry

control, conscious gathering of data, use of confidence limits, simultaneous use of several process capability indices and checking the distribution of the process output.

- **Capable gauges.** It has been found that approximately one third of the respondents have appropriate knowledge of the capability of the gauges used in the process capability studies, since they were conducting R&R-studies. Within approximately the same third of the organisations, strict requirements have been posted that the inherent spread of the gauge must not exceed 10% of the specification interval for the studied characteristic. This seems as a quite fair result, but reflecting that in almost 50% of the respondents' organisations, the basic knowledge about the gauges used is limited, the result may turn out to be devastating. However, this result shall not be exaggerated since the wording of the questions concerning this aspect might have been misinterpreted.

- **Statistical control.** If the process monitored in a process capability study is not in statistical control, the result will only reflect the capability of the process at that very moment and nothing can be predicted about the behaviour of the process within the near future. Therefore, from a theoretical point of view it is correct first of all to make sure that the process is in statistical control before a process capability study is conducted. When focusing this aspect in the questionnaire it was clear that only 25 of the 97 monitored organisations used some sort of control chart in order to assure statistical control before the process capability studies were conducted. It was also found that within 14 of the organisations they had clearly stated that the process must be capable before control charts and SPC can be applied.

- **Conscious gathering of data.** All units measured in a process capability study has to be selected according to some strategy. The organisation has to decide which components of variation are desired to be included in the study. For instance, when conducting machine capability studies, a number of units produced directly after each other are selected while all other components of variation are being held as constant as possible, since the inherent variation of the machine is of interest. On the other hand, when conducting process capability studies it is of importance to include all different kinds of variation. Therefore, the units measured are randomly selected from the process during a much longer period of time, compared to when conducting a machine capability study. In the study it has been found that approxi-
approximately 50% of the organisations monitored did actually make some sort of distinction between machine capability studies and process capability studies. Another aspect is that 25 of the 97 organisations used data collected from their SPC-programme when they conducted process capability studies. Therefore, it is quite common to take groups of data, reproduced from units that were machined directly after each other. This way the measurements from each group are bound to be dependent in one way or another, which is not optimal when establishing reliable estimates of capability.

- **Use of confidence limits.** The basic idea of a process capability study is to make a statement if the process is capable or not, based on a sample drawn from the monitored process. The larger the sample the more reliable the result from the process capability study will be. Most of the organisations studied in this survey had specified some levels to be reached for different process capability indices in order to claim the monitored process capable or not. On the other hand, there were only 10% of the studied organisations where confidence limits were used in order to assure the estimated levels of different process capability indices. This is perhaps one of the most interesting findings in the study. Without applying confidence limits or in some other way evaluating statistical accuracy, it is impossible to claim a specific process capable or not, unless the whole process output is measured, i.e. every single unit produced is checked. But then again the whole idea with process capability studies becomes superfluous.

- **Simultaneous use of several process capability indices.** Since different process capability indices posses different properties it is often a good idea to use several process capability indices in each capability study, in order to reveal changes in the process. In this study it was clear that 64 (70%) of the respondents used both $C_p$ and $C_{pk}$ in every study. Besides, of these 64 respondents there were 15 who used $C_p$, $C_{pk}$ and $C_{pm}$ simultaneously. This is perhaps the theoretical aspect that is best fulfilled in practice. However, it is worth noticing that several other indices, with better statistical properties, have been developed since the introduction of $C_p$, $C_{pk}$ and $C_{pm}$.

- **Checking the distribution of the process output.** If it is desired to compare the capability of different processes it is of utmost importance to check that the distribution of the process output of these processes are approximately identical. Otherwise, the comparison will be made on false grounds. In the study it was found that 80% of the
studied organisations are making some sort of check of the distribution of the process output. It is most common to use histogram or probability plotting paper for the normal distribution. However, it was found that only 10 of the surveyed organisations have got some sort of strategy for handling process capability studies for skewly distributed process outputs.

Every renounce from all six aspects discussed above will more or less seriously influence the correctness of the result from each process capability study negatively. The study presented in this chapter has revealed that only a few of the studied organisations master all aspects described above.

To make a more clear description of the discrepancies between theory and practice, figure 4.30 has been developed.

Figure 4.30 The adherence to the theoretical aspects covered by the study. The figure shows that the adherence to several of the theoretical aspects is quite poor. The abbreviation PCIs stands for process capability indices.
When looking at figure 4.30 it is clear that the adherence to the theoretical aspects, covered by the study, is poor. It would of course be unrealistic to expect that all the theoretical aspects should be perfectly handled by everyone of the surveyed organisations. But since the adherence to the majority of the theoretical aspects is well below 50%, it is reasonable to say that the adherence to the theoretical aspects within the surveyed organisations is poor.

Of the six theoretical aspects shown in figure 4.30 there are some that are more important than others, i.e. they influence the reliability of the result from a process capability study more dramatically.

In order to describe how the six theoretical aspects covered in this study influences the reliability of the results from a process capability study, figure 4.31 has been developed.

Figure 4.31 This figure describes how the six theoretical aspects, covered by the study presented in this chapter, effects the reliability of the results from a process capability study. The aspects connected to the triangle have most effect on the reliability of the result since they are connected to the actual gathering of the data used. If the data used in a process capability study is invalid, it can never be repaired, even how sophisticated the analysis is. The aspects outside the triangle are all connected to a relevant use of process capability indices when analysing the data and have a somewhat smaller effect on the reliability of the results.
Here some comments are made to describe the effect of each theoretical aspect on the reliability of the result from a process capability study. First of all, if the gauge used is not calibrated accurately the whole study will be of no interest at all since the data cannot be trusted. No matter how well the other aspects are handled. If the process monitored is not in statistical control the study will only reflect the capability at the very moment the study is conducted and nothing can be said about the behaviour of the process in the future. The actions taken on the basis of results from a process capability study conducted on an unstable process will probably not improve the capability of the process. In order to act properly on the result from a process capability study it is indeed important to know what components of variation reflected in the data. This can be controlled through a conscious gathering of data.

It is worth noticing that if capable gauges not are used and if the process is not in statistical control and the data is gathered unconsciously, these shortages can never be repaired during data analysis.

If it is decided to use process capability indices when analysing the capability of a process, it is wise to use several process capability indices simultaneously due to their different characteristics. Since estimates of process capability indices often are uncertain it is wise to use confidence limits to assure a certain level of capability. Finally, if the process monitored has a skewly distributed output, this has to be considered when using process capability indices.

Figure 4.31 indicates that in order to really be able to trust the result from the process capability studies conducted, an organisation has to be able to handle all the theoretical aspects presented. It is not good enough just to be good at handling a few of these aspects. When considering this fact the gaps between theory and practice, illustrated in figure 4.30, becomes even more severe.

4.3.2 Practical aspects

The results concerning practical aspects are discussed according to the five areas of interest from a practical point of view, presented in chapter 3. These aspects are implementation aspects of process capability studies, pressure between organisations to conduct process capability studies, setting of specifications, achieved results from process capability studies and finally, advantages and disadvantages of conducting process capability studies.

- **Implementation aspects of process capability studies.** One of the most important aspects when implementing process capability studi-
Part 1: Chapter 4, Process capability studies within Swedish industry

ies is that proper education and training are provided. In the study it was found that within 70% of the studied organisations proper education and training had been provided. There were mainly personnel directly involved in the actual manufacturing parts of the organisations who had received this type of education. Only within 30% of the organisations top managers had received proper training and education. It was also found that most of the organisations had started the implementation process after 1985 and most of them estimate to reach the goal with 100% capable processes before 2000. These findings indicate that no quick results are to be expected by using process capability studies, which emphasises the importance of proper allocation of resources over a long period of time, which on the other hand cannot be established without persistent and committed managers.

• Pressure between organisations to conduct process capability studies. It was found that 50% of the surveyed organisations had experienced some sort of requirement from their customers, that they were expected to actively be conducting process capability studies. And on the other hand, 45% of the surveyed organisations required that their suppliers should conduct process capability studies. Together these findings indicate that it is quite common that organisations more or less force each other to conduct process capability studies. Even though it is quite common to put pressure on suppliers and more or less force them to conduct process capability studies, often the requirements do not seem to be very strict. The suppliers are usually just ordered to conduct process capability studies and are then quite free to do as they please. In some cases however, specific requirements are formulated on what process capability indices to use and what levels to reach. It was found that it is mainly organisations operating within heavy manufacturing industry, motor industry and precision-tool industry that require that their suppliers shall conduct process capability studies.

• Setting of specifications. In order to justify the use of process capability studies, specifications have to be properly set. The ideal situation is that the specifications are based on external customer demands. In the survey it was found that "the voice of the customer" seemed to be either present or not present within the studied organisations. Hopefully, the trend will be that more and more specifications are based on external customer demands. To be able to produce capable products it is extremely important to complement each
Part 1: Chapter 4, Process capability studies within Swedish industry

specification with a target value. Also here it seems as if the concept of target values is either present or not present within the surveyed organisations.

- Achieved results from using process capability studies. As mentioned earlier, most of the surveyed organisations had implemented process capability studies sometime between 1985 and 1995. When analysing the filled in questionnaires it was clear that the percentage of capable processes has increased quite dramatically since they implemented process capability studies, which perhaps is the most important finding of all in the survey. It is not the concept of process capability studies as such that increases the percentage of capable processes, but it helps focusing problems and when these problems then are eliminated properly, the percentage of capable processes within that organisation increases. Some of the surveyed organisations have improved the percentage of capable processes from 20% to 80%. These organisations have most certainly experienced a large drop in the number of defective units produced. The study has shown that the results from process capability studies often is used in the overall improvement process within an organisation. However, the result is also used in several other ways such as an alarm clock if the process changes for the worse, the result tells the organisation what capability to require from newly purchased machinery and so on. It is mainly personnel working close to the actual production processes that use the result from process capability studies. However, top managers also seem to be interested in the result.

- Advantages and disadvantages of conducting process capability studies. According to the respondents' points of view the main advantages with conducting process capability studies seem to be that the method provides a lot of knowledge of the processes that did not exist earlier. Another experience is that more and more decisions are based on facts and the method helps identifying improvement priorities. However, most methods have some disadvantages and when it comes to process capability studies the respondents claim that the largest disadvantages are that the method is resource consuming and that it involves some relatively difficult theory. Combined with the fact that usually there are no immediate results when conducting process capability studies it might be hard to motivate co-workers in the improvement process aimed at achieving all processes capable.
4.4 Generalisation of results

The target population within this study consists of organisations within Swedish industry where process capability studies are conducted, see figure 2.3. All results presented above are based on the answers from 97 organisations that fulfil these requirements. Now, an interesting question is of course how many more organisations there are within Swedish industry that are conducting process capability studies and how would the findings be effected if all these organisations had been surveyed. The exact answers to these two questions we will never know. However, a discussion is given here in order to shed some light on the problem.

First of all, the nonresponse survey showed that there are at least 38 organisations that claim to be conducting process capability studies, even though they did not answer questionnaire 1. On the other hand, question number 26, see enclosure 3a, where the respondents were asked to give addresses of other organisations that they knew were conducting process capability studies, proved to be very effective. Approximately 25% of the 97 surveyed organisations were identified through question number 26.

The second question concerns how well the findings reflect the use of process capability studies within Swedish industry. Unfortunately, the author is prevented from giving the names of the surveyed organisations due to promises of confidentiality in connection to the survey. However, from the authors point of view most of the organisations within Swedish industry that ought to be represented in a study like this are included within the 97 surveyed organisations. The surveyed organisations are located in all different parts of Sweden and as indicated by figure 4.2 many different lines of businesses are included. All these facts indicate that even if the whole target population would have been surveyed, the results would probably not have been that much different. Another aspect which also supports this opinion is that the findings were expected. It was expected to find that many of the theoretical aspects of process capability studies are often not considered in practice. The fact that many of the theoretical aspects seem to be relatively unknown within some of the surveyed organisations indicates that even if a larger part of the target population had been surveyed, the fact that there are gaps between theory and practice would still remain.

Finally, the author is convinced that most of the results from this survey also are applicable within other industrialised countries. This opinion is supported by the fact that other authors also mention that
they have experienced that the concept of process capability indices is misused within some organisations that they have visited, see, e.g., Gunter (1989a-d), Porter & Oakland (1991) or Pignatiello & Ramberg (1993).
Chapter 5

Obstacles when using Process Capability Studies

This chapter will discuss some obstacles which might occur when implementing and conducting process capability studies. These obstacles have been identified as a result from analysing questionnaire 2.

5.1 Questionnaire survey 2

Questionnaire 2, which is given in enclosure 4, was designed to measure why it sometimes is so difficult to implement and conduct process capability studies. Which obstacles are hindering when implementing and conducting process capability studies and how do these obstacles relate to each other?

The questionnaire was sent out to all 205 respondents from questionnaire survey 1 and also to 53 of the respondents from the non-response analysis, who had shown interest in the result from questionnaire 1. Altogether 60 of these respondents filled in and returned questionnaire 2, which gives a response rate of approximately 25%. It was found fruitful to first analyse question number 2 and then connecting the result from question number 2 to question number 1. This is the reason for the order of the next two headings.

5.1.1 Analysis of questionnaire 2, question 2

When analysing all 60 questionnaires, the answers were categorised into different reasons why it sometimes can be difficult to implement and conduct process capability studies. Altogether, 21 different reasons were found and in order to present them clearly, the author has arranged them into an Ishikawa diagram, presented in figure 5.1.
Why is it sometimes so hard to implement and conduct process capability studies?

The Ishikawa diagram shows different reasons why it sometimes is hard to implement and conduct process capability studies. The figure 5.1 is the Ishikawa diagram shows different reasons why it sometimes is hard to implement and conduct process capability studies.
It was found that all 21 different reasons why it sometimes is hard to implement and conduct process capability studies could be arranged into four major categories. First of all there were several reasons that in some way were related to management issues. The other reasons could be categorised into the categories facts of reality, traditional personal attitudes and methodological aspects.

In order to fully understand figure 5.1, all obstacles are described in detail below. The analysis is first of all based on real facts indicated by the study. However, the author has deliberately added some personal reflections based on experiences from co-operation with organisations in their implementation process of process capability studies. A clear description of how the obstacles presented in figure 5.1 were identified is given in enclosure 5.

**Management issues**

First of all it is interesting to notice that one of the obstacles is that the management is too busy with other daily problems. This is perhaps one of the most common reasons why many TQM-programmes often fail. There is an abundance of organisations where managers, and co-workers as well, are buried in all daily problems. In these organisations the implementation of methods such as process capability studies are hindered since everyone's schedule is full. The fact that managers are often too busy with other daily problems directly leads to the fact that their commitment for process capability studies becomes weak. Without knowing it, their weak commitment directly leads to the fact that not enough resources, if any, are allocated to implement and conduct process capability studies. In some cases the organisation is just ordered to implement, without question. The lack of appropriate resources allocated, directly results in a shortage of knowledge of how to conduct process capability studies among all co-workers. Even if all theoretical aspects of how process capability studies are to be conducted sometimes are known within the organisation, the final method used is often too simplified since the lack of resources force the organisation to find the cheapest possible way to proceed, without reflecting on how these simplifications influence the results. The relatively poor knowledge of the theoretical concepts of process capability studies among co-workers, indirectly caused by managers' occupation with solving daily problems, makes it hard for everyone within the organisation to realise the advantages with conducting process capability studies properly.

Another obstacle which sometimes makes it hard to conduct process capability studies is that the studies sometimes are conducted by the quality
Part 1: Chapter 5, Obstacles when using process capability studies

department, which might lead to a modest interest in the concept among co-workers. Another aspect which also influences the interest in the implementation of process capability studies is that often, process capability studies is just another improvement method implemented. Since the implementation of all previous methods more or less failed, the belief in the success of implementing process capability studies is almost immeasurable.

Facts of reality

Some of the obstacles which make it difficult to implement process capability studies can be thought of as facts of reality. For instance, often it is not obvious which characteristics are of interest to measure and control. If a specific function of a product is vital for the final customers, there can be many opinions within the organisation of which characteristics to measure and control in order to achieve that specific function. Furthermore, in some cases, it is not even obvious what functions are of interest from the customers point of view, making it even harder to determine which characteristics to measure and control.

The basic principle of process capability studies is to measure characteristics and compare the process output with the pre-set specifications. Obviously, this method requires that members of the organisation are used to perform measurements. However, in some organisations, there are very few gauges, and those that exist, they are often inadequately calibrated. A well established measurement culture is a prerequisite in order to conduct process capability studies correctly. Another obstacle when conducting process capability studies is the high speed of modern production techniques. In some operations there is simply no time left to perform measurements, which on the other hand enhances the importance of capable processes. This is a rather delicate problem faced by many organisations of today. It can be solved by focusing on measuring and controlling inherent characteristics of the process rather than monitoring the process output. However, using these techniques are not easy. This directly leads to the next obstacle when implementing process capability studies, important parameters are sometime hard to measure and control. This problem has special significance within process industries, where important characteristics sometimes are almost impossible to measure due to practical reasons.

Even if the process output is monitored and the result indicates an obvious need to make changes in the process, it might be difficult to determine what characteristics to change in order to make the process operating efficiently. When it is hard to understand these cause-effect rela-
tionships the enthusiasm decreases and the relevance of conducting process capability studies is immediately questioned. Why check the process output, when we do not know how to control the parameters affecting the output?

Another aspect of reality, affecting the relevance of conducting process capability studies is that it is relatively common that processes are not stable and repetitive enough, in order to justify the use of process capability studies. If the process monitored is not in statistical control, then the result from the process capability study can only be used to determine how the process is operating just now. It could be capable today but due to the lack of statistical control, the process could just as well be judged incapable tomorrow.

**Traditional personal attitudes**

During the study it was found that two obstacles when implementing and conducting process capability studies can be related to traditional personal attitudes.

First of all it is a fact that it is hard to accept that meeting tolerances should not be enough. The concept of process capability studies enhances the idea of achieving a process output with minimal variation centred at a target value, well within the specification limits. The greater the quota between the actual process spread and the allowable process spread, the better. This concept is sometimes hard to accept by co-workers who are used to working under conditions where it always has been accepted to fully use the whole specification interval.

Another aspect is that it is hard to accept a method which questions the workers' own contribution to the process output. When performing process capability studies, the aim is to monitor all components of variation, influencing the process output. Since one of these components is contributed by the operators themselves, a rather intricate problem appears. It is extremely important to insure that the aim of using process capability studies is to reduce the total amount of variation in order to reach a higher level of customer satisfaction and not to check who are the best operators in order to fire the others.

**Methodological aspects**

One obstacle when implementing and conducting process capability studies is that the concept is difficult to conceive. Since the concept involves both mathematical and statistical concepts, many people find the theory of process capability studies complicated and difficult to understand.
Even though the concept is rather complicated, it is possible to grasp if proper education is provided. However, the shortage of resources allocated to educational efforts in connection to the implementation of process capability studies can be one explanation why many people find the concept complicated.

Process capability studies require that a substantial amount of products are available to measure. A usual recommendation is that 50 measurements are to be used in each study in order to reach sufficient accuracy in the estimated process capability index. However, in some types of industry, the runs are to short in order to provide such an output, making the concept of process capability studies irrelevant to use, unless it is possible to monitor an inherent process characteristic affecting the process output.

Another fact influencing negatively when implementing and conducting process capability studies is that the method gives no quick results. Questionnaire 1 indicated that it usually takes between 5 and 20 years from the implementation of process capability studies until all processes within the organisation can be claimed capable. However, even if the implementation of process capability studies is a rather tough process, this time span should be possible to shrink substantially if proper resources were allocated.

Lastly, skew distributions are quite common in industry today, especially for characteristics with single-sided specification limits. Since the theory of process capability studies partly is based on the assumption that the process output is normally distributed, organisations do not know how to handle skewly distributed characteristics.

5.1.2 Analysis of questionnaire 2, question 1

Altogether there were 60 respondents answering questionnaire number 2. Of these 60 respondents there were 29 who worked in organisations where process capability studies were not conducted, which leave 31 respondents to the other category. Since it was considered interesting to analyse if there were any differences of opinion between these two groups, concerning their view on obstacles when implementing and conducting process capability studies, further analyses were performed. Just a short glance at the problem indicates that differences would be quite natural since the 29 respondents mentioned above, who work in organisations where process capability studies are not conducted, naturally cannot have any experiences from actually conducting process capability studies.
The analysis between these two groups was conducted by checking how many respondents within the two separate groups who had mentioned each obstacle described in figure 5.1. The exact mathematical analysis between these two groups is given in enclosure 5 and the most interesting differences found are commented in words below. In order to make the presentation easier to follow, the differences are here also discussed under the separate headings, Management issues, Facts of reality, Traditional personal attitudes and Methodological aspects. Only the obstacles where there seem to be relatively large differences between the experiences between organisations that conduct process capability studies and those that do not, are commented on.

Management issues

First of all it seems as if the weak management commitment has only been experienced within organisations where process capability studies are conducted. Also the problem of getting everybody involved has mainly been experienced within these organisations. All these experiences are quite natural to have been present within organisations that actually conduct process capability studies rather than others.

However, obstacles such as shortage of resources and shortage of knowledge because of deficient education are also well represented among organisations that do not conduct process capability studies. Also these facts are quite natural, some implementation efforts might have failed due to lack of proper allocation of resources and education.

Facts of reality

By looking at all obstacles concerning facts of reality in enclosure 5 it is clear that a majority of these obstacles have been mentioned by respondents working in organisations where process capability studies are conducted. The facts of reality are quite natural to primarily have been experienced within organisations where process capability studies are conducted.

Traditional personal attitudes

As might have been expected all obstacles concerning traditional personal attitudes have been mentioned by respondents working in organisations where process capability studies are conducted. This fact is quite natural since most of these personal attitudes appears when process capability studies actually have been implemented.
Methodological aspects

The theory of process capability studies is often thought of as rather difficult to perceive, which also is heavily emphasised by the fact that many respondents have mentioned that the difficult theories constitute a major obstacle when implementing and conducting process capability studies. The fact that the difficult theories hinder when implementing and conducting process capability studies is mostly experienced within organisations where process capability studies are actually conducted.

Another obstacle, which on the other hand seems to be most common within organisations where process capability studies are not conducted, is that the method is not suitable for short runs. The respondents who have mentioned this obstacle have probably tried to implement process capability studies and failed or avoided an implementation since the runs within their organisations are too short to provide enough data for the capability analysis.

5.1.3 Conclusions from questionnaire 2

In this section, the background of the questionnaire survey will be refreshed and the most interesting results will be discussed.

All results from questionnaire survey 1 clearly show that indeed there are large discrepancies between how process capability studies actually are conducted within Swedish industries compared with the theoretical aspects of how process capability studies ought to be conducted. In order to try to explain these discrepancies, questionnaire survey number 2 has been performed. The open question in questionnaire 2 made it possible for the respondents to give their opinion of why it sometimes is hard to implement and conduct process capability studies.

When analysing all respondents' answers it came clear that 21 obstacles, hindering a proper use of process capability studies, were identified. All these obstacles have been arranged in an easy to understand diagram showed in figure 5.1. It was clear that these obstacles could be categorised into the different categories Management issues, Facts of reality, Traditional personal attitudes and Methodological aspects.

Altogether, six of the 21 obstacles have been mentioned by five or more of the respondents. In figure 5.1, these most frequently mentioned obstacles when implementing and conducting process capability studies have been written in italics.

It is indeed very interesting to notice that four of these obstacles can be thought of as management issues, which indicate that all actions
Part 1: Chapter 5, Obstacles when using process capability studies

taken by managers when implementing and conduction process capability studies clearly effect the results. When looking at figure 5.1 it is clear that the week commitment from managers for process capability studies, leading to a shortage of resources allocated, resulting in insufficient knowledge because of deficient education which makes it hard to realise the advantages, all can be thought of as management issues. However, this result is not very surprising, the importance of managers’ commitment in any improvement process is a well known fact and has been noticed in many research projects.

The other two major obstacles seem to be that often there is no measurement culture within the organisations and the theory of process capability studies is often thought of as complicated.

Upon analysing which obstacles were more common within organisations where process capability studies are actually conducted, compared to organisations where process capability studies are not conducted, it was obvious that the respondents seemed to have answered question number 2 within questionnaire 2 from their own point of view. Without much reflection they actually seem to have described the obstacles experienced within their own organisation. This result is heavily emphasised by the fact that obstacles mentioned by respondents working in organisations where process capability studies actually are conducted, indeed are obstacles more likely to have appeared in this category of organisations, and contrariwise.

Finally, when presenting the result from questionnaire 2, it must be considered that all aspects effecting how organisations implement and conduct process capability studies hardly can be caught and fully analysed by using a single questionnaire. However, the result presented here clearly indicates some major obstacles when implementing and conducting process capability studies which can be used as a proper base for further research.
Part 2

The effect of skewness on some process capability indices
CHAPTER 6

PROCESS CAPABILITY INDICES AND NON-NORMAL DISTRIBUTIONS

In this chapter a description is made of the theoretical efforts made so far, regarding the use of process capability indices when the monitored characteristic is non-normally distributed. The contents of this chapter forms a base which helps to understand the simulation study presented in chapter 7 and 8.

6.1 The basic problem of non-normality

The effects of non-normality of the process output on properties of process capability indices have not been a major research item until quite recently, although some practitioners have been well aware of the possible problems in this respect.

One major problem when using process capability indices in situations when the monitored characteristic is not normally distributed has been indicated earlier, see figure 1.16. Take the process capability index $C_{pk}$ for instance. Under the assumption of normality we have that the percentage of nonconforming items is $\leq 2\Phi(-3C_{pk})$, see, e.g., Pearn, Kotz & Johnson (1992). When we no longer can assume normality the proportion of nonconforming items can be very large for a value of $C_{pk}$ that would result in a small proportion under the assumption of normality, see Grönlund (1990).

Another major problem is that so far confidence intervals and tests have primarily been derived under the assumption that the characteristic monitored is normally distributed.

Due to the inability of process capability indices to handle non-normally distributed characteristics, both researchers and practitioners have become sceptical, see, e.g., Gunter (1989a-d) or Pignatiello & Ramberg (1993).

Basically, there are two solutions to the problem of how to use process capability indices when the output of the process monitored is non-normally distributed.
1 Do something about it.

2 Do not do anything about it.

Since the problem appears when it comes to comparing the capability of different processes or when it comes to statistically assuring a certain level of capability, it would, from a practitioners point of view, be possible to just go on as usual in a process capability study, even though they find the process output non-normally distributed. If the aim is to improve one specific process within an organisation it would do just to check the distribution of the process output for a specific characteristic for several process capability studies conducted in a row, during an improvement process. If the distribution of this characteristic has approximately the same shape, not necessarily as a normal distribution, in all these studies and the estimates of a given process capability index successively becomes larger and larger, then this would probably be enough information for the practitioner. However, as indicated above, if it comes to comparing the capability of different processes or statistically assuring a certain level of capability, it is necessary to consider the non-normality of the process characteristic. The problem can then be divided into two parts, presented in Kotz & Johnson (1993),

1 Investigate the properties of process capability indices and their estimators when the process output has specific non-normal shapes.

2 Develop methods allowing for non-normality and consideration of use of new process capability indices specially designed to be robust, i.e., not sensitive, to non-normality.

Kotz & Johnson (1993) provides an excellent overview of some methods focused on handling process capability indices for non-normally distributed characteristics. The next two sections will deal with the two problems just described. First, the results from some studies concentrating on the effects of non-normality are summarised and then some methods that allows, or compensates for, non-normality are described.

### 6.2 Effects of non-normality

In a series of articles, Gunter (1989a-d) discusses the problem that processes with substantially differently distributed process outputs, actually can give the same value of the process capability index. This problem is illustrated in figure 6.1.
Figure 6.1 Four differently shaped distributions describing different process outputs. The four distributions have the same expected value equal to zero and the same standard deviation equal to one, and hence the same $C_{pk}$. From Kotz & Johnson (1993), who redraw the figure from Gunter (1989b).

Since all processes in figure 6.1 have the same $\mu$ and the same $\sigma$, they will all have the same value of $C_{pk}$. The output of process 1 follows a skew distribution with a finite lower boundary, namely a $\chi^2$-distribution with 4.5 degrees of freedom. The output from process 2 follows a heavy-tailed distribution, namely a $t$-distribution with 8 degrees of freedom. Finally, the output from process 3 follows a uniform distribution, describing a true process output which has been cut off at the specification limits due to inspection where the incapable units have been sorted out. A normal distribution has also been included for comparison purposes.

The proportion of nonconforming items, i.e. the proportion of items outside $\pm 3$ sigma-limits is approximately, 14000 parts per million (ppm) for distribution 1, 4000 ppm for distribution 2 and 0 ppm for distribution 3. For the normal distribution the rate of nonconforming items outside the 3 sigma-limits is 2700 ppm. This example clearly describes the problems with using process capability indices for differently distributed characteristics.

Some simulation studies have been performed to closer analyse the distributional properties of process capability indices when the output from the process monitored is non-normally distributed. English & Taylor (1990) carried out some simulation studies on the distribution of...
\( \hat{C}_p \), with \( C_p = 1 \) for normal, triangular, uniform and exponential distributions, with sample sizes \( n = 5, 10, 30 \) and 50. In English & Taylor (1993) the study in English & Taylor (1990) was expanded and includes properties of both \( \hat{C}_p \) and \( \hat{C}_{pk} \). Price & Price (1992) present values, estimated by simulation, of the expected values of \( \hat{C}_p \) and \( \hat{C}_{pk} \), from normal, uniform, beta and gamma distributions with sample sizes \( n = 10, 30 \) and 100. In Price & Price (1992), the expected value of the process distribution is 50 and the standard deviation is 1, in all simulation cases. Then they alter the specification limits leading to true values of \( C_p \) and \( C_{pk} \) from 0.5 to 2.5, i.e. they cover a broad range of processes from clearly incapable processes to very capable processes.

The most important results from English & Taylor (1990), English & Taylor (1993) and Price & Price (1992) can be summarised as follows:

- The bias of \( \hat{C}_p \) and \( \hat{C}_{pk} \) will increase as the capability of the monitored process increases.
- As the sample size, \( n \), increases the bias of \( \hat{C}_p \) and \( \hat{C}_{pk} \) decreases.
- The bias of \( \hat{C}_p \) and \( \hat{C}_{pk} \) will increase as the skewness of the monitored process increases.
- As a rule of thumb, if the sample size, \( n \), is between 30 and 50, it is reasonable to use \( C_p \) with reasonable accurateness but the use of \( C_{pk} \) should be avoided when severe departures from normality are observed.

If a new simulation study, with somewhat different conditions compared to English & Taylor (1990), English & Taylor (1993) and Price & Price (1992), is performed, results similar to those summarised above would be expected.

### 6.3 Construction of process capability indices for non-normally distributed characteristics

In recent years several process capability indices specially designed for handling non-normally distributed characteristics have been proposed. A summary of some suggested methods for how to use process capability indices when the monitored process has a non-normally distributed output is given in Kotz & Johnson (1993). Here a short description is given of all process capability indices designed for non-normally distributed characteristics, known by the author.
6.3.1 "Distribution free" process capability indices

Chan, Cheng & Spiring (1988b) introduced a process capability index which they called "distribution-free". They noted that the estimator \( \hat{\sigma} \) in the denominator of \( \hat{C}_p \) is used solely to estimate the length, \( 6\sigma \), of the interval covering 99.73% of the values of \( X \). They propose using distribution-free tolerance intervals, as defined, for example, in Guenther (1985) to estimate this length. These tolerance intervals, widely used in statistical methodology for the last 50 years, are designed to include at least \( 100\beta \% \) of the distribution with preassigned probability \( 100(1 - \alpha)\% \), for given \( \beta \), usually close to 1, and \( \alpha \), usually close to zero. As indicated by Kotz & Johnson (1993), a natural choice for \( \beta \) would be \( \beta = 0.9973 \), with perhaps \( \alpha = 0.05 \). Unfortunately, construction of such intervals would require relatively large samples of size 1000 or more. Sample sizes as large as this would often be too expensive to establish in practice. Chan, Cheng & Spiring (1988b) suggest that this difficulty can be overcome by using multiples of intervals with lower value of \( \beta \) but still with \( \alpha = 0.05 \). They recommend taking

- \( \beta = 0.9546 \) and using \( 1.5(\text{length of tolerance interval}) \) in place of \( 6\hat{\sigma} \), or
- \( \beta = 0.6826 \) and using \( 3(\text{length of tolerance interval}) \) in place of \( 6\hat{\sigma} \).

Their choices are based on the fact that, for a normal distribution

- the interval \((\mu - 2\sigma, \mu + 2\sigma)\) of length \( 4\sigma \) contains 95.46% of all values, and
- the interval \((\mu - \sigma, \mu + \sigma)\) of length \( 2\sigma \) contains 68.26% of all values.

However, Kotz & Johnson (1993) question this method based on the argument that it seems unreasonable to use relationships based on normal distributions to estimate values which are supposed to be distribution free.

6.3.2 Transformation of data

Another way of calculating a process capability index for non-normal distributions can sometimes be to transform the observations from the process output so that the distribution of the transformed observations become approximately normally distributed. Then the process capability index is calculated on the base of characteristics of the transformed measurements. This method was initially presented by Gary Stork at the Ford Motor Co., but was presented in Gunter (1989b) and Montgomery (1991).
Here an example is presented to illustrate this method. The example is based on measurements of surface roughness and are made in microinches (10^-6 inch). A histogram of the true process output is given in figure 6.2.

![Histogram of surface roughness measurements](image)

**Figure 6.2** Measurements of surface roughness in microinches for 80 machined parts. The upper specification limit is 32 microinches. From Gunter (1989b).

It is clear that the process output in figure 6.2 is heavily skewed. To estimate \( C_{pk} \), \( \mu \) and \( \sigma \) are estimated by \( \bar{x} = 10.44 \) and \( s = 3.053 \) respectively, hence \( \hat{C}_{pk} = 2.4 \).

If the process output in figure 6.2 would have been normally distributed Pearn, Kotz & Johnson (1992) point out that the rate of nonconforming items never exceeds \( 2\Phi(-3C_{pk}) \), where \( \Phi \) denotes the probability distribution function for a standardised normal distribution. This means that in the long run a maximum of 1 ppm of all parts exemplified in figure 6.4 will be larger than the upper specification limit. But since the process output is clearly not normally distributed this value is not to be trusted.

However, by transforming the data in figure 6.2 according to \( x^* = 1/x \), a distribution quite close to the normal distribution is received, see figure 6.3. In the transformed scale the average and standard deviation are obtained as, \( \bar{x}^* = 0.1025, s^* = 0.0244 \) and furthermore the upper specification limit becomes a lower specification limit, \( LSL^* = 0.03125 \). If \( \hat{C}_{pk} \) is calculated based on these estimates then \( \hat{C}_{pk} = 0.97 \). This estimate corresponds to a percentage of nonconforming items not larger than 1350
ppm or 0.135%. According to Gunter (1989b) this value is much more appropriate than 1 ppm received before the transformation.

![Histogram](image)

**Figure 6.3** By transforming the data in figure 6.2 according to $x^* = 1/x$, a data set that is approximately normally distributed is received. From Gunter (1989b).

However, the fact that the capability of the transformed distribution accurately will reflect the capability of the true distribution is not certain. The simplicity of this method is probably at the cost of its accuracy. Another disadvantage is that not all data can be transformed to a normal distribution.

### 6.3.3 Clements' method

Clements (1989) propose a method based on the assumption that the process output can be adequately represented by a Pearson distribution. Essentially, the aim is to replace $6\sigma$ in the denominator of $C_p$ by $U_p - L_p$, where $U_p$ is the 99.865 percentile and $L_p$ is the 1.135 percentile. This idea is further illustrated in figure 6.4.
Figure 6.4 In the figure, the distribution marked "I" is normal and the distribution marked "II" is non-normally distributed. Clements' method is based on the idea that $6\sigma$ in the denominator of $C_p$, used for a normally distributed characteristic, is replaced by $U_p - L_p$, so that the distance $U_p - L_p$ covers 99.73% of the process output when the tail area probabilities below $L_p$ and above $U_p$ are 0.00135 respectively. Thereby, a base for comparison between normal and non-normal distributions is established.

The basic idea of Clements' method is first to estimate the skewness, $\delta$, and kurtosis, $\gamma$, of the process output according to,

\[
\hat{\delta} = \frac{\sum (x_i - \bar{x})^3}{(\sum (x_i - \bar{x})^2)^{3/2}}
\]

and

\[
\hat{\gamma} = \frac{\sum (x_i - \bar{x})^4}{(\sum (x_i - \bar{x})^2)^2} - 3.
\]

Based on these estimates and the sample average and standard deviation, Clements (1989) provides tables that give estimates of the 0.135-percentile, $L_p$, and the 99.865-percentile, $U_p$. Clements suggests using the median, $M$, instead of an estimate of the expected value in these indices. The reason for choosing the median is to ensure that these indices measure the ratio between the upper and lower half of the data and the lower and upper specification limit, respectively.

The process capability indices are then estimated according to

\[
\hat{C}_p = \frac{USL - LSL}{U_p - L_p},
\]
Part 2: Chapter 6, Process capability indices and non-normal distributions

(6.4) \[ \hat{C}_{pl} = \frac{\hat{M} - LSL}{\hat{M} - \theta_1}, \]

(6.5) \[ \hat{C}_{pu} = \frac{USL - \hat{M}}{\theta_u - \hat{M}}, \]

and

(6.6) \[ \hat{C}_{pk} = \min(\hat{C}_{pu}, \hat{C}_{pl}). \]

Clements (1989) provides examples of how to use this method. In Pearn & Kotz (1995) Clements’ method is applied to \( C_{pm} \) and \( C_{pmk} \). Pearn & Chen (1995) suggest further development of Clements’ method.

Clements’ method is attractive from both a practical and theoretical point of view. From the survey presented in part 1 of this thesis, it is clear that some organisations within Swedish industry are actually using Clements’ method when they find that the process output is non-normally distributed. Kotz & Johnson (1993) do however point out the drawback that Clements’ method requires a relatively large sample to achieve reliable estimates of skewness and kurtosis. Another drawback is that the statistical properties, like expected values, variances and distributions of Clements’ indices are unknown.

6.3.4 The Pearn-Kotz-Johnson method

Application of Clements’ method requires knowledge of the coefficients \( \delta \) and \( \gamma \), which may not be easily obtainable. Rather large sample sizes are needed for accurate estimation of these quantities. Pearn, Kotz & Johnson (1992) provide an alternative approach that tries to avoid this difficulty. They suggest, what they call a robust process capability index, according to

(6.7) \[ C_p(\theta) = \frac{2d}{\theta \sigma}, \]

where \( d = (USL - LSL)/2 \) and \( \theta \) is chosen so that the proportion of non-conforming items is not greatly affected by the shape of the distribution. The original \( C_p \) is, in notation of (6.7), \( C_p(6) \). According to Pearn, Kotz & Johnson (1992), the results of Pearson & Tukey (1965) are relevant to the choice of \( \theta \).
When comparing Clements' method to the Pearn-Kotz-Johnson method it is clear that in Clements' method there is an attempt to make a direct allowance for the values of the skewness and kurtosis coefficients, while the second method aims at getting limits which are insensitive to these values. In the Pearn-Kotz-Johnson method equal tail probabilities are no longer guaranteed, but then again the skewness and kurtosis do not need to be estimated. According to Kotz & Johnson (1993) this is an advantage since, as said before, reliable estimates of the third and fourth sample moments are difficult to achieve with appropriate accurateness since they are subject to large fluctuations. Both methods rely on the assumption that the output from the process has a unimodal shape to a Pearson distribution for Clements' method, and more restrictively, close to a gamma distribution for the Pearn-Kotz-Johnson method.

6.3.5 Bootstrap methods

According to Kotz & Johnson (1993), Franklin & Wasserman (1991), together with Price & Price (1992) should be regarded as the pioneers of application of bootstrap methodology in estimation of $C_{pk}$.

The bootstrap method was introduced some fourteen years ago, see Efron (1982), and has since then achieved remarkably rapid acceptance among statistical practitioners. The bootstrap method is a technique whereby an estimate of the distribution function of a statistic based on a sample size $n$, is obtained from data in a random sample, of size $m \geq n$, by "resampling" samples of size $n$, with replacement, from these $m$ values and calculating the corresponding values of the statistic in question.

Franklin & Wasserman (1992c) deal with bootstrap confidence limits for $C_p$, $C_{pk}$ and $C_{pm}$, which avoid the assumption of normality. They simulate data from three kinds of distributions, normal, symmetric with heavy tails and skewed. Although the result demonstrates the advantages of bootstrapping when working with non-normal process distributions, Franklin & Wasserman (1992) are careful to point out that the capability index one is attempting to estimate may not be meaningful for non-normal process data. Thus the practical significance of this study is not that it eliminates the need for assuming normality, but rather that it provides an understanding of the behaviour of methods based on normality when mild non-normality is encountered.

According to Rodriguez (1992), readers interested in the technical aspects of the bootstrap should be aware that this method is at present the subject of considerable research to determine general conditions
under which it fails or succeeds. It has been suggested by van Zwet (1992) that the naive bootstrap is valid when the statistic of interest is asymptotically normally distributed. An asymptotic normality of $C_{pk}$ has, in fact, been established by Chan, Xiong & Zhang (1990), but the relevance of this result to $C_{pk}$ bootstrap applications has not been explored.

### 6.3.6 Flexible process capability indices

Johnson, Kotz & Pearn (1994) introduce what they call a "flexible" process capability index, which takes into account possible differences in variability above and below the target value, $T$. They define a one-sided flexible process capability index as

\begin{equation}
CU_{jkp} = \frac{1}{3\sqrt{2}} \frac{USL - T}{\text{E}_{x > T}[(X - T)^2]}^{\frac{1}{2}},
\end{equation}

\begin{equation}
CL_{jkp} = \frac{1}{3\sqrt{2}} \frac{T - LSL}{\text{E}_{x < T}[(X - T)^2]}^{\frac{1}{2}},
\end{equation}

where

\begin{equation}
E_{x > T}[(X - T)^2] = E[(X - T)^2 | X > T] \text{Pr}[X > T]
\end{equation}

and

\begin{equation}
E_{x < T}[(X - T)^2] = E[(X - T)^2 | X < T] \text{Pr}[X < T].
\end{equation}

Note that the factors $\text{Pr}[X > T]$ and $\text{Pr}[X < T]$ make allowance for how often positive and negative deviations from $T$ occur.

The multiplier $1/(3\sqrt{2})$, while the earlier process capability indices use $1/3$, is due to the fact that for a symmetrical distribution with variance $\sigma^2$ and expected value $T$ we would have

\begin{equation}
E_{x > T}[(X - T)^2] = E_{x < T}[(X - T)^2] = \frac{1}{2}\sigma^2.
\end{equation}

Finally, Johnson, Kotz & Pearn (1994) define $C_{jkp}$ as the minimum of $CU_{jkp}$ and $CL_{jkp}$, i.e.

\begin{equation}
C_{jkp} = \min[CU_{jkp}, CL_{jkp}].
\end{equation}
Part 2: Chapter 6, Process capability indices and non-normal distributions

The flexible process capability index $C_{jp}$ is quite interesting from a practitioners point of view since it can be calculated quite straightforwardly, the only special procedure needed is separate calculation of sums of squares for $X_i > T$ and $X_i < T$. Kotz & Johnson (1993) provide an analysis of the distributional properties of $C_{jp}$ that indicates that the properties of $C_{jp}$ are neither better nor worse than most other process capability indices.

6.3.7 Wright’s process capability index

A recent effort to construct a process capability index sensitive to skewness has been performed by Wright (1995). The process capability index suggested by Wright (1995), the process capability index $C_{sp}$, generalises the Pearn-Kotz-Johnson’s index $C_{pmk}$ by taking into account the skewness, in addition to the deviation of the mean from the target already incorporated in $C_{pmk}$. The process capability index $C_{pmk}$ proposed by Pearn, Kotz & Johnson (1992) is defined as

$$C_{pmk} = \frac{\text{Min}(USL - \mu, \mu - LSL)}{3\sqrt{\sigma^2 + (\mu - T)^2}}.$$  

(6.14)

The process capability index $C_{sp}$, proposed by Wright (1995) incorporates an additional skewness correction factor in the denominator of $C_{pmk}$ and is defined as

$$C_{sp} = \frac{\text{Min}(USL - \mu, \mu - LSL)}{3\sqrt{\sigma^2 + (\mu - T)^2 + |\mu_3|}}.$$  

(6.15)

where $\mu_3 = \text{E}(X - \mu)^3$, is the third central moment.

Wright (1995) motivates this index by its ability to reflect possible changes in the shape of the distribution describing the process output.

However, adding new factors to statistics like process capability indices can have dramatic effects on their distributional properties, such as bias and dispersion. Chen & Kotz (1995) investigate the distributional properties of Wright’s index and reach the conclusion that the asymptotic behaviour of the estimate of Wright’s index is actually quite sensitive to skewness. They recommend using Wright’s index when $T \neq \mu$ and the skewness, $\mu_3 \neq 0$, at least for large sample sizes irrespectively of the underlying distribution.
6.4 A discussion on the methods developed for handling non-normal situations

All seven methods presented above, are attempts to solve the problem of how to use process capability indices when the process monitored is non-normally distributed. However, all methods described still are surrounded with some questions concerning either the appropriateness or the simplicity of using them in practice.

As indicated earlier in this chapter, Kotz & Johnson (1993) clearly divided the problem of how to use process capability indices for non-normally distributed characteristics into two parts which are repeated here again:

1 Investigate the properties of process capability indices and their estimators when the process output has specific non-normal shapes.

2 Develop methods allowing for non-normality and consideration of use of new process capability indices specially designed to be robust, i.e., not sensitive, to non-normality.

When studying these two parts it seems natural to start with solving the first problem before any fruitful attempts to solve the other problem can be made. However, when looking back at the theoretical overview presented in this chapter it seems as if the main part of the research has been devoted to solving the second problem without really knowing the answer to the first problem.

The author is convinced that before the problem of how to handle process capability indices for non-normally distributed characteristics can be solved, the effects of non-normality upon estimates of process capability indices must first be investigated. This motivates the simulation study presented in this thesis.
CHAPTER 7

THE METHODOLOGY OF THE SIMULATION STUDY

In this chapter the methodology of a simulation study focusing on the effect of skewness on estimates of some process capability indices is presented. Efforts are made to present the assumptions and limitations of the method used.

7.1 Research questions of interest

It is clear from chapter 6 that there is a need of process capability indices that can be used in non-normal situations.

When we no longer can assume that the process output is normally distributed we have a large variety of different distribution shapes to consider. In practice, when the distribution of a process output is not approximately normally distributed, it is not unusual that it is distributed according to some skew distribution, see, e.g., Gunter (1989b). Hence in this study, we will focus on a class of skew distributions as alternative to the normal distribution. We will consider the class of indices \( C_p(u,v) \), defined by Vännman (1995) and investigate properties of this class when the process output follows skew distributions.

The study will focus on answering the following two questions:

1. How does skewness effect the distributional properties as, expectation and standard deviation of the estimated indices of the studied class \( C_p(u,v) \)?

2. In the class of \( C_p(u,v) \), are there some combinations of \( u \) and \( v \) that are suitable to use when the process output is distributed according to a skew distribution?

The study will also shed some light on the question if it is possible, by using alternative interpretations of the class of indices, denoted \( C_p(u,v) \), to differ between capable and non-capable processes if the process output is distributed according to a skew distribution? Since it is
Indeed very complicated to derive the probability distribution functions for process capability indices for non-normally distributed process outputs, we have chosen a simulation study.

To make the results as relevant as possible we have had the ambition to cover situations of interest from a practical point of view.

### 7.2 The method used

When performing a simulation study it is necessary to make some choices of different parameters in order to study some desired phenomenon. In this section, efforts are made to present the assumptions and limitations in connection to this simulation study.

#### 7.2.1 Base for comparison

In the study, there is first of all a need to form some sort of base to use when analysing different process outputs in order to make fair comparisons and reach correct conclusions. When conducting a simulation study focusing on the effect of skewness on estimates of process capability indices there are at least two natural bases for comparison to choose among. One focuses on fix values of a given process capability index for different distributions and the other focuses on fix proportions of nonconforming items for different distributions.

English & Taylor (1993) used the first of these bases for comparison. They focused on cases with different distributions, but all with a capability that corresponds to $C_p$ or $C_{pk} = 1.0$. The limitations of such a base of comparison has been indicated in figure 1.16. Therefore, the base of comparison chosen in this study is focused on the proportion of nonconforming items. The main reason for this choice is that it becomes possible to see if different indices actually can differ between capable and non-capable situations.

The simulation study focuses on a characteristic which is a measure of deviations from a target value. The target value is thereby equal to zero. The upper specification limit ($USL$) is 3 and the lower specification limit ($LSL$) is $-3$. The target value, $T$, is thereby placed in the centre of the specification interval and equal to 0. These specifications are identical to the ones used by English & Taylor (1993). The choice of setting $T$ equal to the midpoint of the specification interval is based on the fact that this situation is common in practice. These choices implies no limitations.
7.2.2 Choice of simulation cases

To study the effect of skewness on estimates of some process capability indices, three basic cases are chosen, see table 7.1.

The three cases have been chosen so that case I corresponds to a non-capable process, case II to a fairly capable process and case III to a clearly capable process with regard to the probability of nonconformance. In all three cases the process has been assumed to be on target in the sense that the expected value of the process output has been set to zero. Furthermore, the process output has been assumed to be distributed according to a three-parameter log-normal distribution with different skewness ranging from 0.5 to 2.0, where the skewness is defined as:

\[
\delta = \frac{E(X_i - \mu)^3}{\sigma^3}
\]

If the skewness is equal to zero, we have a symmetrical distribution, for instance a normal distribution. The larger the skewness the heavier the right tail of the distribution is. For a description of the three-parameter log-normal distribution, see, e.g., Johnson, Kotz & Balakrishnan (1995). The log-normal distribution has been chosen since it is a fairly common model for the skew situations experienced in practice.

Table 7.1 In the study three cases are chosen to be able to analyse the effect of skewness on estimates of process capability indices. Case I is non-capable, case II is just capable and case III is clearly capable. In each case, four levels of skewness have been chosen, where the skewness is defined according to (7.1). In all three cases the process has been assumed to be on target in the sense that the expected value of the process output has been set to zero.

<table>
<thead>
<tr>
<th>Case</th>
<th>Proportion of nonconforming items</th>
<th>Corresponding value of $C_p$</th>
<th>Skewness, $\delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case I</td>
<td>0.045</td>
<td>2/3</td>
<td>0.5, 1.0, 1.5, 2.0</td>
</tr>
<tr>
<td>Case II</td>
<td>0.0027</td>
<td>1.0</td>
<td>0.5, 1.0, 1.5, 2.0</td>
</tr>
<tr>
<td>Case III</td>
<td>1.97E-9</td>
<td>2.0</td>
<td>0.5, 1.0, 1.5, 2.0</td>
</tr>
</tbody>
</table>

Table 7.1 indicates that actually there are twelve different distributions monitored in this study, four in case I, four in case II and four in case III. The three cases, each one with four differently skewed distributions, are described in figure 7.1. The parameters of the log-normal distributions fulfilling the terms described in table 7.1 are given in enclosure 6.
Figure 7.1 In the simulation study three cases have been used, each one representing a fixed proportion of nonconforming items. In each case, there are four different log-normal distributions with skewness 0.5, 1.0, 1.5 and 2.0, the upper specification limit is 3 and the lower specification limit is -3. The target value is zero. The expected value for all 12 distributions has been chosen equal to zero.
Based on the simulated data from the distributions presented in figure 7.1, different process capability indices have been estimated. In each estimate a sample of 50 random values have been used. To derive the empirical distribution of each index for each one of the 12 distributions in figure 7.1, 10000 estimates have been made of each index in accordance with English & Taylor (1993).

By simulating random values from the 12 distributions described in figure 7.1 the effect of skewness on estimates of some process capability indices has been studied.

### 7.2.3 Choice of process capability indices

In the introduction of this thesis, a historical overview of the development of process capability indices is given. It is mainly the four indices $C_p = C_p(0,0)$, $C_{pk} = C_p(1,0)$, $C_{pm} = C_p(0,1)$ and $C_{pmk} = C_p(1,1)$ that constitute this development, prior to the introduction of $C_p(u,v)$. Therefore, it would be suitable to include these indices in this study.

All of these four indices but $C_p$ have been included. The process capability index $C_p$ has been left out due to its inability to monitor any change in location of the process, a characteristic which makes it less interesting to use.

In those situations where the normality of the process output is not severely violated and the target value coincides with the midpoint of the specification interval, Vännman & Kotz (1995b) recommend practitioners to use the indices $C_p(0,3)$, $C_p(1,2)$ and $C_p(0,4)$ since they provide the smallest approximate mean square error and relative bias when the process is on target and since they are quite sensitive to deviations from the target value. Therefore, it has been considered natural to include these indices in the study.

Finally, two more indices have been included, $C_p(4,0)$ and $C_p(4,4)$. The reason for choosing $C_p(4,0)$ is that it is desired to study the effect of a large $u$-value and the reason for choosing $C_p(4,4)$ is that it is desired to study the effect of both a large $u$- and $v$-value. The effect of a large $v$-value is already represented in the study, since $C_p(0,4)$ is included on the base of recommendations made by Vännman & Kotz (1995b).

Altogether there are eight indices used in this study, which are summarised in table 7.2.
Table 7.2  The study is focused on the following eight combinations of \( u \) and \( v \) in \( C_p(u,v) \), where \( C_p(u,v) \) is defined (1.20). \( C_p(1,0) \) is also known as \( C_{pk} \), \( C_p(0,1) \) is known as \( C_{pm} \) and \( C_p(1,1) \) is known as \( C_{pmk} \).

| \( C_p(1,0) \) | \( C_p(0,1) \) | \( C_p(1,1) \) | \( C_p(0,3) \) | \( C_p(0,4) \) | \( C_p(1,2) \) | \( C_p(4,0) \) | \( C_p(4,4) \) |

7.2.4 The simulation routine

All simulations and calculations have been made by using the program Mathematica (Wolfram (1991)). Since it was found that the program is much faster when simulating random values from a normal distribution than from the log-normal distribution, the characteristics of the desired log-normal distributions in figure 7.1 were recalculated to a corresponding normal distribution. The generation of random values was then made from the corresponding normal distribution and later in the simulation routine the values were transformed into the desired log-normal distribution by taking the logarithm. All initial simulation parameters are given in enclosure 6. The simulation routine is given in enclosure 7.

7.2.5 Validity and reliability of the simulation study

Here a short description is given of the aspects that influence the validity and the reliability of the study.

Since it is indeed very complicated to derive the probability distributions for process capability indices for non-normally distributed process outputs, we have chosen a simulation study. We have used as much as 10000 estimates when deriving the empirical distributions of each index for each one of the 12 distributions in figure 7.1, even though our test runs indicated that fairly accurate empirical distributions would have been established using only 5000 estimates. The conclusion that 5000 estimates probably would have been enough was reached by using the simulation routine for a normal distribution and comparing the received empirical distribution with the derived distribution of \( C_p(u,v) \), presented by Vännman & Kotz (1995a).

By using a fix proportion of nonconforming items in each of the three cases a sound base for comparison is provided.

The simulation cases have been chosen to cover the range of interest, from a practitioner's point of view. First of all the three cases cover both incapable processes as well as very capable processes. In all three cases, the skewness has been varied from 0.5 to 2.0, covering a large part of the range of skewness of interest, from a practical point of view. The log-normal distribution has been chosen due to its ability to describe...
naturally skewed characteristics and due to its clear correspondence with the normal distribution. An alternative method could be to use the family of Weibull distributions to derive correspondingly skew distributions as those presented in figure 7.1. However, the calculations for deriving these Weibull distributions would be much more complicated compared to the log-normal ones, due to the three parameters $\alpha$, $\beta$ and $\gamma$ of the Weibull distribution.

The number of measurements in each estimate has been chosen to 50, due to both practical and theoretical aspects. This means that the whole study is to be viewed as a "snapshot" at $n = 50$. Other values of $n$ would influence the result. A discussion on how different values of $n$ would influence the result is given in chapter 8.

The choice of process capability indices used in the study includes some indices used in practice today, and at the same time, the choice enables a study of what combinations of $u$ and $v$ that are suitable to use when the process output is distributed according to a skew distribution?

In all simulation cases the expected value has been equal to the target value, $T$. If deviations of the expected value from $T$ are considered some other results might be found.

The relative smoothness of the effect of skewness has directly revealed any erroneous calculations and they have been corrected.

The results of this study are in accordance with the results found by English & Taylor (1993).

When considering the reliability of the study it would be of no problem at all to repeat the study and reach the same results. All simulation parameters are given in enclosure 6, the simulation routine is given in enclosure 7. All programmes used during simulation and analysis are available.
CHAPTER 8
ANALYSIS AND RESULTS

In this chapter the analysis and results from the study presented in chapter 7 are given.

8.1 Base for analysis

To be able to analyse the results from the simulation study it must first be determined what properties estimates of a suitable process capability index should have.

Assume that we actually know the true distribution of the characteristic studied. This privilege is never an option in reality, but can be obtained in a simulation study. If the true distribution is known, it will correspond to a true value of a given process capability index. On the base of a sample from the process output, the desired properties of any process capability index should then reflect this true value as accurately as possible. The term “as accurately as possible” can be divided into two different aspects:

1. The difference between an estimated value of a given process capability index, based on a sample from a known distribution, and the true value, calculated by using the true parameters of the same distribution, should be as small as possible. This difference is often called the bias of an estimate.

2. Since different estimates of a given process capability index made for the same process will be based on different samples, there will be a certain variability among these estimates. For a suitable process capability index this variability among different estimates from the same process should be as small as possible. This variability is referred to as the dispersion, measured by the standard deviation, of estimates of a process capability index in this study.

The two aspects, the bias and the dispersion of estimates of a process capability index, form a base for analysis in this study. A suitable process capability index give estimates with as small bias and dispersion as
possible. The terms bias and dispersion of estimated process capability indices are further described in figure 8.1.

![Figure 8.1](image)

**Figure 8.1** A schematic picture of the distribution of estimates of any process capability index. A suitable process capability index has characteristics that makes it as capable as possible to estimate the true value, the true capability, i.e. the estimated distribution of a suitable process capability index has as small bias and dispersion as possible. In the study the bias is measured by the difference between the true value and the expected value of the distribution of estimates of the process capability index. The dispersion is measured by the standard deviation of the distribution of estimates of the process capability index.

In the study, three cases, each one with four differently skewed log-normal distributions, have been used, see figure 7.1. Altogether, this gives twelve distributions and for each distribution 10000 estimates have been made for each one of the eight indices given in table 7.2. The empirical distributions for all indices in all cases have then been analysed. The parameters of these distributions are given in enclosure 8.

In the next two sections the two research questions of interest, presented in chapter 7, are analysed. In section 8.2 the effect of skewness upon estimates of some process capability indices is analysed and in section 8.3 it is investigated if there are some combinations of $u$ and $v$ in $C_p(u,v)$ that are suitable to use when the process output is distributed according to a skew distribution. In section 8.4 the effect of skewness on the ability of $C_{pk}$ to differ between capable and non-capable processes is studied.
8.2 The effect of skewness on statistical properties of the estimated process capability indices

When analysing the effect of skewness on estimates of process capability indices it is necessary to define what is meant by a suitable process capability index in this study. A definition of a suitable and process capability index is:

The most suitable process capability index is the index that has as small bias and dispersion as possible, regardless of the skewness of the process output monitored.

The effect of skewness on the dispersion of the studied process capability indices is analysed in section 8.2.1 and the effect of skewness on the bias of the studied process capability indices is analysed in section 8.2.2.

8.2.1 Effect of skewness on the dispersion of estimates of process capability indices

It is a fact that the dispersion of estimates of the process capability indices included in this study increases as the capability of the process increases, for a fixed value of \( n \), when the process output is normally distributed, see, e.g., Kotz and Johnson (1993), Deleryd (1993) or Vännman (1995).

From figures 8.2a-1 it is clear that the increase of the dispersion of the studied process capability indices for increased capability, also is present when the distribution of the process output is skew. In fact, figures 8.2a-1 shows that the increase in dispersion is magnified as the skewness increases. In figures 8.2a-1 the standard deviation and the bias are given for all indices in all simulation cases. Since there are eight indices monitored, see table 7.2, there are eight dots in each figure 8.2a-1. To make it easy to study the effect of skewness, figures from simulations made on distributions with equal skewness are gathered in the same column. In the first column of figure 8.2a-1, figures 8.2a-c, the skewness is 0.5, in the second column, figures 8.2d-f, the skewness is 1.0, in the third column, figures 8.2g-i, the skewness is 1.5 and in the fourth column, figures 8.2j-l, the skewness is 2.0.

The fact that the increase in dispersion for more capable processes also is present when the distribution of the process output is skew can for instance be realised by looking at the three figures 8.2a - 8.2c. In 8.2a the standard deviation is approximately 0.1 for all indices, in 8.2b the
standard deviation is approximately 0.15 for all indices and in figure 8.2c, representing the most capable case of the three, the standard deviation is approximately 0.25. This effect is also present when comparing 8.2d - 8.2f or 8.2g - 8.2i or 8.2j - 8.2l. When performing such a comparison we can see a pattern that the increase in dispersion is magnified as the skewness increases. In the most capable and at the same time most skewly distributed case, see figure 8.2l, the standard deviation is approximately as high as 1.4.

One interesting result is that the standard deviation for the estimated indices in figures 8.2a-l are almost constant. Take for instance the two ultimate cases included in the study, figure 8.2a representing an incapable process with moderate skewness and figure 8.2l representing a clearly capable process that is heavily skewed. In figure 8.2a all dots are at a level of approximately 0.1 and in figure 8.2l all dots are at a level of approximately 1.4. In figure 8.2l, the dispersion among the dots along the standard deviation-axis is somewhat larger compared to figure 8.2a but the increase is very moderate.
Figure 8.2a-f  The figure text for figures 8.2a-l is given on the next page.
In Figure 8.2a-l the standard deviation and the bias are given for all indices in all simulation cases. Since there are eight indices included in the study, see Table 7.2, there are eight dots in each plot from 8.2a-l. It is clear that the increase of the dispersion of any process capability index for increased capability is magnified as the skewness increases.
8.2.2 Effects of skewness on the bias of estimates of process
capability indices

When analysing the effect of skewness on the bias of estimates of process
capability indices it is advantageous to rearrange all figures in
figure 8.2 so that all figures, derived from simulations on distributions
with the same proportion of nonconforming items, are placed together.
This has been done in figure 8.3.

By looking at figures 8.3a-d, case I, it is apparent that most indices,
included in the study, tend to underestimate the true capability, i.e. the
bias is negative. However, as the capability of the process increases all
indices, included in the study, sooner or later will overestimate the true
capability. This effect can for instance be seen by comparing figures
8.3a-d with figures 8.3i-l. In figures 8.3i-l, representing case III, the most
capable case, almost all indices overestimate the true capability, i.e. the
bias is positive. By comparing the figures 8.3a-l it is also apparent that,
the effect that all included indices tend to overestimate the true capabil-
ity as the capability of the monitored process increases, is magnified as
the skewness increases.

Another interesting result is that the dispersion between of the bias
among the different process capability indices included, i.e. how spread
out the dots are along the bias-axis, seems to increase as the capability
of the monitored process increases. This increase can for instance be
realised by looking back at the three figures 8.2j-l. In figure 8.2j the dots
are quite close to each other along the bias-axis, in figure 8.2k they are
more spread out and in figure 8.2l, the most capable situation of the
three, the dots are really spread out along the bias-axis. This increased
variability among the bias for increased capability seems to accelerate as
the skewness increases. This can for instance be realised by looking at
the four figures 8.3i-l. In figure 8.3i representing the less skewed situa-
tion of the four, the dots are quite close to each other along the bias-axis.
However, in figure 8.3l, representing the most skewed situation of the
four, the dots are really spread out along the bias-axis.
Case I, proportion of nonconforming items = 0.045

Figure 8.3a $p = 0.045$, skewness = 0.5

Figure 8.3b $p = 0.045$, skewness = 1.0

Figure 8.3c $p = 0.045$, skewness = 1.5

Figure 8.3d $p = 0.045$, skewness = 2.0

Case II, proportion of nonconforming items = 0.0027

Figure 8.3e $p = 0.0027$, skewness = 0.5

Figure 8.3f $p = 0.0027$, skewness = 1.0

Figure 8.3g $p = 0.0027$, skewness = 1.5

Figure 8.3h $p = 0.0027$, skewness = 2.0

Figure 8.3a-h The figure text for figures 8.3a-l is given on the next page.
Case III, proportion of nonconforming items = 1.97E-9

Figure 8.3i  \( p = 1.97\times10^{-9}, \text{ skewness} = 0.5 \)

Figure 8.3j  \( p = 1.97\times10^{-9}, \text{ skewness} = 1.0 \)

Figure 8.3k  \( p = 1.97\times10^{-9}, \text{ skewness} = 1.5 \)

Figure 8.3l  \( p = 1.97\times10^{-9}, \text{ skewness} = 2.0 \)

Figure 8.3a-l The figures 8.2a-l have been rearranged so that figures representing an equal proportion of nonconforming items are placed between each other. In figure 8.3a-l the standard deviation and the bias are given for all indices in all simulation cases. Since there were eight indices monitored, see table 7.2, there are eight dots in each plot from 8.3a-l. It is clear that as the capability of the monitored process increases, all included indices tend to start overestimating the true capability. From figure 8.3a-l it is also clear that the tendency to overestimate the true value, as the capability of the monitored process increases, is magnified as the skewness of the monitored process increases. Figure 8.3a-l also shows that the dispersion among the bias increases as the capability of the monitored process increases and that this increase is magnified when the skewness of the monitored process increases.
8.3 Suitable $u$- and $v$-values of $C_p(u,v)$

By varying the parameters $u$ and $v$ in $C_p(u,v)$ different process capability indices with different characteristics are received. To understand how $u$ and $v$ affect $C_p(u,v)$ it is appropriate to study the formula

$$C_p(u,v) = \frac{d - u|\mu - M|}{3\sqrt{\sigma^2 + v(\mu - T)^2}}.$$ (8.1)

If the value of $u$ is increased the deviation from the midpoint of the specification interval $M$ is emphasised and if $v$ is increased the deviation from the target value $T$ is emphasised. In this simulation study the target value has been chosen as $T = M$, therefore $C_p(u,v)$ can be written as

$$C_p(u,v) = \frac{d - u|\mu - T|}{3\sqrt{\sigma^2 + v(\mu - T)^2}}.$$ (8.2)

This restriction is made due to the fact that it is quite common that the target value is symmetrically placed in practical situation. If it is of interest to have a process capability index that is very sensitive with regard to departures of the process mean, $\mu$, from the target value, $T$, then the values of $u$ and $v$ should be large.

However, Vännman (1995) proves that it is not desirable to increase $u$ and $v$ too much since the process capability indices then will have undesirable statistical properties. For instance, values of $u$ and $v$ that are larger than five seem to be of very little interest. The indices $C_p(0,4)$, $C_p(4,0)$ and $C_p(4,4)$ are therefore to be considered as some sort of upper limits for suitable values of $u$ and $v$ to choose.

Since different values of $u$ and $v$ provide different process capability indices, different values of $u$ and $v$ will probably provide a more suitable process capability index when the studied characteristic is skewly distributed. To analyse what combinations of $u$ and $v$ that might be suitable when the studied characteristic is skewly distributed figures 1-8 in enclosure 9 have been plotted. In these figures the relative bias has been plotted against the standard deviation for all simulation cases. A suitable process capability index has as small relative bias and standard deviation as possible. Therefore, when searching for a suitable process capability index, all dots in the figures in enclosure 9 should be as close
When analysing the figures in enclosure 9 it is much easier to say what indices are clearly unsuitable to use, than to determine what index is most suitable of all of them, when it comes to differently skewed distributions. The indices $C_p(4,0)$ and $C_p(4,4)$ seem to be the most unsuitable indices. The fact that $C_p(4,0)$ and $C_p(4,4)$ heavily underestimate the true capability can be explained by looking at the empirical distributions derived from the simulated data, see figure 8.4. The approximate probability distribution functions for $C_p(4,0)$ and $C_p(4,4)$ in figure 8.4g-h, clearly show a heavy left tail, compared to the other indices in figures 8.4a-f. This tail is caused by the large $u$-value and is apparent in all the simulation cases, even if just the case with the proportion of nonconforming items equal to 0.045 and the skewness equal to 0.5, is shown in figure 8.4.

When analysing the effect of different values of $v$ it is appropriate to study figure 2 describing $C_p(0,1)$, figure 4 describing $C_p(0,3)$ and figure 5 describing $C_p(0,4)$. From these three figures it is clear that when $v = 1$ in figure 2 the true capability is overestimated in all covered cases. However as $v$ increases the index tends to more and more underestimate the true value.

When searching for a suitable combination of $u$ and $v$ it seems as if neither large $u$-values, nor large $v$-values in $C_p(u,v)$ are desired. In fact the most suitable index of all eight seems to be $C_p(1,1)$, even though the difference between the indices in figures 1-6 in enclosure 9 are relatively small. Perhaps the most suitable process capability index is received when there is some sort of balance between $u$ and $v$ in $C_p(u,v)$, that is when $u$ and $v$ are almost identical.

One thing that is interesting with $C_p(1,1)$, also known as $C_{pmk}$, is that the bias seems to be relatively independent of how capable the monitored process is. In this sense $C_{pmk}$ seems to be robust. This result is further illustrated in figure 8.5 which is based on figure 3 in enclosure 9. The line indicated as 1 in figure 8.5 shows that the relative bias when the skewness is 0.5 is approximately -1%, regardless of how capable the process is. The lines 2, 3 and 4 indicate the same phenomenon.
Case I, proportion of nonconforming items = 0.045, skewness = 0.5

Figure 8.4a, $C_p(0,1)$

Figure 8.4b, $C_p(0,3)$

Figure 8.4c, $C_p(0,4)$

Figure 8.4d, $C_p(1,0)$

Figure 8.4e, $C_p(1,1)$

Figure 8.4f, $C_p(1,2)$

Figure 8.4g, $C_p(4,0)$

Figure 8.4h, $C_p(4,4)$

Figure 8.4a-h The empirical distributions of all indices included in the study when the proportion of nonconforming items is 0.045 and the skewness is 0.5. It is clear that when $u$ is large, figure 8.4g-h, a heavy left tail appears that makes these indices inappropriate to use, since they heavily will underestimate the true capability.
For the process capability index $C_p(1,1)$ it seems as if the relative bias is roughly independent of how capable the monitored process is. Line number 1 shows that the relative bias is approximately -1% when the skewness is 0.5, regardless of how capable the process is. Line number 4 shows that the relative bias is approximately 2.5% when the skewness is 2.0, regardless of how capable the process is.

8.4 The ability of $C_{p_{mk}}$ to differ capable processes from non-capable processes

In order to give an idea of the ability of $C_p(u,v)$ to differ between capable and non-capable processes when the process outputs are skewly distributed, figure 8.6a-e has been developed. Since it has been indicated that of the indices included in this study $C_p(1,1) = C_{p_{mk}}$ seems to be most suitable to use when the process outputs are skewly distributed, figure 8.6a-e has been based on this index.
Figure 8.6a: Skewness = 0, n = 50
The probability distributions functions for $\hat{C}_{pmk}$ for three normally distributed process outputs. The most peaked distributions corresponds to 4.5% nonconforming items, the middle distribution to 0.27% and the distribution that is less peaked to 0.00197 ppm of nonconforming items. This figure is derived from results presented in Värnman & Kotz (1995a).

Figure 8.6b: Skewness = 0.5, n = 50
The probability distributions functions for $\hat{C}_{pmk}$ for three skewly distributed process outputs. The most peaked distributions corresponds to 4.5% nonconforming items, the middle distribution to 0.27% and the distribution that is less peaked to 0.00197 ppm of nonconforming items. This figure is derived by connecting the top of bars in histograms based on simulated data.

Figure 8.6c: Skewness = 1.0, n = 50
The probability distributions functions for $\hat{C}_{pmk}$ for three skewly distributed process outputs. The most peaked distributions corresponds to 4.5% nonconforming items, the middle distribution to 0.27% and the distribution that is less peaked to 0.00197 ppm of nonconforming items. This figure is derived by connecting the top of bars in histograms based on simulated data.

Figure 8.6d: Skewness = 1.5, n = 50
The probability distributions functions for $\hat{C}_{pmk}$ for three skewly distributed process outputs. The most peaked distributions corresponds to 4.5% nonconforming items, the middle distribution to 0.27% and the distribution that is less peaked to 0.00197 ppm of nonconforming items. This figure is derived by connecting the top of bars in histograms based on simulated data.

Figure 8.6e: Skewness = 2.0, n = 50
The probability distributions functions for $\hat{C}_{pmk}$ for three skewly distributed process outputs. The most peaked distributions corresponds to 4.5% nonconforming items, the middle distribution to 0.27% and the distribution that is less peaked to 0.00197 ppm of nonconforming items. This figure is derived by connecting the top of bars in histograms based on simulated data.

Figure 8.6a-e The ability of $C_{pmk}$ to differ between capable and non-capable processes when the process outputs are differently skewed are described in figures 8a-e. In all distributions n = 50.
In figure 8.6a-e, the distribution most peaked in all figures corresponds to processes with 4.5% of nonconforming items, i.e. clearly non-capable processes. The middle-peaked distributions corresponds to a process with 0.27% of nonconforming items, i.e. fairly capable processes. The less peaked distributions corresponds to clearly capable processes with 0.00197 ppm of nonconforming items. In figure 8.6a the skewness is = 0 and the skewness is then successively enlarged for each figure. In figure 8.6 the skewness is 2.0.

From figures 8.6a-e it is clear that the ability of $C_{pmk}$ to differ between capable and non-capable processes is not effected by the skewness of the monitored process. This can be realised since the distributions in figures 8.6 do not cover each other very much. In all distributions in 8.6, 50 measurements have been used for each estimate of $C_{pmk}$. If the number of measurements used is less than 50 then the dispersion of these distributions would increase and they would cover each other to a larger extent.

It must also be remembered that the capability represented by the three situations described in each figure from figure 8.6a-e differs quite substantially, which might be a quite natural reason for the distributions not to cover each other. Let us instead study a situation with two processes which are almost equally capable. Consider the situation where we have two suppliers that produce the same article and we want to buy from the supplier with the most capable process. Pretend for a second that we know for certain that the capability of the process of supplier 1 is $C_{pmk} = 1.25$ and the capability of the process of supplier 2 is $C_{pmk} = 1.40$. However, knowing the true capability is never an option in reality, then we have to estimate the capability. Assume that both the suppliers' processes are normally distributed and we use 50 measurements when estimating $C_{pmk}$, then the distributions of $C_{pmk}$ for the processes of these two suppliers are given in figure 8.7. When analysing these probability distribution functions it is clear that they cover each other to a very large extent. This means that if we are conducting one single process capability study on each one of the processes there is a large possibility that we will reach the conclusion that the process of supplier 1 is more capable than the process of supplier 2, even though this actually is not the case. Figure 8.7 clearly shows the importance to use confidence limits when assuring a certain level of capability or when comparing two processes in order to reach more correct decisions.
Figure 8.7  The distributions of $\hat{C}_{\text{pmk}}$ for processes at two suppliers. The process of supplier 1 has a true capability of $C_{\text{pmk}} = 1.25$ and the process of supplier 2 is $C_{\text{pmk}} = 1.40$. Since the two distributions covers each other to a large extent there is a large risk of claiming the process of supplier 1 more capable than the process of supplier 2 even though this is not correct.

8.5 Summary of results from the simulation study

In this section a summary of some results of importance are summarised. The results are divided into four parts, first the results concerning the effect of skewness on the dispersion of estimates of the studied process capability indices is described. Then the effects of skewness on the bias of estimates of the studied process capability indices are summarised. Then some results regarding suitable $\psi$- and $\phi$-values of $C_p(u,v)$ when the studied characteristic is skewly distributed are described. Finally, the effect of skewness on the ability of $C_{\text{pmk}}$ to differ between capable and non-capable processes is summarised.

Effects of skewness on the dispersion of estimates of process capability indices

- The dispersion for any process capability index increases as the capability of the monitored process increases. This increase in dispersion for successively more capable processes is magnified as the skewness increases.

- The dispersion between the values for the standard deviation among the different process capability indices included seems to be relatively constant. This result holds regardless of how skewly distributed the monitored characteristic is.
Effects of skewness on the bias of estimates of process capability indices

• For all indices included in the study, the bias successively gets larger and larger as the capability of the monitored process increases. This increase of the bias for successively more capable processes is magnified as the skewness increases.

• The dispersion among the bias of the different process capability indices included seems to increase as the capability of the monitored process increases. This increase is magnified when the skewness of the monitored characteristic increases.

Suitable $u$- and $v$-values of $C_p(u,v)$ when the studied characteristic is skewly distributed

• Large $u$-values cause a heavy left tail in the distribution for the index, which causes heavy underestimates of the true capability. It seems as if the $u$-value should not be larger than 1 if a suitable process capability index is desired.

• As the $v$-value gets larger the index will successively underestimate the true capability more and more. However, large $v$-values have not the same dramatic effect as large $u$-values.

• It seems as if the process capability index $C_p(1,1)$, also called $C_{pmk}$ is the most suitable index of the studied ones when it comes to handling skewness.

The ability of $C_{pmk}$ to differ capable processes from non-capable processes

• The ability of $C_{pmk}$ to differ between capable and non-capable processes is not effected by the skewness of the monitored process.

8.5.1 Practical significance of the results

It is apparent that skewness effects the statistical properties of all process capability indices included in the study. However, the study has shown that these effects are systematic. For instance, the study shows that both the dispersion and the bias of the distributions of estimates of the studied process capability indices are magnified as the skewness increases. The increase is moderate for low values of skewness but more dramatic for larger values of the skewness.
The effect of skewness on the bias of estimates of the studied indices seems to have relatively little practical significance. For $C_{pk_k}$, which was found to be most suitable to use when the process output is skewly distributed, the relative bias is not larger than 2.5% for the most skewed situation in the study. The effect of skewness on the dispersion of distributions of estimates of process capability indices is probably more severe from a practitioners point of view since the dispersion of the distributions of estimates increases quite substantially for skew processes. This fact makes it hard to tell, on the base of the indices included in the study, if a process is capable or not.

However, it is extremely important to remember some of the limitations of this simulation study. Most of all, the following limitations could influence the result of this study:

- The whole study is a snapshot at $n = 50$. The effects of different values of $n$ used in a similar study have however already been enlightened by English & Taylor (1993) and Price & Price (1992). They found that the effects of skewness become less pronounced as the number of measurements used in each estimate, $n$, increases. Thereby, the effect of different values of $n$ would probably not change the major results.

- In all simulation cases, the target value, $T$, has been equal to the mid-point of the specification interval, $M$. If instead $T \neq M$, then some of the results might be changed.

- In all simulation cases the expected value has been equal to the target value, $T$. If deviations of the expected value from $T$ are considered some other results might be found.

The major result from the study is perhaps that the effect of skewness has been found to be relatively systematic, and therefore there are some hope that future investigations might use these results when formulating some practical solution to the problem of how to use process capability indices when the process monitored is skewly distributed. The study suggests that when it comes to moderate skewness, there are probably no reason to change the method of how to conduct process capability studies in any way. However, if the process monitored has as large skewness as 2.0 the simulation study indicates that the result will probably mislead the practitioner if it is not handled with care. The risk of misinterpretations is mainly due to the substantially increased dispersion of the distributions of estimates of the process capability indices studied that is present when the process output is skewly distributed.
Part 3

Discussion, conclusions and future research
CHAPTER 9

DISCUSSION, CONCLUSIONS AND FUTURE RESEARCH

In this chapter the most important results from the studies included in the thesis are presented and the conclusions are shortly summarised. Finally, some suggestions for future research are given.

9.1 A discussion on the thesis' results and conclusions

Basically it all comes down to mastering variation. Since variation exists and constantly effects the outcome of all processes, some strategies for how to handle variation have to be developed.

Shewhart (1931) developed control charts to be used for monitoring variation and successively eliminating as many assignable causes as possible, with minimised variation as a result. Taguchi (1986) presents an even more proactive strategy, which is based on the idea of developing the product in such a way that no matter what causes of variation encountered when producing and using the product, its function should not be interfered. By using both Shewhart's and Taguchi's strategies simultaneously, our chances of mastering variation are probably maximised.

In the war against variation, constantly in progress within industry, some limits for "acceptable variation" have to be determined to make the whole system work, otherwise no products would ever leave our factories. The limits for "acceptable variation" are called specification limits. Then there is also a need to judge how capable a specific process is of meeting these specification limits, this is where process capability studies come into the picture. The process capability studies themselves do not improve the capability of the process but they enlighten all kinds of improvement opportunities.

This is a short summary of the theoretical view on how process capability studies fit into a strategy focused on mastering variation, presented in the introduction of this thesis. The summary helps putting
process capability studies into perspective and it is clear that process capability studies are not to be viewed as a single method without connection to other methods. For instance, the close relationship between statistical process control and process capability studies has been enlightened in the thesis.

Part 1 of this thesis shows that many organisations within Swedish industry have difficulties when conducting process capability studies. Many of the theoretical aspects of how to conduct process capability studies are ignored, or unknown, within many of the surveyed organisations. Only few of these organisations master all theoretical aspects of how to conduct process capability studies.

Despite the fact that many of the organisations are not fully aware of the theoretical aspects of process capability studies, they seem to have experienced an increase in the percentage of capable processes just by starting to measure the output of processes and acting on the base of the result. One explanation is perhaps that they have identified some major disproportions, that have been corrected. However, if these organisations will succeed in the long run with minimising variation and achieving more and more capable processes, they will have to consider the theoretical aspects of process capability studies more thoroughly.

When analysing why some of the surveyed organisations ignore or are unaware of some of the theoretical aspects, the study was directed to find answers to why it sometimes is so hard to implement and conduct process capability studies. It was found that the major obstacles occurring when implementing and conducting process capability studies could somehow be related to management issues. Proper education and training is essential to successfully conducting process capability studies and appropriate resources have to be allocated. Only managers have the authority to allocate such resources.

In the study presented in part 1 of the thesis, three rather serious misconceptions were identified:

- It seems as if some practitioners believe that if the process is not normally distributed, there is some cause effecting the process output and if this cause is removed the process will automatically become normally distributed. The fact that it can be perfectly natural, having a non-normal process output is not always realised.

- It has been found that approximately 50% of the respondents that combine statistical process control with process capability studies actually require that the process must be capable before statistical process control and control charts can be used. This is totally against
the theories that requires the process to first be in statistical control before any meaningful process capability studies can be conducted.

- It seems as some practitioners are discouraged to conduct process capability studies if they find that the process monitored is non-normally distributed. Some even believe that it is impossible. The reason is probably that they have heard about some of the relatively poor properties of most process capability indices. However, if the aim of a process capability study is to improve a specific process within an organisation the poor statistical properties of process capability indices do not need to be considered, given that the shape of the process output remains approximately the same during the improvement efforts. On the other hand, if the aim is to compare the capability of the process with another process, it is wise to not fully trust the estimated values of a given process capability index. But the fact that some practitioners of today have misinterpreted this and now believe that it is impossible to conduct process capability studies for non-normally distributed parameters, is unfortunate.

Part 2 focus on the problem of how skewness effects the statistical properties of some process capability indices. In literature, there are several methods presented for how to handle non-normally distributed characteristics. This thesis presents all these methods, known by the author, and it is also indicated that none of these methods is perfect. Some of the methods are directly questionable from a theoretical point of view and on the other hand, the methods reasonable from the theoretical point of view are quite comprehensive from a practical point of view. Therefore, the search for a method of how to handle process capability studies when the process monitored is non-normally distributed carries on.

When formulating the major result of the simulation study, focusing on the effect of skewness on estimates of some process capability indices, it is perhaps that the effect of skewness seems to be systematic and thereby there ought to be some possible way of solving the problem of how to use process capability indices for skewly distributed characteristics. However, there still remains lots of research before this problem will be solved.
9.2 Suggestions for future research

The study started with a few question to be answered, but during the process of answering these questions, many more popped up. Here some interesting topics to further investigate, are presented:

• The study in part 1 showed that many of the theoretical aspects of how to conduct process capability indices are not applied, or not even known in practice. Then the natural question is of course why this gap between theory and practice exists. This thesis provides some answers to this question, but it would be of interest to further investigate this problem by performing case studies, both within organisations that have succeeded with implementing process capability studies and also within organisations where the implementation more or less have failed.

• When mastering variation the main objective in the short run is to achieve stable and capable processes. In the long run the aim is to make these capable processes even more stable and capable. It is apparent that it is not the process capability studies themselves that make the processes capable, but rather the actions taken on the base of the result from the process capability studies. Therefore, it would be of interest to study how a strategy for handling variation aimed at successively achieving more and more capable processes should be designed. What methods are to be used? In what order are they best utilised? How should education and training be set up? How should managers act? What resources are to be allocated? These are some of the questions surrounding a strategy for how to master variation. Some of the possible methods in such a strategy are illustrated in figure 9.1.
The second survey, presented in chapter 5 points out some methodological aspects of process capability studies that still would be suitable topics for further research. One such aspect is that theories for how to conduct process capability studies for short runs are not sufficiently developed. Since the concept of short run statistical process control has been the topic of much research, some ideas from this field might be used to establish a method for how to handle process capability studies when it comes to short runs.

The simulation study presented in part 2 of the thesis points out some promising statistical properties of $C_{pmk}$ that makes it more suitable to handle skewly distributed characteristics compared to the other indices studied. One interesting property of estimates of $C_{pmk}$ is that the bias seems to be relatively independent of how capable the monitored process is. This means that it would be possible to make some corrections of the estimates of $C_{pmk}$ to receive a more unbiased estimate when the process monitored is skewly distributed. It is important to remember that before such a method can be put into practice, it is necessary to further analyze the effects of skewness.
These are some topics for future research identified during this research. However, there is one last research topic that the author wants to enlighten.

There is no doubt that by using process capability studies together with other improvement methods, most organisations have much to gain. However, the fact that all process capability indices presented so far, have more or less poor statistical properties, sometimes leading users to wrong conclusions, suggests that efforts are to be allocated to find new measures of capability, quite different from the process capability indices used today. Perhaps the answer lies in graphical techniques, perhaps the answer is some other method. Here lies the real challenge when it comes to future research concerning process capability studies.
REFERENCES


References

enkätstudie (Process Capability Studies in Swedish Industry - 
Results from a Questionnaire Survey). Research Report, Division of 

Deleryd M. (1996). Why is it sometimes so hard to implement Process 
Capability Studies? To be presented at the conference "TQM in 
action", Sheffield, UK, 8-9 July 1996.


Education. MIT center for Advanced Engineering Study, 
Massachusetts. ISBN 0-911379-07-X.


Dovich R. A. (1991b). Statistical Terrorists II - it's not safe yet, $C_{pk}$ is out 
there. MS, Ingersoll Cutting Tools Co., Rockford, Illinois.

Duncan A. J. (1986). Quality Control and Industrial Statistics. 5th ed, 
Homewood, Ill. ISBN 0-256-60353-X.

Efron B. (1982). The Jacknife, the Bootstrap and other Re-sampling 
Plans. SIAM, CBMS-NSF Monograph, 38, SIAM: Philadelphia, 
Pennsylvania.

robustness Study, MS, Dept. Industr. Eng., University of Arkansas, 
Fayetteville.

robustness Study. International Journal of Production Research, vol. 31, 
no. 7, pp. 1621-1635.


Estimates of $C_{pk}$: An introduction. Communications in Statistics - 


References


References


Enclosure 1: Design of questionnaire 1

Table 1. This table describes how the different aspects of process capability studies identified through the literature review or interviews are operationalised into questions in questionnaire 1. The questions covering demographical aspects of the respondents' organisations have been introduced in order to be able to analyse the material properly. Question number 26 has been added in order to reach as many organisations as possible, where process capability studies are conducted, within Swedish industry. The final questionnaire is presented in enclosure 3a.

<table>
<thead>
<tr>
<th>Different aspects of process capability studies covered by questionnaire 1</th>
<th>Motivation for inculdance</th>
<th>Question number in questionnaire 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capable gauges</td>
<td>Theoretical aspect</td>
<td>No. 16 - 17</td>
</tr>
<tr>
<td>Statistical control</td>
<td>Theoretical aspect</td>
<td>No. 14</td>
</tr>
<tr>
<td>Conscious gathering of data</td>
<td>Theoretical aspect</td>
<td>No. 13</td>
</tr>
<tr>
<td>Use of confidence limits</td>
<td>Theoretical aspect</td>
<td>No. 15</td>
</tr>
<tr>
<td>Simultaneous use of several process capability indices</td>
<td>Theoretical aspect</td>
<td>No. 8 - 9</td>
</tr>
<tr>
<td>Check of the distribution of the output of the process</td>
<td>Theoretical aspect</td>
<td>No. 18</td>
</tr>
<tr>
<td>Implementation aspects of process capability studies</td>
<td>Practical aspect</td>
<td>No. 5 - 7</td>
</tr>
<tr>
<td>Pressure between organisations to conduct process capability studies</td>
<td>Practical aspect</td>
<td>No. 10 - 11</td>
</tr>
<tr>
<td>Setting of specifications</td>
<td>Practical aspect</td>
<td>No. 12</td>
</tr>
<tr>
<td>Achieved results from using process capability studies</td>
<td>Practical aspect</td>
<td>No. 19 - 23</td>
</tr>
<tr>
<td>Advantages and disadvantages of conducting process capability studies</td>
<td>Practical aspect</td>
<td>No. 24 - 25</td>
</tr>
<tr>
<td>Demographical aspects of the respondents' organisations</td>
<td>Introduced due to analyse purpose</td>
<td>No. 1 - 4</td>
</tr>
<tr>
<td>Hints to other organisations where process capability studies are conducted</td>
<td>Introduced in order to reach as many as possible</td>
<td>No. 26</td>
</tr>
</tbody>
</table>
Enkätundersökning kring
duglighetsstudier i svensk industri


För att kunna dra så säkra slutsatser som möjligt är vi beroende av Ditt svar. Vi är därför tacksamma om Du tar Dig tid att så noga som möjligt besvara medföljande enkäten och returnera den i svarskuvertet som bifogats, senast 950619. Även om Ni inom Dinorganisation inte studerar och följer upp Era processers duglighet/kapabilitet så ber vi Dig ändå att svara på enkätens första och sista fråga, samt därefter returnera enkäten. I enkäten ber vi Dig ange namn och adress för att kunna följa upp eventuella oklarheter kring Din enkät. Fullständig anonymitet både vad gäller Dig som person och Ditt företag garanteras emellertid i samband med publicering av resultatet från undersökningen. Du kommer att erhålla en sammanställning av resultatet från undersökningen som tack för att Du svarade på enkäten.

Om Du anser att någon annan person inom Dinorganisation är mer lämpad att fylla i enkäten så ber vi dig att vidarebefordra enkäten.

För Din information vill vi tala om att uppgifterna om Din adress har vi fått av Sveriges Verkstadsindustrier (VI) eller Svenska Förbundet för Kvalitet (SFK).

Tack för Din medverkan!

Om det är något Du undrar över eller har synpunkter på angående enkäten, är Du välkommen att vända dig till vår kontaktperson i samband med enkätundersökningen:

Mats Deleryd
IES/Kvalitetsteknik & statistik
Högskolan i Luleå
971 87 Luleå
Telefon: 0920-98879
ENKÄT:
DUGLIGHETSSTUDIER I SVENSK INDUSTRI
Avdelningen för kvalitetsteknik & statistik
Högskolan i Luleå
971 87 Luleå
För att kunna returnera det sammanställda resultatet från enkätundersökningen, samt ta kontakt med Dig om eventuella frågor uppkommer ber vi Dig lämna följande uppgifter. Fullständig anonymitet både vad gäller Dig som person och Ditt företag garanteras i samband med publicering av resultatet från undersökningen.

Namn: __________________________________________
Formell befattning: __________________________________________
Företag: __________________________________________
Adress: __________________________________________
Postadress: __________________________________________
Telefon: __________________________________________
Telefax: __________________________________________

Del 1 Bakgrundsfakta
För att konkreta slutsatser skall kunna dras behöver vi en del bakgrundsfakta kring Din organisation.

1. Bedrivs någon form av duglighetsstudier/kapabilitetsstudier inom din organisation?
   □ Ja  (Fortsätt fyll i enkäten.)
   □ Nej  (Gå vidare till enkätens sista fråga, nr. 26.)

2. I enkäten ber vi Dig svara på frågor kring hur Din organisation bedriver duglighetsstudier/kapabilitetsstudier. Vilket av följande alternativ beskriver bäst vad Du avser med Din organisation när Du besvarar enkäten?
   □ En koncern
   □ Ett företag inom en storkoncern
   □ Ett enskilt företag
   □ En del av ett enskilt företag
3. Hur många anställda finns inom Din organisation, dvs den organisation som Du i fråga 2 har valt att besvärta enkäten enligt?

______________ personer

4. Vilket av följande alternativ beskriver bäst den verksamhet som Din organisation bedriver?

- Tung verkstadsindustri
- Finmekanisk industri
- Bilindustri
- Processindustri
- Tjänsteproducerande verksamhet
- Annan typ av verksamhet, nämligen:

Del 2 Introduktionen av duglighetsstudier i Din organisation
För att försöka se samband mellan hur duglighetsstudier har introducerats och de resultat som uppnåtts så ställs följande frågor.

5. När började Ni studera processers duglighet och beräkna duglighetsindex eller andra typer av mått på processduglighet inom Din organisation?

19

6. Finns det en i ord formulerad definition på vad duglighet är inom Din organisation?

- Ja  - Nej

(Om ja) 6a. Återge den definition på duglighet som finns inom Din organisation.

________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

(Om Nej) 6b. Om en gemensam definition på duglighet saknas. Hur skulle Du själv vilja definiera begreppet duglighet? Börja till exempel så här: Med duglighet menas inom vår organisation.................
7. Har någon utbildningsinsats genomförts inom Din organisation där frågor kring processers duglighet tagits upp?

☐ Ja  ☐ Nej

(Om ja) 7a. Beskriv utbildningen i stort, vad togs upp?

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________

(OmJa) 7b. Markera vilka av följande personalkategorier som har erhållit utbildning kring duglighet/kapabilitet inom Din organisation?

☐ Ledning

☐ "Mellanchefer"

☐ Konstruktörer

☐ Produktionsberedare

☐ Produktionspersonal

☐ Annan: ______________________

☐ Annan: ______________________
Del 3 Duglighetsmått i Din organisation?
För att mäta processers duglighet tillämpas ofta olika duglighetsindex men även andra typer av duglighetsmått kan finnas. I detta avsnitt ställs ett antal frågor för att få en uppfattning om vilka duglighetsmått som tillämpas och i vilken omfattning respektive mått används.

8. Används något duglighetsindex som mått på duglighet inom Din organisation?
   □ Ja  □ Nej

   (Om Ja) 8a. Vilka av följande duglighetsindex används inom Din organisation?

   Beteckningarna i formlerna nedan har följande betydelse:
   
   \[ T_0 = \text{Den övre toleransgränsen} \]
   \[ T_u = \text{Den undre toleransgränsen} \]
   \[ \mu = \text{Fördelningens väntevärde} \]
   \[ \sigma = \text{Fördelningens spridning} \]
   \[ M = \text{Målvärde} \]

   \[ Cp = \frac{T_0 - T_u}{6\sigma} \]

   □ Ja  □ Nej

   \[ Cpk = \frac{\text{Min}(T_0 - \mu, \mu - T_u)}{3\sigma} \]

   □ Ja  □ Nej

   \[ Cpm = \frac{T_0 - T_u}{6\sqrt{\sigma^2 + (\mu - M)}} \]

   □ Ja  □ Nej

   (Om Nej) 8b. Vad är anledningen till att inte några av ovanstående duglighetsindex tillämpas inom Din organisation?

   

9. Tillämpar Din organisation några andra duglighetsmått än de "traditionella" duglighetsindex som angivits i fråga 8a ovan?

   □ Ja  □ Nej

   (Om Ja) 9a. Hur har Ni definierat dessa? (Bifoga gärna mer information kring detta duglighetsmått tillsammans med enkäten i svarsuppsättning.)

   

- 4(10) -
10. Har någon eller några av Din organisations externa kunder ställt krav på Er att Ni skall bedriva duglighetsstudier eller att duglighetsindex skall användas som mått på duglighet?
   □ Ja  □ Nej

  (Om Ja) 10a. Ange hur många av Era kunder har ställt sådana krav?
  _______ av våra kunder har krävt att vi skall bedriva duglighetsstudier.

  (Om Ja) 10b. Ge ett exempel på hur dessa krav har formulerats?

  __________________________________________________________

11. Ställer Ni inom Din organisation i Er tur krav på några av Era leverantörer att de skall bedriva duglighetsstudier eller att duglighetsindex skall användas som mått på duglighet hos dem?
   □ Ja  □ Nej

  (Om Ja) 11a. Ange hur många av Era leverantörer som Ni ställer sådana krav på?
  _______

  (Om Ja) 11b. Ge ett exempel på hur Ni formulerat dessa krav?

  __________________________________________________________

---

Del 4 Toleranssättning inom Din organisation
I detta avsnitt ställs ett antal frågor för att få en uppfattning om utifrån vilka grunder som toleranser sätts inom svensk industri.

12a. Uppskatta hur stor andel av de toleranser som sätts inom Din organisation som sätts utifrån externa kunders krav eller önskemål. Ungefär _____ %.

12b. Hur stor andel av de toleranser som sätts inom Din organisation är enkelsidiga? Ungefär _____ %.

12c. Hur stor andel av de toleranser som sätts inom Din organisation kompletteras även med ett målvärde, dvs ett värde inom toleransområdet som operatören bör sträva efter att ligga så nära som möjligt? Ungefär _____ %.
### Del 5 Duglighetsstudier inom Din organisation

För att kunna se samband mellan olika organisationers genomförande av duglighetsstudier och de resultat som uppnåtts ställs följande frågor.

<table>
<thead>
<tr>
<th>13. Skiljer man inom Din organisation på maskinduglighetsstudier och processduglighetsstudier?</th>
</tr>
</thead>
<tbody>
<tr>
<td>□ Ja □ Nej (Om Nej, hoppa till fråga 13e.)</td>
</tr>
</tbody>
</table>

(Om Ja) 13a. Hur tas de enheter ut som ligger till grund för mätningar vid en maskinduglighetsstudie i Din organisation och hur många enheter tar Ni vanligtvis ut?

---

(Om Ja) 13b. Om duglighetsindex tillämpas i maskinduglighetsstudierna: Vilka krav har man inom Din organisation ställt på värdena på respektive duglighetsindex för att processen som studeras skall anses vara duglig?

---

(Om Ja) 13c. Hur tas de enheter ut som ligger till grund för mätningar vid en processduglighetsstudie i Din organisation och hur många enheter tar Ni vanligtvis ut?

---

(Om Ja) 13d. Om duglighetsindex tillämpas i processduglighetsstudierna: Vilka krav har man inom Din organisation ställt på värdena på respektive duglighetsindex för att processen som studeras skall anses vara duglig?

---
4. Vilket av följande alternativ beskriver bäst hur Ni inom Din organisation hanterar den osäkerhet som finns i de duglighetsindex som Ni beräknar.

- Vi tar ingen hänsyn till den osäkerhet som kan finnas i de beräknade duglighetsindexen.
- Vi beräknar konfidentsintervall för att säkerställa att värdena på de beräknade duglighetsindexen med en viss säkerhet överstiger ett givet värde.
- Annat:

13e. Hur tas de enheter ut som ligger till grund för mätningar vid en duglighetsstudie i Din organisation och hur många enheter tar Ni vanligtvis ut?

13f. Om duglighetsindex tillämpas i duglighetsstudierna: Vilka krav har man inom Din organisation ställt på värdena på respektive duglighetsindex för att processen som studeras skall anses vara duglig?

14. Kopplas duglighetsstudierna inom Din organisation till någon form av processstyrning där Ni tillämpar styrdiagram?

- Ja
- Nej

(Om Ja) 14a. Beskriv kortfattat kopplingen mellan duglighetsstudier och processstyrning i Din organisation.

15. Vilket av följande alternativ beskriver bäst hur Ni inom Din organisation hanterar den osäkerhet som finns i de duglighetsindex som Ni beräknar.

- Vi tar ingen hänsyn till den osäkerhet som kan finnas i de beräknade duglighetsindexen.
- Vi beräknar konfidentsintervall för att säkerställa att värdena på de beräknade duglighetsindexen med en viss säkerhet överstiger ett givet värde.
- Annat:
16. Studerar Ni dugligheten hos den mätutrustning som används i de "vanliga" duglighets-

   studierna?

   [ ] Ja  [ ] Nej

   (Om Ja) 16a. Beskriv kortfattat hur dugligheten hos mätutrustningen som tillämpas i de
   
   "vanliga" duglighetsstudierna säkerställs.

   ________________________________________________________________

   ________________________________________________________________

   ________________________________________________________________

17. Finns det formulerade krav inom Din organisation för hur mätutrustningens spridning bör

   förhålla sig till bredden på det toleransintervall som gäller för den parameter som mäts?

   [ ] Ja  [ ] Nej

   (Om Ja) 17a. Återge det krav som ställts på mätutrustningens spridning i förhållande till
   
   bredden på det toleransintervall som gäller för den parameter som mäts.

   ________________________________________________________________

18. Studerar Ni inom Din organisation om det insamlade datamaterialet kan anses vara

   normalfördelat i samband med att processers duglighet studeras?

   [ ] Ja  [ ] Nej

   (Om Ja) 18a. Markera med ett kryss den eller de metoder som används för att studera om det
   
   insamlade datamaterialet kan anses vara normalfördelat?

   [ ] Histogram

   [ ] Normalfördelningspapper

   [ ] Ett statistiskt test, nämligen: ____________________________

   [ ] Annat: _________________________________________________

   (Om Ja) 18b. Hur påverkas duglighetsstudierna om det visar sig att det insamlade data-

   materialet inte kan anses vara normalfördelat utan kommer från en mer eller

   mindre sned fördelning?

   ________________________________________________________________

   ________________________________________________________________

   ________________________________________________________________
Del 6 Resultatet från duglighetsstudierna

För att kartlägga hur långt olika organisationer kommit i arbetet med att uppnå och upprätthålla dugliga processer ställs följande frågor. Dessutom ställs frågor om hur resultatet från duglighetsstudierna tillämpas inom olika organisationer.

| 19. | Uppskatta hur stor andel av processerna inom Din organisation som var dugliga enligt de krav som Ni hade på en duglig process då Ni började studera processers duglighet. | Ungefär ____ % |
| 20. | Uppskatta hur stor andel av processerna inom Din organisation som är dugliga enligt de krav som Ni idag har på en duglig process. | Ungefär ____ % |
| 22. | Nämn kortfattat, gärna i punktform, vad Ni använder resultatet från duglighetsstudierna till inom Din organisation. | |
|     | Ledning |          | |
|     | "Mellanchefer" |          | |
|     | Konstruktörer |          | |
|     | Produktionsberedare |          | |
|     | Produktionspersonal |          | |
|     | Annan: |          | |
|     | Annan: |          | |
Del 7 Fördelar och nackdelar med duglighetsstudier
Det finns fördelar och nackdelar med alla metoder. Nedan ställs frågor kring vilka erfarenheter Ni inom Din organisation har av att tillämpa duglighetsstudier och duglighetsindex.

24. Beskriv kort de tre största fördelarna med att tillämpa duglighetsstudier som Ni upplevt inom Din organisation.
   1
   2
   3

25. Beskriv kort de tre största nackdelarna med att tillämpa duglighetsstudier som Ni upplevt inom Din organisation.
   1
   2
   3

26. För att resultatet av denna undersökning skall bli så tillförlitligt som möjligt är det av stor vikt att kunna nå en stor andel av de organisationer inom svensk industri som bedriver duglighetsstudier. Därför ber vi Dig att nedan ge tips på andra organisationer där Du vet (eller tror) att duglighetsstudier bedrivs, så att vi kan skicka en enkät även till dem. Var snäll och ange så fullständiga adresser som möjligt.

   Kontaktperson: ____________________________  Organisation: ____________________________
   Adress: ____________________________    Adress: ____________________________
   ____________________________    ____________________________
   ____________________________    ____________________________

   Kontaktperson: ____________________________  Organisation: ____________________________
   Adress: ____________________________    Adress: ____________________________
   ____________________________    ____________________________
   ____________________________    ____________________________

Returnera enkäten i det bifogade svarskuvert. Sammanställningen av enkäten kommer att skickas till Dig så snart alla svar sammanställts.

Tack för Din hjälp!
Duglighetsstudier i svensk industri 1995

I slutet av maj 1995 erhöll Du en enkät genom vilken vi försökte att kartlägga hur duglighetsstudier bedrivs i svensk industri. Adresserna hade vi fått från Sveriges Verkstadsindustrier (VI) samt Svenska Förbundet för Kvalitet (SFK). Enligt våra noteringar har vi inte erhållit något svar från Dig.


1. Hur många anställda finns inom Din organisation?
   _______________________________________________
   personer

2. Vilken är Din formella befattning?
   Jag arbetar som: _______________________________________

3. Vilket av följande alternativ beskriver bäst Din organisations verksamhet?
   □ Tung verkstadsindustri
   □ Processindustri
   □ Finmekanisk industri
   □ Tjänsteproducerande verksamhet
   □ Bilindustri
   □ Annan typ av verksamhet, nämligen:
   ___________________________________________________

4. Vilken av följande anledningar beskriver bäst orsaken till varför just Du inte besvarade enkäten?
   □ Vi bedriver duglighetsstudier men jag hann ej besvara enkäten.
   □ Vi bedriver inte duglighetsstudier.
   □ Jag vet ej vad duglighetsstudier innebär.
   □ Annan orsak, nämligen: ________________________________

Resultatet från enkätsstudien analyseras just nu. Totalt har drygt 200 organisationer medverkat. Vill Du ta del av resultatet så ange Din postadress på baksidan av detta brev så kommer slutresultatet att skickas till Dig.

Tack för Din medverkan!

Mats Deleryd

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S-971 87 Luleå
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Int. +46 920 721 60

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Mats.Deleryd@ies.luth.se
Enclosure 4: Questionnaire 2

Tack för Din medverkan!


Sammanfattningsvis kan man säga att undersöknings pekar på att det finns en skillnad mellan hur teorin beskriver hur duglighetsstudier bör bedrivas och hur de verkligen bedrivs. Undersökningen avslöjar emellertid inte *varför* dessa skillnader mellan teori och praktik tycks existera. Skillnaderna mellan teori och praktik behandlas närmare i rapportens kapitel, 5 *Slutsatser, jämförelse mellan teori och praktik*.

För att försöka få svar på orsakerna till detta skulle jag vilja be Er att besvara följande två korta frågor.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Bedrivs någon form av duglighetsstudier/kapabilitetsstudier inom Din organisation?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ja</td>
</tr>
<tr>
<td></td>
<td>Nej</td>
</tr>
</tbody>
</table>

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Ange Din syn på varför det ibland kan vara svårt för en organisation att implementera och bedriva duglighetsstudier enligt de teorier som presenteras i forskningsrapporten.</td>
<td></td>
</tr>
</tbody>
</table>

---

Var vänlig och returnera dina svar på fråga 1 och 2 genom att utnyttja det bifogade svarskuvertet!

Tack ännu en gång för Din medverkan!

[Signature]

Mats Deleryd
Enclosure 5: Analysis of questionnaire 2

Since question number 2 in questionnaire number 2, see enclosure 4, was open, all answers given by the respondents have been categorised into different obstacles when implementing process capability studies. All these obstacles have then been arranged in an Ishikawa diagram, see figure 5.1. In the tables below it is shown how many of the respondents who mentioned each obstacle. Category 1 consists of the 29 respondents who work in organisations where process capability studies are not conducted (No PCSs) and category 2 consists of the 31 respondents who work in organisations where process capability studies are conducted (PCSs). The row, category 1 + 2, contains the answers from all 60 respondents. All obstacles are presented under the separate headings Management issues, Facts of reality, Traditional personal attitudes and Methodological aspects.

<table>
<thead>
<tr>
<th>Management issues</th>
<th>Category 1 + 2</th>
<th>Category 1 (No PCSs)</th>
<th>Category 2 (PCSs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Management is too busy with other daily problems</td>
<td>4</td>
<td>2 (50%)</td>
<td>2 (50%)</td>
</tr>
<tr>
<td>Week management commitment for process capability studies</td>
<td>5</td>
<td>0 (0%)</td>
<td>5 (100%)</td>
</tr>
<tr>
<td>Shortage of resources</td>
<td>22</td>
<td>7 (30%)</td>
<td>15 (70%)</td>
</tr>
<tr>
<td>Shortage of knowledge because of deficient education</td>
<td>19</td>
<td>8 (43%)</td>
<td>11 (57%)</td>
</tr>
<tr>
<td>Hard to realise the advantages</td>
<td>7</td>
<td>3 (40%)</td>
<td>4 (60%)</td>
</tr>
<tr>
<td>Too much simplifications in the search for an easy to use method</td>
<td>1</td>
<td>0 (0%)</td>
<td>1 (100%)</td>
</tr>
<tr>
<td>The studies are often conducted by the quality department</td>
<td>2</td>
<td>0 (0%)</td>
<td>2 (100%)</td>
</tr>
<tr>
<td>Hard to get everybody involved</td>
<td>4</td>
<td>0 (0%)</td>
<td>4 (100%)</td>
</tr>
<tr>
<td>Interpreted as just another quality initiative</td>
<td>3</td>
<td>0 (0%)</td>
<td>3 (100%)</td>
</tr>
</tbody>
</table>
### Enclosure 5: Analysis of questionnaire 2

#### Facts of reality

<table>
<thead>
<tr>
<th>Obstacles mentioned</th>
<th>Category 1 + 2</th>
<th>Category 1 (No PCSs)</th>
<th>Category 2 (PCSs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard to determine what to measure</td>
<td>2</td>
<td>0 (0%)</td>
<td>2 (100%)</td>
</tr>
<tr>
<td>No measurement culture</td>
<td>5</td>
<td>0 (0%)</td>
<td>5 (100%)</td>
</tr>
<tr>
<td>High speed in production gives no time for measurements</td>
<td>2</td>
<td>0 (0%)</td>
<td>2 (100%)</td>
</tr>
<tr>
<td>Important parameters are sometimes hard to measure and control</td>
<td>2</td>
<td>0 (0%)</td>
<td>2 (100%)</td>
</tr>
<tr>
<td>Hard to understand cause-effect relationships in order to act properly</td>
<td>1</td>
<td>0 (0%)</td>
<td>1 (100%)</td>
</tr>
<tr>
<td>Sometimes the processes are not stable and repetitive enough</td>
<td>1</td>
<td>1 (100%)</td>
<td>0 (0%)</td>
</tr>
</tbody>
</table>

#### Traditional personal attitudes

<table>
<thead>
<tr>
<th>Obstacles mentioned</th>
<th>Category 1 + 2</th>
<th>Category 1 (No PCSs)</th>
<th>Category 2 (PCSs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard to accept that meeting tolerances should not be enough</td>
<td>2</td>
<td>0 (0%)</td>
<td>2 (100%)</td>
</tr>
<tr>
<td>Hard to accept a method which questions the operators own contribution to the process output</td>
<td>3</td>
<td>0 (0%)</td>
<td>3 (100%)</td>
</tr>
</tbody>
</table>

#### Methodological aspects

<table>
<thead>
<tr>
<th>Obstacles mentioned</th>
<th>Category 1 + 2</th>
<th>Category 1 (No PCSs)</th>
<th>Category 2 (PCSs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Difficult theory</td>
<td>10</td>
<td>2 (20%)</td>
<td>8 (80%)</td>
</tr>
<tr>
<td>Not suitable for short runs</td>
<td>5</td>
<td>4 (80%)</td>
<td>1 (20%)</td>
</tr>
<tr>
<td>No quick results</td>
<td>2</td>
<td>0 (0%)</td>
<td>2 (100%)</td>
</tr>
<tr>
<td>Lack of theory for skew distributions</td>
<td>3</td>
<td>0 (0%)</td>
<td>3 (100%)</td>
</tr>
</tbody>
</table>
Enclosure 6: Initial simulation parameters

The three tables below describe all initial values used in the simulation study. The columns with \(\sigma(N)\) and \(\mu(N)\) give the parameters \(\sigma\) and \(\mu\) of the normal distributions used when generating the random values. Then the random values are transformed using the logarithm transformation function and the scale parameter \(\alpha\), see the simulation routine in enclosure 7. Finally, the columns with \(\sqrt{V(X)}\) and \(E(X)\) give the standard deviation and the expected value of the lognormal distributions described in figure 7.1. In the tables below \(X\) denote the process output and \(p\) the proportion of nonconforming items. On the next page all information needed for deriving the parameters in these tables are given.

**Case 1, \(E(X) = 0, \ p = 0.0455\)**

<table>
<thead>
<tr>
<th>Skewness</th>
<th>(\sigma(N))</th>
<th>(\mu(N))</th>
<th>(\alpha)</th>
<th>(\sqrt{V(X)})</th>
<th>(E(X))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.164055</td>
<td>2.20414</td>
<td>-9.18519</td>
<td>1.51707</td>
<td>0</td>
</tr>
<tr>
<td>1.0</td>
<td>0.314264</td>
<td>1.51643</td>
<td>-4.78656</td>
<td>1.54216</td>
<td>0</td>
</tr>
<tr>
<td>1.5</td>
<td>0.443493</td>
<td>1.08595</td>
<td>-3.26837</td>
<td>1.52378</td>
<td>0</td>
</tr>
<tr>
<td>2.0</td>
<td>0.551384</td>
<td>0.78001</td>
<td>-2.53964</td>
<td>1.51381</td>
<td>0</td>
</tr>
</tbody>
</table>

**Case 2, \(E(X) = 0, \ p = 0.0027\)**

<table>
<thead>
<tr>
<th>Skewness</th>
<th>(\sigma(N))</th>
<th>(\mu(N))</th>
<th>(\alpha)</th>
<th>(\sqrt{V(X)})</th>
<th>(E(X))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.164055</td>
<td>1.66974</td>
<td>-5.38277</td>
<td>0.889037</td>
<td>0</td>
</tr>
<tr>
<td>1.0</td>
<td>0.314264</td>
<td>0.800992</td>
<td>-2.34052</td>
<td>0.754081</td>
<td>0</td>
</tr>
<tr>
<td>1.5</td>
<td>0.443493</td>
<td>0.252258</td>
<td>-1.41992</td>
<td>0.661996</td>
<td>0</td>
</tr>
<tr>
<td>2.0</td>
<td>0.551384</td>
<td>-0.146308</td>
<td>-1.00572</td>
<td>0.599482</td>
<td>0</td>
</tr>
</tbody>
</table>

**Case 3, \(E(X) = 0, \ p = 1.97E-9\)**

<table>
<thead>
<tr>
<th>Skewness</th>
<th>(\sigma(N))</th>
<th>(\mu(N))</th>
<th>(\alpha)</th>
<th>(\sqrt{V(X)})</th>
<th>(E(X))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.164055</td>
<td>0.935456</td>
<td>-2.5829</td>
<td>0.426605</td>
<td>0</td>
</tr>
<tr>
<td>1.0</td>
<td>0.314264</td>
<td>-0.276279</td>
<td>-0.797002</td>
<td>0.256782</td>
<td>0</td>
</tr>
<tr>
<td>1.5</td>
<td>0.443493</td>
<td>-0.978642</td>
<td>-0.414659</td>
<td>0.193323</td>
<td>0</td>
</tr>
<tr>
<td>2.0</td>
<td>0.551384</td>
<td>-1.63912</td>
<td>-0.226026</td>
<td>0.134728</td>
<td>0</td>
</tr>
</tbody>
</table>

* Note that in case 1 when the skewness is 0.5 and 1.0 and in case 2 when the skewness is 0.5 we get \(\alpha < -3\). In these cases we have positive probability to obtain values both below and above the specification interval \([-3, -3]\). In all other cases the probability is 0 of obtaining values below \(-3\).

* For a description of how to derive the parameters in the tables see next page.
Enclosure 6: Initial simulation parameters

* Here a principal description is given of how the values in the tables above were derived:

Assume the following premises:

[1] \( X \) is lognormally distributed with the parameters \((\mu, \sigma)\) starting at \( \alpha \).

[2] \( E(X) = 0 \) for all cases.

[3] A fix proportion of nonconforming items = \( p \) has been used in each case. In case I \( p = 0.0455 \), in case II \( p = 0.0027 \) and in case III \( p = 1.97E-9 \).

[4] Four different levels of skewness have been used in all three cases. The skewness is here denoted as \( \sqrt{\beta_1} \). The skewness has been 0.5, 1.0, 1.5 and 2.0.

Then the following formulas are used:

1 By using the values of skewness, corresponding values of \( \sigma \) are calculated according to:
   
   \[
   \sqrt{\beta_1} = (\omega - 1)^{1/2}(\omega + 2), \quad \text{where} \quad \omega = \exp(\sigma^2)
   \]

2 By using the different values of \( \sigma \), calculated by using [A] and premise [3], values of \( \alpha \) are calculated so that [B] is fulfilled:
   
   \[
   \phi\left(\frac{\ln(-3 - \alpha) - \ln(-\alpha) + \frac{\sigma^2}{2}}{\sigma}\right) + \phi\left(-\frac{\ln(3 - \alpha) - \ln(-\alpha) + \frac{\sigma^2}{2}}{\sigma}\right) = p
   \]

3 By using premise [2], the values of \( \alpha \) from [B] and the values of \( \sigma \) from [A], then values of \( \mu \) are calculated according to [C]:
   
   \[
   E(\xi) = \alpha + \exp(\mu + \frac{\sigma^2}{2}) = 0
   \]

   \[
   \alpha = -\exp(\mu + \frac{\sigma^2}{2})
   \]

   \[
   \mu = \ln(-\alpha) - \frac{\sigma^2}{2}
   \]

4 Use \( \sigma \) from [A] and \( \mu \) from [C] to derive \( \sqrt{V(X)} \) according to:
   
   \[
   V(X) = \exp(2\mu + \sigma^2)(e^{\sigma^2} - 1)
   \]
Enclosure 7: Simulation routine

An example of the simulation routine for the distribution where the percentage of nonconforming items is 0.045 and the skewness is 2.0. First the package "Statistics'ContinuousDistributions" is loaded. Then the vectors a-h are emptied, just as a precaution. Then the desired normal distribution used for generating random values is defined. Then the actual simulation routine generating 10000 estimates for the desired indices is started. First 50 values are generated randomly, the mean and the standard deviation of these 50 values are estimated. By using these estimates, the desired indices are then calculated and named j-h. The estimated values of the desired indices are then added to the vectors a-h. This procedure is repeated 10000 times and then the vectors a-h are saved with appropriate names.

```
<<Statistics'ContinuousDistributions'

a={}
b={}
c={}
d={}
e={}
f={}
g={}
h={}

ndist = NormalDistribution[0.78001, 0.551384]

Do[i = Table[-2.53964 + Exp[Random[ndist]], {50}];
    My = Mean[i];
    Sigma = StandardDeviation[i]Sqrt[49/50];
    ab[u_, v_] := N[((((3 - (-3))/2) - (u)Abs[My - 0])/(3Sqrt[Sigma^2 +
    v(My - 0)^2]))];
    j = ab[1, 0];
    k = ab[0, 1];
    l = ab[1, 1];
    m = ab[0, 3];
    n = ab[0, 4];
    o = ab[1, 2];
    p = ab[4, 0];
    q = ab[4, 4];
    AppendTo[a, j];
    AppendTo[b, k];
    AppendTo[c, l];
    AppendTo[d, m];
    AppendTo[e, n];
    AppendTo[f, o];
    AppendTo[g, p];
    AppendTo[h, q];
    , {10000}];

Save["Cp(1.0)*Ln(0.78001)" , a]
Save["Cp(0.1)*Ln(0.78001)" , b]
Save["Cp(1.1)*Ln(0.78001)" , c]
Save["Cp(0.3)*Ln(0.78001)" , d]
Save["Cp(0.4)*Ln(0.78001)" , e]
Save["Cp(1.2)*Ln(0.78001)" , f]
Save["Cp(4.0)*Ln(0.78001)" , g]
Save["Cp(4.4)*Ln(0.78001)" , h]
```
Enclosure 8: Bias and standard deviation in all simulation cases

In this enclosure all values used in the analysis of the simulation study are given. \( C_p(u,v) \) denotes the true value. \( E(X)^* \) denotes the estimated expected value received in the simulation study. The bias is the difference between \( E(X)^* \) and \( C_p(u,v) \). The relative bias is the bias in percentages compared to the true value. The standard deviation is an estimate, \( s \), of the dispersion of the distribution of each index.

**Case 1, Proportion of nonconforming items = 0.045**

<table>
<thead>
<tr>
<th>Skewness 0.5</th>
<th>( C_p(u,v) )</th>
<th>( E(X)^* )</th>
<th>Bias</th>
<th>Rel. bias (%)</th>
<th>Std. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_p[1.0] )</td>
<td>0.659165</td>
<td>0.671632</td>
<td>0.012467</td>
<td>1.89132222</td>
<td>0.0735947</td>
</tr>
<tr>
<td>( C_p[0.1] )</td>
<td>0.659165</td>
<td>0.659295</td>
<td>0.00013</td>
<td>0.01972192</td>
<td>0.0734309</td>
</tr>
<tr>
<td>( C_p[1.1] )</td>
<td>0.659165</td>
<td>0.653759</td>
<td>-0.005406</td>
<td>-0.8201285</td>
<td>0.0743302</td>
</tr>
<tr>
<td>( C_p[0.3] )</td>
<td>0.659165</td>
<td>0.640327</td>
<td>-0.018838</td>
<td>-2.857858</td>
<td>0.0765993</td>
</tr>
<tr>
<td>( C_p[0.4] )</td>
<td>0.659165</td>
<td>0.634111</td>
<td>-0.025054</td>
<td>-3.8201285</td>
<td>0.0780028</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Skewness 1.0</th>
<th>( C_p(u,v) )</th>
<th>( E(X)^* )</th>
<th>Bias</th>
<th>Rel. bias (%)</th>
<th>Std. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_p[1.0] )</td>
<td>0.648441</td>
<td>0.666343</td>
<td>0.017902</td>
<td>2.76077546</td>
<td>0.0863978</td>
</tr>
<tr>
<td>( C_p[0.1] )</td>
<td>0.648441</td>
<td>0.65371</td>
<td>0.005269</td>
<td>0.81256429</td>
<td>0.0842495</td>
</tr>
<tr>
<td>( C_p[1.1] )</td>
<td>0.648441</td>
<td>0.648059</td>
<td>-0.000382</td>
<td>-0.0589105</td>
<td>0.0842589</td>
</tr>
<tr>
<td>( C_p[0.3] )</td>
<td>0.648441</td>
<td>0.6349</td>
<td>-0.013541</td>
<td>-2.0882393</td>
<td>0.0879621</td>
</tr>
<tr>
<td>( C_p[0.4] )</td>
<td>0.648441</td>
<td>0.628518</td>
<td>-0.019923</td>
<td>-3.0724461</td>
<td>0.0881399</td>
</tr>
<tr>
<td>( C_p[1.2] )</td>
<td>0.648441</td>
<td>0.622672</td>
<td>-0.025769</td>
<td>-3.973993</td>
<td>0.0889834</td>
</tr>
<tr>
<td>( C_p[4.0] )</td>
<td>0.648441</td>
<td>0.518981</td>
<td>-0.12946</td>
<td>-19.964808</td>
<td>0.133803</td>
</tr>
<tr>
<td>( C_p[4.4] )</td>
<td>0.648441</td>
<td>0.504623</td>
<td>-0.143818</td>
<td>-22.179042</td>
<td>0.141581</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Skewness 1.5</th>
<th>( C_p(u,v) )</th>
<th>( E(X)^* )</th>
<th>Bias</th>
<th>Rel. bias (%)</th>
<th>Std. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_p[1.0] )</td>
<td>0.656263</td>
<td>0.682766</td>
<td>0.026413</td>
<td>4.02475837</td>
<td>0.106816</td>
</tr>
<tr>
<td>( C_p[0.1] )</td>
<td>0.656263</td>
<td>0.669206</td>
<td>0.012943</td>
<td>1.9722276</td>
<td>0.102366</td>
</tr>
<tr>
<td>( C_p[1.1] )</td>
<td>0.656263</td>
<td>0.663211</td>
<td>0.006948</td>
<td>1.05872188</td>
<td>0.101437</td>
</tr>
<tr>
<td>( C_p[0.3] )</td>
<td>0.656263</td>
<td>0.651328</td>
<td>-0.004935</td>
<td>-0.7519851</td>
<td>0.107638</td>
</tr>
<tr>
<td>( C_p[0.4] )</td>
<td>0.656263</td>
<td>0.644447</td>
<td>-0.011816</td>
<td>-1.8004977</td>
<td>0.106215</td>
</tr>
<tr>
<td>( C_p[1.2] )</td>
<td>0.656263</td>
<td>0.63818</td>
<td>-0.018038</td>
<td>-2.7554502</td>
<td>0.105789</td>
</tr>
<tr>
<td>( C_p[4.0] )</td>
<td>0.656263</td>
<td>0.5341</td>
<td>-0.122163</td>
<td>-18.614946</td>
<td>0.143063</td>
</tr>
<tr>
<td>( C_p[4.4] )</td>
<td>0.656263</td>
<td>0.518439</td>
<td>-0.137824</td>
<td>-21.001336</td>
<td>0.149919</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Skewness 2.0</th>
<th>( C_p(u,v) )</th>
<th>( E(X)^* )</th>
<th>Bias</th>
<th>Rel. bias (%)</th>
<th>Std. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_p[1.0] )</td>
<td>0.660585</td>
<td>0.699038</td>
<td>0.038453</td>
<td>5.82105255</td>
<td>0.126418</td>
</tr>
<tr>
<td>( C_p[0.1] )</td>
<td>0.660585</td>
<td>0.684345</td>
<td>0.02376</td>
<td>3.59681192</td>
<td>0.119015</td>
</tr>
<tr>
<td>( C_p[1.1] )</td>
<td>0.660585</td>
<td>0.677876</td>
<td>0.017291</td>
<td>2.6175284</td>
<td>0.116991</td>
</tr>
<tr>
<td>( C_p[0.3] )</td>
<td>0.660585</td>
<td>0.667822</td>
<td>0.007237</td>
<td>1.0955441</td>
<td>0.126082</td>
</tr>
<tr>
<td>( C_p[0.4] )</td>
<td>0.660585</td>
<td>0.660168</td>
<td>-0.000417</td>
<td>-0.0631259</td>
<td>0.12269</td>
</tr>
<tr>
<td>( C_p[1.2] )</td>
<td>0.660585</td>
<td>0.653288</td>
<td>-0.007297</td>
<td>-1.104627</td>
<td>0.120813</td>
</tr>
<tr>
<td>( C_p[4.0] )</td>
<td>0.660585</td>
<td>0.548428</td>
<td>-0.112157</td>
<td>-16.978436</td>
<td>0.150008</td>
</tr>
<tr>
<td>( C_p[4.4] )</td>
<td>0.660585</td>
<td>0.531077</td>
<td>-0.129508</td>
<td>-19.605047</td>
<td>0.155706</td>
</tr>
</tbody>
</table>
Case 2, Proportion of nonconforming items = 0.0027

<table>
<thead>
<tr>
<th>Skewness 0.5</th>
<th>( C_p(u,v) )</th>
<th>( E(X)^* )</th>
<th>Bias</th>
<th>Rel. bias (%)</th>
<th>Std. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_p[1.0] )</td>
<td>1.12481</td>
<td>1.14472</td>
<td>0.01991</td>
<td>1.77007672</td>
<td>0.124659</td>
</tr>
<tr>
<td>( C_p[0.1] )</td>
<td>1.12481</td>
<td>1.12371</td>
<td>-0.0011</td>
<td>-0.0977943</td>
<td>0.12436</td>
</tr>
<tr>
<td>( C_p[1.1] )</td>
<td>1.12481</td>
<td>1.11428</td>
<td>-0.01053</td>
<td>-0.9361581</td>
<td>0.125887</td>
</tr>
<tr>
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<th>( E(X)^* )</th>
<th>Bias</th>
<th>Rel. bias (%)</th>
<th>Std. dev.</th>
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<th>Std. dev.</th>
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<td>0.06265</td>
<td>4.14741358</td>
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<td>( C_p[0.1] )</td>
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<th>Rel. bias (%)</th>
<th>Std. dev.</th>
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### Enclosure 8: Bias and standard deviation in all simulation cases

#### Case 3, Proportion of nonconforming items = 1.97E-9

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<th>Std. dev.</th>
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<th>Std. dev.</th>
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<th>Bias</th>
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<th>Std. dev.</th>
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</table>
Enclosure 9: The effect of skewness on some process capability indices

This enclosure describes the effect of skewness on the statistical properties, relative bias and standard deviation, of some process capability indices. A suitable process capability index has as small relative bias and standard deviation as possible.

**Figure 1**

![Graph showing Cp(1,0)]

**Figure 2**

![Graph showing Cp(0,1)]
Enclosure 9: The effect of skewness on some process capability indices

Figure 3

C_p(1,1)

Standard deviation

Relative bias (%)

-25 -20 -15 -10 -5 0 5 10

Relative bias (%)

Case I, p=0.045, skewness=0.5

Case I, p=0.045, skewness=1.0

Case I, p=0.045, skewness=1.5

Case I, p=0.045, skewness=2.0

Case II, p=0.0027, skewness=0.5

Case II, p=0.0027, skewness=1.0

Case II, p=0.0027, skewness=1.5

Case II, p=0.0027, skewness=2.0

Case III, p=1.97E-9, skewness=0.5

Case III, p=1.97E-9, skewness=1.0

Case III, p=1.97E-9, skewness=1.5

Case III, p=1.97E-9, skewness=2.0

Figure 4

C_p(0,3)

Standard deviation

Relative bias (%)

-25 -20 -15 -10 -5 0 5 10

Relative bias (%)

-2(4)
Enclosure 9: The effect of skewness on some process capability indices

Figure 5

Cp(0.4)

0 2 4 6 8 10 12 14 16
Relative bias (%)

Case I, p=0.045, skewness=0.5
Case I, p=0.045, skewness=1.0
Case I, p=0.045, skewness=1.5
Case I, p=0.045, skewness=2.0
Case II, p=0.0027, skewness=0.5
Case II, p=0.0027, skewness=1.0
Case II, p=0.0027, skewness=1.5
Case II, p=0.0027, skewness=2.0
Case III, p=1.97E-9, skewness=0.5
Case III, p=1.97E-9, skewness=1.0
Case III, p=1.97E-9, skewness=1.5
Case III, p=1.97E-9, skewness=2.0

Figure 6

Cp(1.2)

0 2 4 6 8 10 12 14 16
Relative bias (%)

-3(-4)-
Enclosure 9: The effect of skewness on some process capability indices

Figure 7

- 4(4) -
This thesis, which focuses on both theoretical and practical aspects of process capability studies, is divided into two parts.

Part 1, which is based on a study among Swedish organisations, reveals that many of the theoretical aspects of how to conduct process capability studies, in order to achieve reliable results, are often not known or not regarded in practice. The thesis also provides some preliminary answers to the question why this gap between theory and practice exists.

In part 2, a simulation study, focusing on the effects of skewness on estimates of some process capability indices belonging to the family of indices named $C_p(u,v)$, is presented. The results from the simulation study indicate that the effect of skewness on these estimates of process capability indices is relatively systematic, and therefore there are some hope that future investigations might use these results when formulating some practical solution to the problem of how to use process capability indices when the process monitored has a skewly distributed output.

Finally, the results are summarised and discussed and some suggestions for future research are given.

Nyckelord, högst 8 / Keywords, max 8
Process capability studies; process capability analysis; process capability indices; variation; implementation; obstacles; non-normality; skewness