

Structure and applicability of quality tools : decision support for the application of process control and improvement techniques

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Structure and applicability of quality tools

Decision support for the application of process control and improvement techniques

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Structure and applicability of quality tools

Decision support for the application of process control and improvement techniques

PROEFSCHRIFT

ter verkrijging van de graad van doctor aan de Technische Universiteit Eindhoven, op gezag van de Rector Magnificus, prof.dr. M. Rem, voor een commissie aangewezen door het College voor Promoties in het openbaar te verdedigen op woensdag 21 juni 2000 om 16.00 uur

door

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Preface

This thesis is based on research into the applicability of quality tools in industry. It is the result of my assignment as a research assistant in the Department of Technology Management of the Eindhoven University of Technology. I would like to use this opportunity to thank those who have in one way or another contributed to this book.

First of all I would like to thank prof.ir. P.W. Sanders, who allowed me to write a research proposal and subsequently start this research in the Fabrication Technology section. Next I would like to thank prof.dr.ir. A.C. Brombacher who took over the role of first supervisor after the Fabrication Technology section was changed to the Quality of Products and Processes section. In the last three years, during which I had a part-time appointment as a university teacher, he was not only my supervisor as a Ph.D. candidate but also my section leader. I would also like to thank my copromotor dr.ir. A.J. de Ron for his coaching activities, and especially for stimulating me to write papers during the first years of this research. I would like to thank prof.dr. R.J.M.M. Does of the University of Amsterdam for his contributions as my second supervisor. The visits to Amsterdam were not only very useful but also very 'gezellig' (which, unfortunately, can only be rather poorly be translated as 'enjoyable').

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not allow me to express my special thanks to you. I hope you think it was all worthwhile. Of course, the very last words of thanks are for my fiancée, Jacqueline. For her support and companionship, her help in designing and producing furniture in our company, and especially for not resenting the fact that I postponed our wedding because I was too busy with this thesis. It's ready now!

Eindhoven, April 2000,
Werner Schippers.

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1 Introduction and problem statement

1.1 Relevance of looking at quality tools

After the acceptance of the three traditional performance aspects costs, timeliness and quality, nowadays flexibility, innovation [Bolwijn and Kumpe, 1990] and environmental quality are hot topics in management of industrial companies. Despite the emergence of these 'new' performance aspects, excellent quality is still a 'conditio sine qua non' in business practice. Both external drivers (such as improving product quality, reducing prices and shortening delivery times) and derived internal drivers (such as reducing scrap, rework and downtime) require a continuing effort to control and improve production processes.

Research in the field of quality is still developing. The two major directions of development are:

- Development and refinement of quality tools: A large variety of mainly quantitative tools (such as Control Charts and Design of Experiments), but also qualitative tools (such as Quality Function Deployment and Failure Mode and Effect Analysis) have been developed and refined to fit specific circumstances or to improve their performance. Journals in which these developments can be followed are e.g. Journal of Quality Technology, Quality Engineering and Technometrics. Through the continuing development of quality tools, there is a huge amount of literature in this area.
- Development of quality management concepts and tools: Whereas the application of quality tools started in production areas, it is now expanding into a company wide issue. This has led to the development of management systems and organizational quality tools, such as ISO 9000, benchmarking and employee suggestion systems as part of 'Total Quality Management' (TQM). Journals in which these developments are reported are e.g. the International Journal of Quality and Reliability Management, Total Quality Management, and Quality Progress.

In business practice, companies such as Motorola, General Motors, Toyota and General Electric have a leading position in applying quality systems and tools. Large improvements in business performance have been reported [Klaus, 1997; Harry, 1998; Stratton, 1998]. Also outside these companies positive experiences are frequently reported for most of the quality tools found in literature.

From this, one could conclude that the area of quality tools should be sufficiently known by now and that it is indeed time to shift attention to performance aspects such as flexibility and innovation. Therefore the question may arise why the research reported in this thesis deals with quality, and in particular with quality tools. The two main reasons why this research subject is still relevant are discussed below.

The first reason for paying attention to quality tools is the fact that, in business practice, problems are still encountered in applying quality tools (as will be demonstrated in this thesis). Besides companies that are successful in applying quality tools, there also seems to be a group of companies that is not successful in applying quality tools adequately. Lack of confidence in potential benefits prevents some companies from trying to implement quality tools. Other companies encounter problems determining how to choose from the large amount of existing tools in various programs such as Statistical Process Control (SPC), Total Productive Maintenance (TPM), Taguchi or Six Sigma. Furthermore, problems are encountered in determining how to react to new developments in quality tools and programs. Some people conclude that this group of companies is lagging behind, i.e. they are not able to follow developments and apply tools that were applied successfully in other companies. In literature, one often starts from such a 'best practice' viewpoint. This research, however, questions whether companies are indeed lagging behind, and aims to determine the causes of the problems observed in applying tools. The insights resulting from this research should be used to support companies in applying tools successfully.

The second reason why this research on quality tools is considered to be relevant concerns the level at which tools are studied. As mentioned above, a wide variety of tools has been developed in various programs. To control or improve a specific production process, only part of these tools will be used. Thus in practice companies have to decide which set of tools to select from all available tools. Research on quality tools, however, is often directed at the methodology of individual tools or at management aspects of a quality program. This type of research provides little support for a company that has to determine which tools to select and how to use them. Research should therefore not start from a tool or a program, but from the needs for controlling or improving production processes. Thus, in explaining causes of problems in the application of quality tools, and in finding solutions for these problems, this research studies multiple tools, of various programs, as coherent activities directed at controlling and improving a production process. In literature this 'intermediate' level, addressed as the operational level, gets little attention compared to the two levels of research indicated above.

1.2 Research question and research objective

As described in the previous section, the main observation leading to this research was the fact that, despite the vast amount of literature on quality tools, there are still problems in making effective use of these tools in practice. The initial research questions resulting from the observed problems were:

1. What are the main causes of problems in applying existing quality tools successfully?
2. How can the problems in applying quality tools be solved?

The research objective is to put the answers to these questions in a form that supports practitioners in making effective use of existing quality tools. Since the nature of the problems in applying quality tools was not clear, the actual form and content of this support could not be specified beforehand.

After the first, exploratory phase of this research, the above-mentioned initial research questions are answered. To achieve the research objective, the answers will be translated into more detailed questions and objectives for the second part of this research. This part will be directed at generating decision support, i.e. providing knowledge that supports practitioners in making effective use of existing quality tools. In doing this, the focus should be on those aspects that do not yet receive much attention in literature. As a result, this research does not deal with the development and refinement of tools, although a hypothesis may be that some problems arise because existing tools are not perfect. This research is also not concerned with the development and refinement of new quality management systems or organizational concepts, although part of the problems encountered may stem from poor management of the application of quality tools. If encountered, problems of this nature should be observed and indicated, but not solved.

1.3 Initial research method and overview of this thesis

The research was started with a review of literature and exploratory case studies, which are reported in Chapter 2. The first objective of the literature review was to get an overview of the area of quality tools. In Section 2.1 the results are presented in the form of an historical overview. The second objective was to review the success factors for applying quality tools as reported in literature. The results are presented in Section 2.2. The objective of the exploratory case studies was to gather additional empirical material to answer the initial research questions. The case studies should therefore focus on those aspects that appear to be relevant, but get little attention in the reviewed literature. The results of the cases are reported in Section 2.3.

Chapter 3 starts with a discussion of the first part of the research to answer the initial research questions. The insights resulting from this exploratory research are translated into more detailed research activities and objectives directed at generating decision support to solve the observed problems. Chapter 3 also contains a conceptual framework, and a discussion of the scope and method for the remaining part of the research.

Chapters 4 and 5 describe the research activities and results directed at generating knowledge for decision support for the two areas considered: process control (Chapter 4) and process improvement (Chapter 5). Chapter 6 summarizes and discusses the results presented in Chapters 4 and 5 in the light of the initial research objective and ends with directions for further research.

2 Review of literature and exploratory case studies

This chapter describes the first part of this research, concerned with finding answers to the initial research questions of Section 1.2. Parts of this chapter were published previously in a paper on the applicability of Statistical Process Control techniques [Schippers, 1998a].

2.1 Literature on quality tools: an historical overview

This section describes the results of a literature review on quality tools. The goal of the review was to get an overview of and insight into the area of quality tools. Based on the overview the scope of this research can be indicated in terms of the considered tools. Furthermore, within this thesis, this section serves as a brief introduction to the field of quality tools; it also illustrates the wide variety of tools available. Note that the goal of this section is not to give an in-depth discussion of the (single) tools.

The starting point of this research were problems encountered in applying Statistical Process Control techniques (SPC-techniques). A first review of literature showed that in literature and business practice, not everyone uses the same definition of SPC. Traditionally the term SPC was used to address the use of Control Charts [e.g. Wadsworth et al., 1986; Grant and Leavenworth, 1988]. Other authors, e.g. Montgomery [Montgomery, 1996], use the term SPC to address a set of tools known as the Seven Tools (Histogram, Check Sheet, Pareto Chart, Cause and Effect Diagram, Defect Concentration Diagram, Scatter Diagram and Control Charts), that includes Control Charts, but also non-statistical tools. Montgomery uses the term Statistical Quality Control (SQC) to address various other statistical tools directed at quality, including SPC, Acceptance Sampling, and Design of Experiments. Some authors [e.g. Wetherill and Brown, 1991] also include these techniques in the definition of SPC. Others, such as [Vasilash, 1993] use an even broader definition of SPC, that equals Total Quality Management (TQM), thus referring to a concept that includes a wide range of tools.

Within the broader definitions of SPC there is a wide variety of tools, but the total field of activities referred to as quality tools is even wider. Since the beginning of the 20th century, quality tools with various goals and application areas were developed. Thus, activities denoted as quality tools include a wide range of tools such as Control Charts, Acceptance Sampling plans, Analysis of Variance, Cause and Effect diagrams, Design of Experiments, Failure Mode and Effect Analysis, Taguchi Methods, and Quality Function Deployment.

The historical overview enables us to give a logical, step-by-step, description of how groups of tools with new goals and application areas were added in the course of time. Although presented as an historical overview, this review will not always describe developments in their exact chronological order. One of the reasons is that some tools

were 'developed' long before they were actually used. Furthermore, there are also chronological differences between developments in the Western world and Japan. At the end of this section a list of important trends in the application of quality tools will be given to summarize the historical developments. (See also [Banks, 1989] and [Montgomery, 1996] for a description of the history and evolution of quality tools).

The first systematic quality related activities, in the beginning of the 20th century, were mainly inspection oriented: through inspection of finished production lots and comparing product measurements with product specifications, companies tried to assure product quality. Often products were only checked after a series of processes. The goal was to separate good batches from bad ones before delivery to customers. In Figure 2.1 this is depicted schematically. Near the end of the 1920's statistical acceptance sampling plans were developed as an alternative for 100% inspection. These sampling plans were later refined [see e.g. Dodge and Romig, 1959] and standardized in e.g. MIL-STD-105d [MIL-STD-105d, 1964], and MIL-STD-414 [MIL-STD-414, 1968]. Using these sampling plans, the percentage of defective products could be estimated without checking every product. The percentage was compared with Accepted Quality Levels (AQL's) agreed with customers.

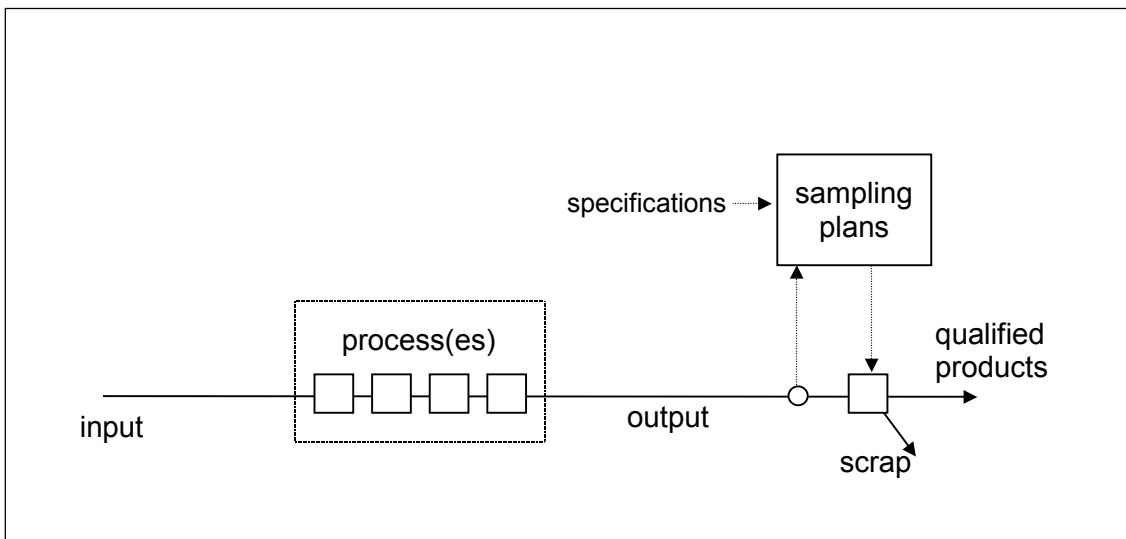


Figure 2.1: Quality by inspection

However, using sampling plans to achieve quality was still very costly because of inspection costs, costs for 100% selection of rejected batches, and costs for rework and scrap. Especially when quality demands rose, it was not possible to achieve the lower AQLs without taking very large and costly samples. Filtering out all defective products was not possible at all. The conclusion was that it was better (more efficient and more effective) to prevent failures than trying to filter them out using sampling (prevention instead of detection).

The development of the Control Chart (the first Statistical Process Control tool) by W.A. Shewhart in 1924, was an important change towards prevention. The concept and techniques were published by Shewhart in various papers [Shewhart, 1926a, 1926b

and 1927] and his classic book on quality control [Shewhart, 1931]. Although Shewhart invented his Control Charts in the 1920's, it was not until the 1950's that Control Charts became more popular and widely applied in practice. The first improvement introduced with the Control Charting methodology was not to wait until a batch of products has finished, but to take samples during production and for each process used. Thus, when a deviation occurs during production, the process must be adjusted, with a direct effect on the remaining part of the production lot.

The second, and even more important, improvement introduced with the Control Chart was the introduction of process thinking and variation thinking as an alternative to product thinking and tolerance thinking. One realized that, to prevent failures, one should not inspect a product and compare measurements to tolerances, but one should use these measurements to examine the variation of the process that generates these products. The starting point of examining process variation was that some level of variation was inherent to the process as long as it was stable and predictable in time.

Instead of comparing product measures to tolerances, the original \bar{X} -R Control Chart can be used to plot the mean and range of samples taken from a running process against time, and to compare them with 'control limits'. These control limits are calculated from the data of a stable process. Thus, one can determine whether the process is running stable, i.e. whether it follows a fixed probability distribution, or whether there are special causes of variation leading to an 'out of control' situation. If an out of control situation is detected, special causes occur, which have to be found and corrected before continuing production (see Figure 2.2). The Out of Control Action Plan (OCAP) was later developed as a tool to prescribe what action can be undertaken to remove a special cause of variation [Sandorf and Bassett, 1993].

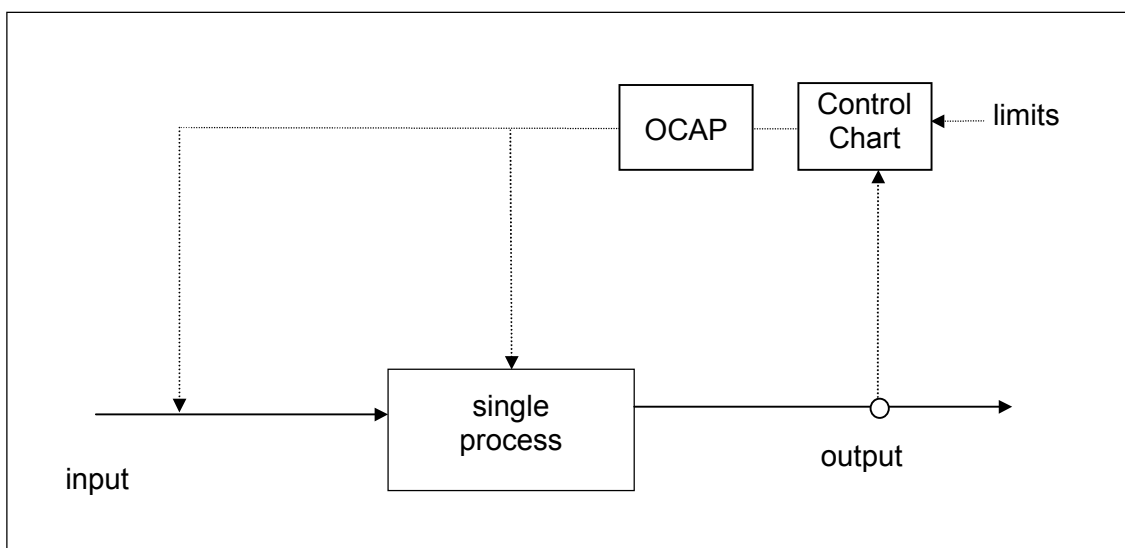


Figure 2.2: Control Charts: process control during production using control limits

In the course of time, various Control Charts have been developed for specific situations, e.g. for low volumes and small batches [Wheeler, 1991; Quesenberry, 1991] and for serially correlated data [Wieringa, 1999]. Changes in Control Chart

methodology were also made to detect small shifts in mean or variance more quickly and more efficiently. Moreover, Control Charts were developed to control other kinds of quality characteristics (such as the number of defects per unit). For an overview of various types of Control Charts we refer to [Cowden, 1957 (for an indication of tools developed until 1957); Montgomery and Woodal, 1997]. Note that the primary purpose of the Control Chart is not to assure that products conform to specifications, but to control the stability of a process. To determine how well process variation fits within tolerances, and thus to estimate the number of non-conformities, an additional tool was developed: the Process Capability Study (PCS) (c.f. [Kane, 1989]).

When an out of control situation occurs, it is not always directly clear what the special cause of this out of control situation is, and how the process should be adjusted. Therefore the 'black box' of the process has to be opened to look for disturbing process factors such as machines, materials, tools et cetera. For this purpose SPC-techniques were extended with 'problem solving tools' (see Figure 2.3) such as Pareto analyses and Fishbone diagrams [see e.g. Wadsworth et al., 1986; Brassard and Ritter, 1994]. Although not all of these tools are of a statistical nature, they are often seen as part of the SPC-toolkit.

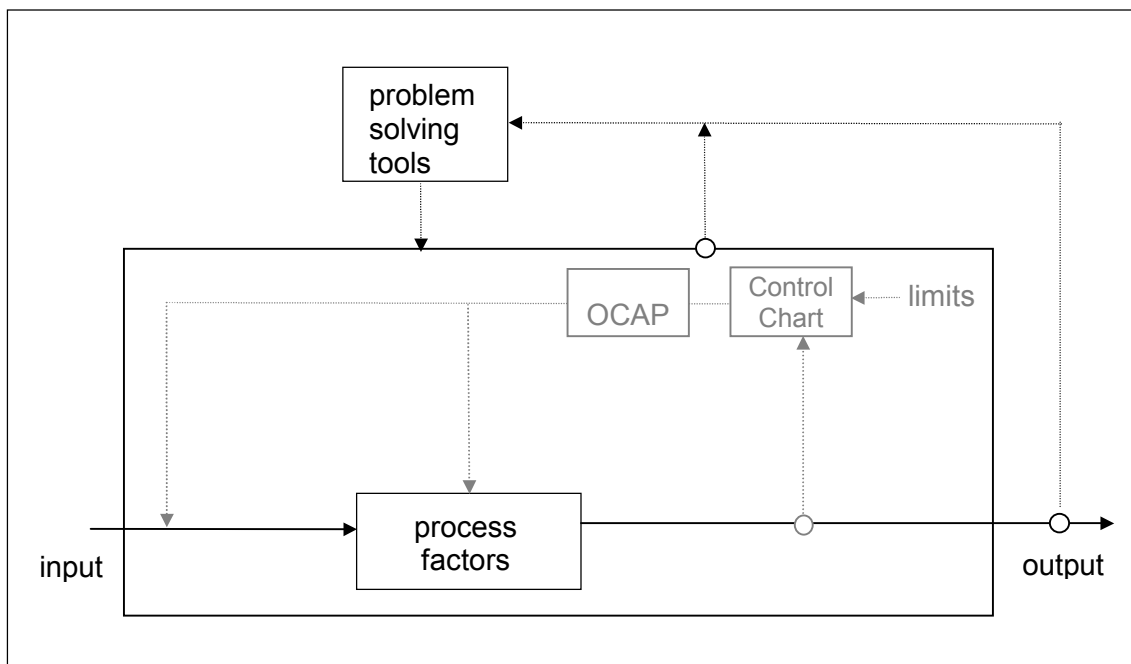


Figure 2.3: Problem solving: finding (root) causes

Another improvement towards prevention was to learn from errors in the past. This means that an out of control situation should not only lead to solving this specific occurrence of the problem, but also to more structural improvements that can prevent this kind of problem in the future. Especially when a certain out of control situation occurs frequently, one has to search for root causes and take actions to prevent this situation in the future. Besides the simpler problem-solving tools, more complex statistical tools such as Design of Experiments and Multiple Regression Analysis are

also used for this purpose. Furthermore, also the Failure Mode and Effect Analysis (FMEA) is used as a tool for qualitative analysis in problem solving [Stamatis, 1995].

Often, the causes of an out of control situation are changes in the influencing factors of the process, such as materials, tools, machine, and settings. The next step towards prevention is the shift from controlling a process as a whole, based on output measurements, to controlling specific (dominant) process factors such as the material inputs or tooling of a process. The result should be that, besides -or instead of- products, the process and the inputs of the process are also measured and controlled to prevent errors in products (see Figure 2.4).

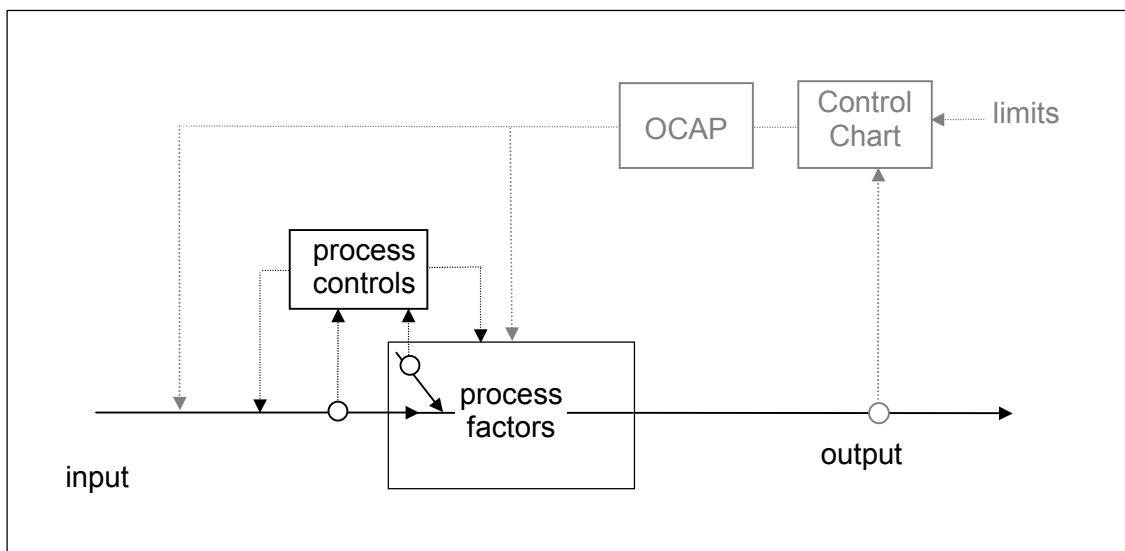


Figure 2.4: Process control on process factors

The improvement activities described above could be used to 'debug' processes by analyzing problems that occurred during production. A development which started earlier but became popular in the 1980's is 'Quality by Design'. This concept was popularized by Taguchi [Taguchi, 1986]. The main point is not to wait with improvement activities until a problem occurs during actual production, but to look at possible failures during the pre-production phase, in which products and processes are defined. This means prevention upstream in the flow from customer demands to production. Most of the improvement tools discussed earlier can also be used in the pre-production phase. However, special tools, such as Taguchi methods [Taguchi, 1986; Lochner and Matar, 1990] and Quality Function Deployment (QFD) [Sullivan, 1986; King, 1989; Akao, 1990] were also developed for Quality by Design.

A first possible step upwards in the pre-production phase is trial production (in the cases where it is used). In this phase one can already check whether the process can run stable and is able to produce products within specifications. Capability studies are often used for this purpose. Another possibility is to check whether the process is sensitive to disturbances. This can be done by deliberately introducing potential

disturbing factors during trial production. To do this systematically one may use Design of Experiments (DoE) [Montgomery, 1997] or Taguchi methods.

The next step is to look at process control during process definition, i.e. before the process is actually built. This can be done by using past experience on similar processes or by building and checking parts of the total process. Another possibility is to check whether a defined product fits within the constraints of existing processes, or newly developed processes, e.g. using Process Capability Studies. It is also possible to determine the optimal process definition based on past experience or theoretical process knowledge (using e.g. Quality Function Deployment) or by planning and executing experiments (DoE). One can also check for possible risks in the process and define activities to control them using a process FMEA [Stamatis, 1995]).

The final step in upwards prevention of failures is to use quality tools during product definition. Examples of such activities are: to determine the optimal product definition (Quality Function Deployment) or to check whether the designed product gives reason for production problems (Design for Manufacturing). Also the design of products and processes that are robust (insensitive) for disturbances, as promoted by Taguchi [Taguchi, 1986] has become an important part of quality related activities during the design phase (e.g. using Taguchi methods or DoE).

In the 1980's and 1990's attention to quality issues expanded to other areas than the traditional production area, not only to process and product development, but also to e.g. purchasing and marketing. The realization grew that quality control and improvement should be an issue throughout the organization, i.e. also in supporting processes such as purchasing, accounting, customer service, et cetera. As a result of these developments, the concept of Total Quality Management originated. The area of TQM now gets much attention in research and business practice, also in non-industrial companies. Within the area of TQM a wide range of tools is used, including not only process control and improvement tools but also 'organizational' tools such as Benchmarking, ISO 9000 certification and Quality Awards (see the list of tools provided by Mann & Kehoe [Mann, 1992; Mann and Kehoe, 1994]). However, these organizational tools are outside the scope of this research.

The historical developments in process control techniques can be summarized with the following trends:

- Shift from detection to prevention: preventing failures instead of filtering out defective products.
- Shift from product oriented to process oriented process control: open the black box of the process and look at process factors.
- Shift from tolerance thinking (i.e. focussing on conformance to specifications) to variation thinking: using measurements to control and reduce variation instead of classifying products as 'conforming' or 'non-conforming'.
- Shift from output oriented quality tools to process oriented tools: controlling process factors instead of the output of processes.

- Quality by design: prevention of production problems through the use of quality improvement tools upstream during the design phase,
- Total Quality Management: the development of organizational tools and concepts and the application of quality tools throughout an organization (i.e. also in other areas than production and design).

As mentioned in the introduction, this section mainly serves as an overview of the field of quality tools. It turns out that the tools related to SPC (Statistical Process Control) are not limited to *statistical* tools. One can also observe that, besides *control*, tools are also used for *design, analysis and improvement*, and the application area was extended to *products* in addition to *processes*. After the exploratory research reported in this chapter, it was decided to limit the scope of this research: although SPC-related tools are more widely applied, the second part of this research focuses on the areas of process control tools in production and improvement tools used to improve existing production processes. The areas of product improvement and first design of products and processes are not included in this research.

For a clarification of definitions and acronyms used in this thesis we refer to Appendices 1 and 2, respectively.

2.2 Literature review on causes of problems in applying quality tools

This section reports on a literature review of factors that cause poor success in applying quality tools, in particular Statistical Process Control techniques. The purpose was to gain insight into the main reasons why, in some companies, quality tools are not applied at all or not applied successfully (cf. the first research question). A summary of the findings in each paper is given below. (The papers are listed in chronological order.)

Lockyer et al. (1984) used a postal questionnaire, supplemented with a large program of structured interviews, to discover the barriers to acceptance of statistical methods for quality control in UK manufacturing firms. The tools considered are Sampling and Control Charting (addressed as Statistical Quality Control or SQC). The following problems are reported: Poor application of tools is related to lack of knowledge of tools, caused by lack of training which is, in turn, attributed to lack of support and low priority from management. A customer who demands the application of SQC is reported to be an important influencing factor. Respondents also state that SPC is not applied because it is believed to be inappropriate in their situation. Strangely, the authors do not further discuss this type of problem; this as opposed to the issue of lack of training. Lack of training is partly attributed to a shortage of training programs offered in education.

Oakland and Sohal (1987) performed a survey among UK manufacturing firms concerning usage and barriers to acceptance of production management techniques, including various SPC related techniques. 1500 questionnaires were sent out, 140 were returned. The survey results show that lack of knowledge of tools and the perception that various tools (among which quality tools) are not applicable in a company, are the most important reasons for not making (sufficient) use of tools. Both causes are found to be of more influence in those cases where the level of training is low. Inadequate training is thus concluded to be an important cause of poor application of tools.

Levi and Mainstone (1987) describe some psychological obstacles that prevent individuals from fully understanding and using Statistical Process Control effectively. Some of these obstacles are: difficulties in understanding and using the concept of randomness, difficulties in relying on statistical information instead of intuition or beliefs, and a tendency to search for external causes, i.e. outside the own influence. To enhance the success of SPC implementation, practitioners should become aware of these problems.

Lascelles and Dale (1988) address various issues involved in quality improvement, based on a literature review. They relate the problems encountered to various issues in the field of management of organizational change and difficulties in making effective

use of the large amount and confusing variety of literature on quality issues. Concerning success factors they conclude that well-known gurus (Crosby, Deming and Juran) have the following points in common: The importance of support and participation of top management; the need for workforce training and education; quality management requires careful planning and a philosophy of company wide involvement; quality improvement programs must represent permanent, ongoing activities.

Chaudry and Higbie (1989) report on a case concerning the implementation of SPC in a chemical industry. They report the following factors needed for successful implementation of SPC: commitment from top management, willingness to make a continuous long-term effort for implementation, training in SPC tools, overcoming resistance to change, selection of suitable processes for implementing SPC, exposure of SPC (e.g. by success stories) and the availability of equipment such as statistical software. They suggest providing information about and training on SPC before starting the implementation and ensuring the availability of SPC coordinators to provide support during implementation are suggested.

Modarress and Ansari (1989) used a survey among 1000 U.S. firms known to be using quality control techniques (205 were returned). For various departments of the firm, the level of application of both statistical and non-statistical tools, and reasons for slow implementation were assessed. The survey results show that the main area of application of quality tools is still the manufacturing department. The majority of companies does not use quality control techniques in other departments, such as the design department. The main reasons reported for slow implementation are: lack of participation and commitment of both top and middle management. Furthermore, lack of mathematical skills, lack of support from employees, and high costs for implementation are reported. The authors do not suggest any specific solutions for these problems.

Dale and Shaw (1991), report on some questions raised by companies in their application of SPC. The authors encountered these questions through their involvement with the introduction of SPC in the automotive industry. Furthermore, they used the results of two SPC questionnaire surveys. They attribute most problems to a lack of understanding of the tools and underlying concepts. This may cause the following problems: people use tools for wrong purposes; tools are not applied because the possible benefits are not understood; tools may not be applied or applied in the wrong way because one does not see how it can be applied in a non-text book situation; tools may also be poorly applied because the role within the total area of quality improvement is not understood. It is suggested that the poor understanding of tools and concepts is caused by the inadequacy of training and education provided on SPC. Furthermore, organizational causes such as lack of training, lack of support from an SPC facilitator, and lack of vision and support from top management are reported to cause the problems observed.

Gaafar and Keats (1992) identify various issues that need to be addressed when implementing SPC. The research method is not specified; apparently the paper is

based on literature review and experiences of the authors. The most important conclusions concerning success factors are: training is essential both for learning tools and to ensure involvement; training should be provided in all steps of the implementation process. Ensuring management commitment and handling inherent resistance to change are necessary to get started. Implementation of SPC should be plant-wide to become fully effective. An evolutionary way of implementation, planning the implementation, maintaining the program to ensure continuing attention and integration in the regular working methods and organization, are necessary to prevent an early termination of the program. The authors provide a framework with steps for SPC implementation to address these issues.

Wood and Preece (1992) discuss the practice, problems and possibilities of using quality measurements based on practical experience. The problems reported are largely of an organizational nature. Examples are lack of available time to implement SPC and lack of management commitment. Another group of problems is caused by poor (technique-based) training and wrong motives for implementation: e.g. when tools are applied because it is a customer's requirement, this may lead to a tool-oriented approach in which tools are chosen from a list of standard procedures without a thorough understanding of their nature and purpose. Also, directly adopting an approach that has been successful at another company may lead to a tool-oriented approach. In general, lack of training and wrong motives for implementation led to a poor understanding of the purpose and underlying concepts of techniques. This subsequently resulted in the application of standard textbook techniques that were not suitable for the situation at hand, or in tools being wrongly applied.

Stephen (1993) reports on the following pitfalls leading to unsuccessful implementation of SPC, based on practical experience: Unreliable data due to poor measurement methods and gages. Wrong objectives lead to a tool-oriented approach in which applying a tool is seen as a goal instead of a means; the actual goal of the tool is not understood. Application of control tools by quality specialists instead of operators leads to poor commitment of operators. If tools are not reviewed periodically to check whether their application is still appropriate, problems will arise. If commitment of top management is poor, the implementation of SPC is likely to fail.

Wozniak (1994) reports on causes of poor success related to the way of implementing SPC, based on practical experiences. The problems observed are of an organizational nature: SPC is often upper-management driven, whereby acceptance and understanding by lower level management is not ensured. SPC is seen as the task of one person instead of a team including operators. This causes poor acceptance by and commitment of operators. SPC is presented as a project, rather than a continuous process that should be incorporated in everyone's job, as a result of which attention will fade in time.

Based on a survey and structured interviews among leading UK TQM firms, Mann and Kehoe (1995) report on factors affecting the implementation and success of Total Quality Management. In their study, a wide range of quality tools is considered. The

most important influencing factors reported were organizational stability and management commitment. They also conclude that the factors differ for various quality tools, e.g. the type of products and production processes influenced the implementation of Statistical Process Control, but not the implementation of delegated teams (also considered to be a quality tool). Since the majority of the quality tools considered were mainly organizational, it is hard to draw conclusions for the more production process oriented tools considered in this thesis.

Does et al. (1997) report on experiences in implementing SPC in Dutch industry. They report the following important issues in implementing SPC: It takes several years to implement SPC; time and money must be invested before SPC becomes fully effective throughout the whole organization; constant attention of top management is necessary; SPC requires delegation of tasks, responsibility and authority to the lowest possible level; implementation of SPC must be guided by an expert with thorough understanding of the possibilities and problems of statistics; the organization must be familiar with tackling problems through the use of data; teamwork and project management is essential.

In Table 2.1 the various factors causing poor success, as reported in literature, are listed together with the number of times they were mentioned in the reviewed literature. Various statements are listed without being categorized or reformulated. Some similar statements were clustered. (The references are listed using the initial letter(s) of the first authors name.)

The overview in Table 2.1 shows that an important part of the causes of problems in applying quality tools is clearly of an organizational nature. Examples of organizational factors influencing success mentioned by several authors are: lack of management commitment, lack of training, lack of support from an SPC facilitator, lack of involvement of operators, and poor ways of implementing and managing SPC. It also shows that a problem may have multiple causes and root causes. For example, Wood and Preece report that the application of tools that were unsuitable was attributed to poor understanding of the purpose and underlying concepts of techniques which, in turn, was thought to be caused by poor training and wrong motives for implementation.

Although organizational causes clearly play an important role, not all differences in the success of using quality tools can be explained by these factors. Some of the causes reported suggest that a part of the problems is not necessarily of an organizational nature. For example, Mann and Kehoe report that the type of products and processes influence the implementation and success of SPC. Although the types of products and processes may vary between organizations, this does not seem to be an organizational problem. Related to this are the observations of Oakland and Sohal, and Lockyer et al., that some companies gave 'not applicable' as a reason for no application or poor application. Apparently there are problems in finding a fit between quality tools and production processes. Organizational factors, such as lack of training, are likely to influence this. Yet, it is quite possible that in some situations it is more difficult to find a

good fit between a situation and the type of tool to be applied, thus placing higher demands on training, support of specialists and commitment from management. Thus an organizational problem may be caused by technical circumstances.

Problem cause	count	#	References
Lack of (top) management commitment	IIIIIIIIII	10	CDaDoGLaLoMa MoSWoo
Lack of training / skills	IIIIIIII	8	CDGLaLoMoOWoo
Involvement/support of operators / not only specialists	IIIIII	6	GDoLaMoSWoz
Lack of understanding of tools and concepts / goals	IIIII	5	DLeLoOWoo
Tool not appropriate for situation / type of process	III	3	LoMaO
Overcoming resistance to change / change management	III	3	CGLa
Integration into regular working methods required	III	3	GLaWoz
Careful planning and management of implementation	III	3	DoGLa
Lack of support of SPC co-ordinator	III	3	CDaDo
Inadequacy of training	II	2	DWoo
Wrong objectives / tool oriented approach	II	2	SWoo
Plant-wide implementation required	II	2	DoG
Difficulties in relying on statistical information / data	II	2	DoLe
Long term effort needed for implementation	II	2	CDo
High costs for implementation	II	2	DoMo
Lack of top management vision	I	1	Da
Making choices from large amount of literature	I	1	La
Unreliable data / poor gages	I	1	S
Organizational stability	I	1	Ma
Possible benefits are not understood	I	1	Da
Problems in fitting standard textbook approach	I	1	Da
Role of tool in larger whole not understood	I	1	Da
Selecting suitable processes to start implementation	I	1	C
Lack of time to implement SPC	I	1	Woo
Tendency to search for external causes	I	1	Le
Tools used for wrong purposes	I	1	Da

Table 2.1 Summary of causes of problems reported in literature.

Compared to organizational problems, the role of technical circumstances gets less attention in literature. One often starts from the point of a 'best practice' for the application of SPC. To find this best practice, research is carried out on quality activities of 'leading' companies [e.g. Mann 1992, Mann & Kehoe 1994]. As a result, most of the problems reported are organization-wide problems and not specified for a specific tool or process. Studying 'technical' problems requires information on a more detailed level: one needs to know the characteristics of products and processes, which can vary even within one company. Furthermore, some tools may be more difficult to fit

than others, so that when looking for success factors one should differentiate between tools.

Most of the literature does not consider influencing factors on this level of detail. Exceptions are papers on the subject of tailoring a tool methodology to a specific situation [see e.g. Quesenberry, 1991]. However, these papers are often focussed on mathematical aspects and are limited to a single tool.

As described in Section 1.3, case studies were planned to collect additional empirical material on causes of problems in applying quality tools, with a focus on those aspects that get little attention in literature. Based on the above discussion of literature, it was decided that a more detailed view on success factors should be obtained and that special attention should be paid to technical problems in relation to characteristics of the product and process at hand. The case studies, carried out in four companies, are described in the following section. Since the cases should provide additional information concerning success factors, the above review of literature and the case studies will be discussed and analyzed simultaneously in more detail in Section 2.4. The purpose will be answering the first research question.

2.3 Exploratory case studies in four companies

This section describes four case studies performed in four different companies. The goal of the case studies was to gain additional information concerning problems in applying quality tools, with a focus on the influence of technical circumstances. Based on the results of the literature review presented in Section 2.2, the application of specific tools in actual production processes was studied. Thus the case studies should provide more detailed insight into problems (and their causes) in applying quality tools on the operational level, i.e. as applied to actual production processes.

2.3.1 Research method

Although relatively time-consuming in relation to the number of tools and situations that can be studied, the case study was chosen as a research tool to obtain additional knowledge on causes of problems in applying quality tools. The research method used and the main considerations for selecting this method are discussed below.

The previous section shows that most of the research specifically directed at finding causes of problems in applying quality tools was based on questionnaires. This way of gaining additional knowledge might have allowed coverage of a wider range of situations and tools, but there are some drawbacks to using a questionnaire. Lockyer et al. [Lockyer et al., 1984] give the following problems:

- No sample is completely random, since only people who are interested in the questionnaire will answer it.
- Respondents will tend to answer questions in a manner that will show them in the best possible light.
- The necessarily brief nature of the questionnaire does not facilitate the exploration of the attitudes and prejudices involved in the development of a Quality Control system.
- Open questions such as "Why does your company not use SQC?" tend to have a low response rate.

Concerning a survey on causes of problems in the application of quality tools, we add the following drawbacks:

- People are often not able to see the causes of problems they encounter (otherwise they might have solved them).
- Using surveys it is difficult to get a more detailed view on causes and root-causes.

The case study was considered and selected as an alternative. The main advantage of case studies lies in the fact that they provide more detailed information. A drawback, however, is that only a limited number of tools and a limited set of situations in which these tools are applied can be studied. Since the case studies are part of the exploratory part of this research, and are intended to provide supplementary

information (to the literature review), this drawback was considered acceptable. The case studies will be used to find patterns of causes of problems.

Four companies that were interested in the research questions, provided the opportunity for studying cases. Two of these companies were in the field of mass production. In one company the use of SPC-related tools was demanded by customers. The production volumes of the other two companies are smaller. They use processes on which a large variety of products can be produced. Although the use of SPC related tools was not a customer requirement, these companies were starting projects to implement SPC. The selection of the cases was largely determined by the SPC-related projects that were started or running during the exploratory phase of this research. The projects that were suggested as cases were those where some problems were encountered. Within the project the role of the researcher was to follow the projects and provide knowledge from literature where possible.

Since not all relevant quality tools could be studied, it was decided to study the application of three popular SPC-related tools in three areas of operational activities (regular production, trial production and process design). The selected tools are basic elements of the SPC methodology. Selecting popular tools for this study increases the chance that the company is aware of their existence and that their application has been considered. The following tools and areas were selected:

- \bar{X} -R Control Charts in regular production,
- Process Capability Studies in trial production,
- Process FMEA's in process design.

In each company the application of the above tools was studied by observing an improvement project for a specific production process. Information was gathered by reading instructions and reports, by attending meetings of the improvement project, through observation of the process, and by interviewing people involved.

For each tool it was assessed whether or not it was applied. If so, it was determined how it was applied and whether the application was successful. However, it turned out to be difficult to determine whether a tool was being successfully applied. Simply asking whether a tool was being used successfully was unsuitable. In order to study the success of a technique, it is necessary to understand its purpose. Therefore, the goal of each tool was determined. In this way it is easier to understand when and why a technique is effective. Another important observation was that in some cases the tool in question was not used to accomplish (one of) its goals, but that another tool was used instead. Using the goals of a tool as a starting point gives a better understanding of which tools or activities can be seen as alternatives for tools studied here.

Therefore in Section 2.3.2 the underlying goals of a technique are described. Section 2.3.3 describes the case study results. For each case a description is given of how the goals of the techniques are fulfilled. If a standard technique is used, a discussion on how well it fulfils its goals is given, and possible factors that cause problems are

described. Where alternative techniques are used, the factors causing this are addressed. As a result of the focus of the case studies, the circumstances studied not only involved characteristics of the organization, but also characteristics of the process and product at hand.

2.3.2 Brief description of the goals of the tools under study

Before case descriptions are given, the goals and working method of a standard application of the three tools under study are discussed. The description of the method is very brief and only intended to indicate the type of application considered in the cases. (For a more detailed description of the methodology a reference to a textbook is given.) Specific attention is given to the goals (or functions) of the tools. Describing goals allows us to judge the effectiveness of a technique when it is applied. Furthermore, alternative activities that are used to fulfil functions instead of or in addition to a standard technique can be recognized.

\bar{X} -R Control Charts applied in production

Control Charts are generally based on measurements of a certain product characteristic. In an \bar{X} -R Control Chart the mean and range of samples taken during a production run are plotted against time, and compared with control limits. Control limits are based on measurements from a stable process. By comparing sample mean and range with these limits one can detect when special causes of variation cause an out of control situation. [See also Section 2.1 and e.g. Montgomery, 1996; Wheeler and Chambers, 1992].

The functions of a Control Chart are:

- *Process Control*: to monitor whether a process is in statistical control (i.e. stable mean and variation) using control limits. (Note that to really control a process, action must be taken in out of control situations.)
- *Process Analysis*: to find and analyze problems in the control of the process.
- *Product Assurance*: although the Control Chart was not intended to be used for this purpose, under specific circumstances it can be used to ensure that delivered products are of acceptable quality.

Process Capability Studies (PCS) applied in trial production

A minimum of thirty products from a test run are measured and a graphical summary of the data is made (e.g. a histogram). Based on the data, the mean and the standard deviation are estimated. Together with the tolerance limits, they are used to calculate capability indices. These indices (C_p and C_{pk}) give an indication of how well the process is actually capable of producing products within specifications (C_{pk}) and how well the process could be capable when centered between tolerance limits (C_p) [see e.g. Kane, 1989]. The process should be in statistical control (i.e. there should be no special causes) in order to calculate these capability indices. Patterns from a non-stable process can be used to find causes of problems.

Thus the functions of a Process Capability Study in trial production are:

- *Problem detection*: to detect potential problems by studying the pattern of measurements of the trial run, using a histogram, a Control Chart, or trend plot.
- *Feasibility testing*: to test how well a new product can be produced by calculating capability indices that compare the mean and variation of a trial run with product tolerances.

Process FMEA's applied in process design

The Process FMEA (Failure Mode and Effect Analysis) is a qualitative tool for identifying weak points in a process based on existing process knowledge of the people involved. Before actual production of a new product starts, possible failures in the process are listed. Numbers are assigned to the chance of occurrence, the severity of the effects of each failure and the likelihood it is detected and resolved. By multiplying these numbers, a risk priority number is calculated. In this way the weak parts of the process can be pinpointed and improvements to lower the risk can be sought after and evaluated [see e.g. Stamatis, 1995]. (Note that to be able to use a process FMEA one has to have sufficient relevant knowledge of the process under study, e.g. based on experience with similar processes.)

The functions of a Process FMEA in process design are:

- *Problem identification*: to find potential process failures and their effects.
- *Problem prioritization*: to identify the most disturbing problems that should be subject for improvement.

2.3.3 Case study results

The results of the case studies are summarized below. (In the case-descriptions the goals of each tool are highlighted in the text by using *Italics*.)

Case A: Grinding process in mass production of a metal part on a dedicated production line. Automotive industry.

Control Charts in applied production:

In this process, specially designed gages and automated \bar{X} -R Control Charts are used. One of the main reasons for using \bar{X} -R Control Charts is that this is prescribed by the QS-9000 standard (which is a customer requirement). Another reason is that the producing company wants to be sure that the final product will not fail when used in a car, since this would involve huge costs. Therefore, additional checks are carried out to make sure that parts are within specification.

However, this focus on product quality caused the Control Charts to be used mainly for *product assurance* (i.e. to assure that products conform to specifications) rather than for *process control*. Tool-wear trends and different batches of incoming material cause the process to be out of control. Control Charts are not used to control or compensate

for these trends or to monitor process variation using ranges. Instead they are used to see when the trend is going too far and the grinding tool has to be replaced. The assurance orientation led to the monitoring of product-functional measures and not those product measures that directly visualize tool-wear effects. Control Charts are not used for *process analysis* as a basis for process improvement.

Although the process was clearly not in statistical control, no actions were taken to solve this problem. Thus the Control Chart limits were calculated in the wrong way (i.e. based on a non-stable process) and cannot be used to control the process. Control Charts could have been adapted for known tool wear trends, but the people involved were not aware of this possibility. Furthermore, this type of Control Chart was not supported by the software package used for on-line charting.

The improvement project showed that there were also other possibilities for controlling the process. Possible improvements were: Preventive maintenance and replacement of grinding wheels, measurement and control of material input, or automated feedback adjustment to adjust for tool-wear trends and differences in material input. These improvements were not made, one of the reasons being lack of insight in trends and relations of process output and process factors. Furthermore, the management did not support any large investments in the process, since it would not be used for a new generation of products. Due to all these reasons, the process is not controlled. This makes a 100% check and matching of the produced parts at the end of the production line necessary.

Process Capability Studies applied in trial production:

Process Capability Studies were used in trial production for the same reasons as Control Charts, i.e. it was a customer requirement. However, the main purpose for the company was to show that the product can be produced within specification limits (*product feasibility*). To achieve this, the trial production was executed under favorable conditions. However, under real production circumstances, the process shows uncontrolled trends and shifts that cause the process to be out of control. Because capability studies were not used for *problem detection*, this was not foreseen.

Capability indices calculated based on samples that are also used for Control Charts are worse than the original indices (calculated for trial production), and substantially lower than the desired values. Correct interpretation of capability indices in this situation is difficult, since the process should be in statistical control.

Process FMEA applied in process design:

Process FMEA's were used during process design (as part of the requirements of the QS 9000 standard). Although some *problems were identified*, due to lack of process knowledge, not all factors that disturbed the process were foreseen. Process knowledge could have been expanded e.g. by analyzing production data or by using designed experiments.

Case B: Laser welding process in mass production on dedicated line.

Control Charts applied in production:

The production line has an automated 100% inspection station *to assure product quality* for one important specification. This is necessary because some problems in the production line occur suddenly and incidentally so that they cannot be signaled by Control Charts. Measurement data of the 100% inspection were not used for Control Charting, partly because this in-line measurement is rather inaccurate (it only provides a rough measurement that can be used to filter out poor products.)

Nevertheless using Control Charts was part of company policy, mainly because of their good reputation in other companies. Knowledge of Control Charts methodology was present, but using Control Charts was seen as an obligation rather than an opportunity for process control and analysis.

Additional Control Chart samples were taken and measured off-line in a special measurement laboratory. These measurements were mainly used for *product assurance* by a sign-off sample at the beginning of a batch and a few extra samples during the batch. Control Charts were shipped together with the products. Control Chart samples were rarely used to *control processes* by feedback loops, since it takes a long time to measure them. Furthermore, large differences between batches caused the process not to be in statistical control. Measurement error was relatively large compared to process variation, which makes proper process control using Control Charts very difficult. Hardly any *process analysis* of Control Charts was done to improve the process. Because of all this, production problems occurred regularly and were not solved.

Process Capability Studies applied in trial production:

As in Case A Process Capability Studies were used in trial production, however, mainly under optimal conditions. The main purpose was demonstrating *product feasibility* by producing products within tolerances. Therefore some *problems were not detected* and actual production often is not within specification. Moreover, interpretation of capability indices is difficult since the process is not in control.

Process FMEA's applied in process design:

No Process FMEA was used for this process, the main reason being that the engineers responsible were not familiar with this technique. A traditional engineering approach was used, directed at finding optimal process conditions but not at preventing poor conditions. Therefore some potential *problems were not identified*. The technique could have been applied in this case. However, lack of knowledge on the influence of process factors could have caused difficulties as in Case A.

Case C: Standard CNC-bending process on which a large variety of products is made in low volumes.

Control Charts applied in production:

No \bar{X} -R charts are used in this process. \bar{X} -R charts are known, but were considered to be inappropriate for this situation, the main reason being that a wide variety of products is produced in low volumes. Separate Control Charts for each product would be very expensive compared to product turnover. Furthermore, the production volumes are too small to apply the statistical rules for calculating limits. The use of another type of Control Chart for the whole process or standardized Control Charts for groups of products as described by e.g. [Al-Salty and Statham, 1994], [Wheeler, 1991] and [Quesenberry, 1991], was also contemplated, but was considered to be too complicated because of the large product variety and too expensive to introduce compared to the relatively small turnover of this process.

Instead of Control Charts, periodic capability studies are performed (twice a year) on a standard product to *control the process variation* and to *analyze possible problems*. These studies show that the process is quite stable within a batch but can shift between different batches of a product. Therefore set-up control at the beginning of each batch is used to *control the process mean* and to *assure product quality*. Once the process has been set up, it is assumed that it is stable and does not change significantly within the batch. Although not statistically perfect; the approach seems to work. By analyzing capability studies and results from set-up measurements, process problems are detected and adjusted.

Process Capability Studies applied in trial production:

No capability studies are applied to new products during trial production. Only one to five products are measured completely. The number of products depends on the ease of measuring. This is done to prevent high costs and capacity problems at measuring machines. However, the main reason is that a Process Capability Study is not found to be of use. The capabilities that can be achieved are largely predictable, based on the periodic capability studies mentioned above. New products will resemble products already produced. The small sample measured during trial production can be used to check the mean values of measurements. Thus the capability study is used mainly for another purpose: controlling the level of variation in a process as an alternative for a Control Chart.

When a new product is designed the constraints and the known capabilities of the process are taken into account to *detect potential problems*. Since the process is already in use and new products are largely similar to existing products, this information is present in written construction guidelines. Trial production is used only to check whether the product mean is satisfactory when using the prescribed tooling and machine program (*product feasibility*), since variation is considered to be controlled by the periodic capability studies described in the previous subsection.

Process FMEA's applied in process design:

No product-specific Process FMEA's are used in trial production, mainly for the same reasons as described under capability studies. A product-independent process FMEA was used as a part of the improvement project to *identify and prioritize potential problems* of the existing process. To make sure that new products do not cause uncontrolled problems, the constraints and capabilities of the machine are present at the product development department, in the form of construction guidelines.

It turned out to be necessary to assist process engineers in the use of this technique, to ensure correct used and interpretation. Although the methodology is clear, expertise is necessary to determine how elaborately or precisely the process FMEA should be used to achieve its goal. Without this support, there is a danger that the use of the FMEA will take too much time or will become a goal in itself.

Case D: Production line to apply powder coating to a wide variety of metal products.

Control Charts applied in production:

Although knowledge of Control Charts was available in this company, and the management was committed to implementing SPC tools, no Control Charts were used for this process. To *assure product quality*, products were visually checked after the powder coating was melted and hardened in an oven. Since this is done when products are taken from the conveyer belt, no extra costs were involved. However, it was not possible to *control the process* effectively using this check because a large part of the batch will be coated before the first part can be checked. Feedback adjustments were thus difficult. Furthermore, real quantitative measurements were only appropriate for a few product characteristics and could only be measured in a laboratory.

Therefore *to control the process*, the company started to set controls on process factors that caused problems. Examples are periodic cleaning and maintenance of essential machine parts, monitoring process parameters, and checking material levels. Besides this, the powder flow (amount of powder generated in e.g. half an hour) at each pistol was measured periodically and the values were compared to a minimum value and to previous values. This powder flow is influenced by various important process factors such as the state of the tubes and pumps. It also directly influences the quality of the powder coating on the product. It is thus a good alternative for measuring products as a basis for process control.

When problems occur despite these controls, the *problem was analyzed* and, if possible, actions were taken to improve process control. Instead of Control Charts, the company used tools such as Pareto charts, fishbone diagrams and FMEA's *to analyze the process*.

Process Capability Studies applied in trial production:

No Process Capability Studies were used, mainly due to a lack of suitable quantitative measurements. A checklist with design rules was used to *detect possible problems* that are not controlled (see Case C). No real trial production run was done. However, special attention was given to the first production run *to assure product feasibility*.

Process FMEA's applied in process design:

No product-specific Process FMEA's were used. However, the company had started to use process FMEA's to make a thorough analysis of the process. Periodically FMEA's were carried out on the existing process *to identify and prioritize problems*. This led to the definition of process controls on inputs and process parameters.

Before FMEA's were used, a Pareto Analysis of major problems and a Fishbone Diagram were made to determine causes. This approach was still used by workgroups consisting of a quality engineer and a group of operators. The use of formal Process FMEA's would be too difficult for the operators, given their level of education. Although they have trouble grasping abstract concepts such as risk priority numbers, they do have a large amount of process knowledge that should be utilized.

2.3.4 Discussion of case study results

The case studies reported in this section confirm the influence of various organizational causes of problems as found in literature. Examples are lack of knowledge on tools, lack of management commitment and wrong motives for implementation leading to a tool oriented approach. With regard to lack of knowledge on tools, it shows that, besides a lack of knowledge on methodology, a lack of knowledge on the underlying goals of a tool can also cause problems. Although the basic methodology of the tools is understood, in some situations tools are being applied without an understanding of the underlying goal of a tool.

Furthermore, the case studies provide some additional insights with respect to the influence of technical circumstances. Especially characteristics of the production process to be controlled or improved influence the application of tools. Examples of such characteristics are: process variation patterns, measurability of products, disturbing process factors, and the turnover of a process. In Table 2.2 both the organizational influences and the technical circumstances found to be of influence are listed together with the cases in which they were observed.

Problem cause	count	#	Case
Lack of knowledge of tools	IIII	4	ABCD
Lack of / availability of process knowledge	IIII	4	ABCD
Process failure/variation patterns	III	3	ABC
Poor motives for implementing tools	II	2	AB
Measurability of products	II	2	BD
Number of product variants produced on the process	II	2	CD
Disturbing process factors	II	2	AD
Product risk	II	2	AB
Lack of management commitment	I	1	A
Turnover of process / too expensive	I	1	A
Available software	I	1	A

Table 2.2: Summary of influencing factors found in cases

It appears that differences in technical circumstances may cause use of an alternative approach, which differs from the standard popular approach. Alternatives may be part of the field of SPC (such as a PCS instead of a Control Chart in Case C), but it is also possible that tools or activities outside the field should be used as an alternative (such as maintenance or automated controls in Case A). In these cases it is very unlikely that the tool considered can be applied in a standard way. Sometimes techniques are used in another way, but it is also possible that alternative techniques should be used.

The case studies show various situations in which, due to technical circumstances, one of the tools studied was either not applied at all or not applied in a standard way. A

combination of these situations may occur. The separate types of situations are illustrated by the following examples, which are also depicted in Figure 2.5.

1. In some cases the standard approach does not seem to be applicable, either now or in the future, e.g. in Cases C and D. Although management is committed and knowledge of standard techniques is present, Control Charts are not applied. Instead, alternative tools are used to address its functions. The alternative approaches used may not be perfect, but it is unlikely that Control Charts can be used efficiently in this situation.
2. In other cases the standard techniques are only partly effective (i.e. for part of their functions) and need to be combined with other techniques, for instance in Cases A and B, Control Charts are combined with 100 % checks to assure product quality. Another example is the use of an APC feedback loop or maintenance activities as a possibility to control the process in Case A.
3. It is also possible that a technique is not applicable now, but may become applicable after combining it with another technique first. For instance Design of Experiments or analyzing production data to obtain more process knowledge for Process FMEA's in Case B.
4. Another possibility is that a standard technique is not applicable if used as prescribed, but that its concepts can be used in another way to make it effective. For instance product-independent Process FMEA's and Capability Studies in Cases C and D.
5. Situations occur where the present situation causes that the standard approach cannot be applied successfully, but where it is possible to change this situation in such a way that the tool will be successful. Thus the tool could be applicable but does not work e.g. because certain prerequisites were not filled in. An example is better measurement tools to reduce measurement error in Case B and more flexible software in Case A.
6. Finally it is possible that the standard tool is not used, and that no other tool is used instead to fulfil its functions, because these functions are not relevant. E.g. FMEA and PCS in case D.

Note that the above does not imply that the three tools considered in the case studies cannot be applied successfully in practice. What can be concluded is that part of the problems encountered in the studied projects are caused by the fact that through technical circumstances the standard approach could not be applied successfully.

Although in most companies more than one process was studied, in this thesis only one illustrative example is discussed for each technique. The fact that only one example of each case is described does not imply that technical circumstances do not differ within a company. The opposite is true. Technical circumstances were found to vary and cause different alternative approaches between departments and also between processes in a department. Organizational factors were often found to be comparable within a company and a similar effect on all techniques could be seen.

Although the cases do not necessary reveal all possible causes of problems that may be encountered in practice, they do provide additional and more detailed insights with

respect to these causes. The next section discusses the results of both the case studies and the literature review presented in the previous section.

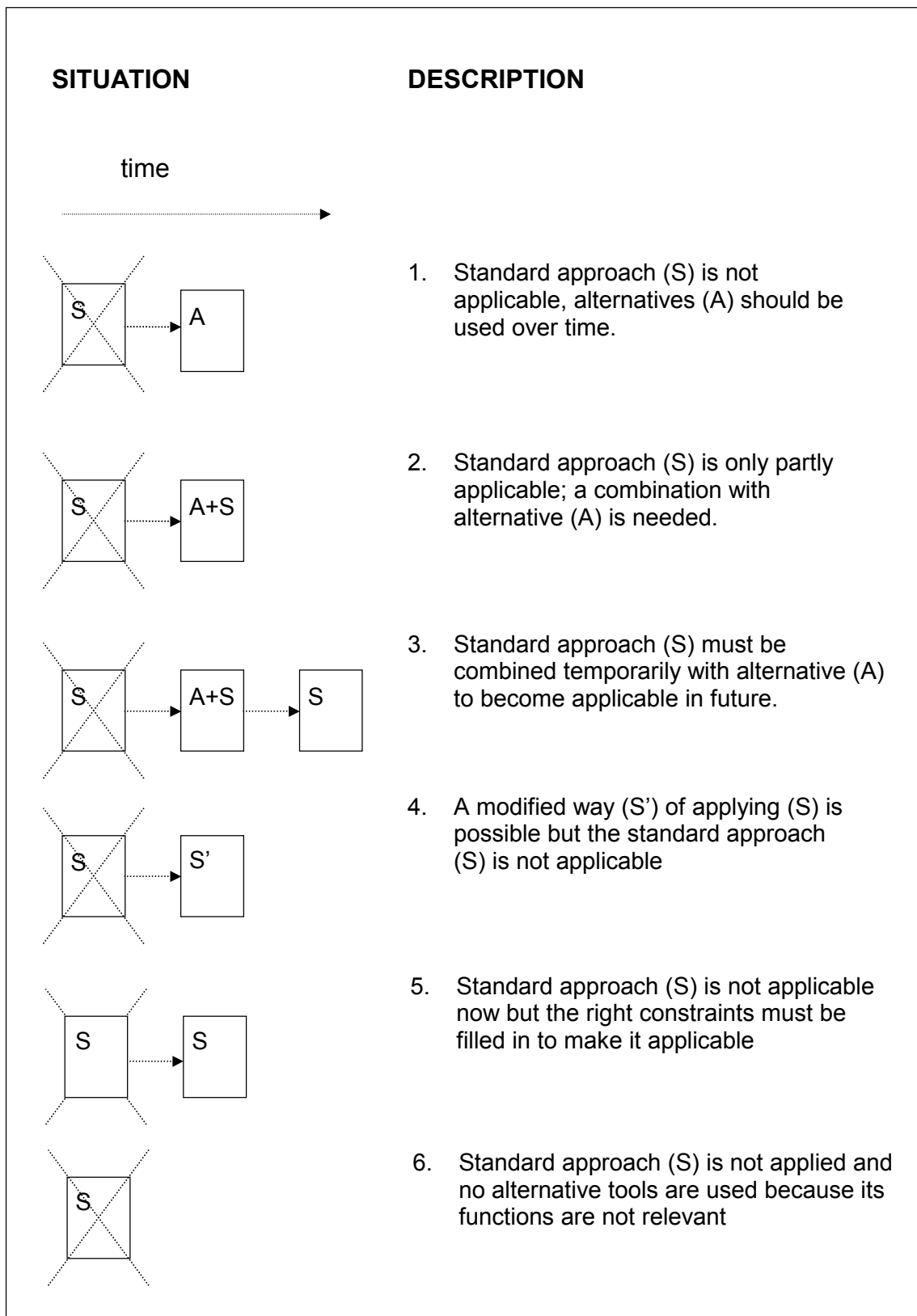


Figure 2.5: Types of situations where the standard approach is not used

2.4 Causes of problems: a discussion of the exploratory research

In this section the results presented in Sections 2.2 and 2.3 will be summarized and discussed in the light of the first research question: 'What are the main causes of problems in applying quality tools successfully?'

The problems addressed in the introduction in Chapter 1, concerned both situations where tools were not applied and situations in which tools were not applied successfully. The case studies in Section 2.3, however, show that not every situation in which a certain tool is not applied is actually a problem (even if it concerns a popular tool that is a basic element of the SPC methodology). The reason is that in some cases the functions of a tool are not relevant. Therefore, before going into the causes of problems in applying quality tools, we will discuss various types of unsuccessful application. Although these situations are a 'cause' of poor success, they are characteristics of unsuccessful applications rather than the actual cause of problems. Therefore these situations will be called symptoms. When taking a closer look at the problems described in this chapter, various symptoms can be observed or derived. Especially the case studies show various types of application that are unsuccessful. Although not completely disjunctive, the symptoms can be categorized into the following four clusters.

The first cluster of symptoms refers to applications where there is a *poor fit between tools and the relevant functions in a situation*. Situation '6' of the case studies shows that it is important that there is a fit between relevant functions in a situation and the functions of a tool. Thus two symptoms can be derived concerning a misfit between tools and relevant functions:

- A tool is applied although its functions are not relevant.
- Although a certain function is relevant, no tool is applied for this specific function.

The second cluster refers to the *possibility of applying a tool effectively in a certain situation*. Situations '1' and '5' in the case studies, indicate that it can be difficult to realize the functions of a tool in a particular situation, both in terms of effectiveness (desired results), and efficiency (effort needed). In these situations another tool may be more suitable. This results in the following symptoms:

- Although the functions of a tool that is used are relevant, the situation does not allow effective or efficient use of it. An alternative tool may be more suitable in the situation at hand (Situation 1).
- Although the functions of a tool that is used are relevant, the situation does not allow effective or efficient use of it. However, it is possible to enable use of the tool by creating the right conditions (Situation 5).

The third cluster refers to *correctness of the methodology, used in the application of a tool*. Both the literature review and situation '4' of the case studies show that the following symptoms can occur concerning the methodological application of a tool:

- Although the tool is suitable, its implementation is not successful because the basic methodology is not applied correctly.
- Although the tool is suitable, its implementation is not successful because the basic methodology should have been adapted to fit the situation.

The fourth cluster refers to the necessity of *defining proper relations between tools*. Situations '2' and '3' of the case studies and some of the reported problems in literature show the importance of relations with other tools. Controlling or improving a process will not be achieved by using one tool. It is more likely that a set of tools needs to be used in combination (parallel or in a sequence). Thus the following symptom may occur:

- Although a tool is applied correctly for a relevant function, it is not successful because it is applied in isolation: the relations with other tools and activities are not defined (correctly).

Both the literature review and the case studies show that the above symptoms may have multiple causes. One cause may be a root cause for another, or a problem may be brought about by interrelated causes. Although in practice the influence of various types of causes often cannot be isolated and separated, they can be discerned to indicate the main categories of causes. Especially in finding answers to the second research question ('How can the problems in applying quality tools be solved?') it is necessary to be able to discern various types of causes since they may require different solutions.

In literature especially organizational factors are reported to be a cause of unsuccessful applications. The case studies also support the conclusion that organizational causes are of influence. However, the case studies show that problematic applications may be the result of both organizational factors and technical circumstances. E.g. an application that is not methodologically correct may be attributed to poor methodological knowledge of the user (i.e. an organizational cause), but technical circumstances may cause that the application of quality tools is less straightforward and thus larger demands are placed on the methodological knowledge of the user. This may be compensated by organizational activities such as training, but it is not solely an organizational problem that can be qualified as a company that is lagging behind (as questioned in Chapter 1).

The case studies show examples of how technical circumstances influence the application of quality tools. Examples of technical circumstances that were observed to be of influence are: measurability of products, the nature of influencing process factors, process turnover, and process failure patterns. Although, in general, these circumstances can not be easily changed, they can be seen as part of the problem, since they can cause that in some situations the users are not able to define proper

applications. Thus situations that require approaches which deviate more from standard approaches, place higher demands on the abilities of users when applying quality tools.

Besides a knowledge of tools, there are some other characteristics of users that influence their ability to apply quality tools successfully. Examples are: knowledge of the process at hand, involvement in and support of the application of quality tools, and the availability of time. If users lack these characteristics, this may result in the symptoms observed. The abilities and effort of the user can be improved by organizational influences such as training, support of a specialist and management commitment. Conversely, lack of training et cetera, may cause poor abilities, which may, in turn, cause problems, especially in more difficult situations. Organizational activities can influence only part of the technical circumstances, e.g. the availability of means such as software and gages.

Thus applications that are not successful (symptoms) are caused by both user characteristics and technical characteristics. The relations between symptoms and various causes are depicted in Figure 2.6. The user characteristics can be influenced by organizational causes. The possibilities to change technical circumstances through implementation and organization are very limited (which is indicated by the thin dotted arrow). The literature review mainly provided insight into causes concerning implementation, organization and user characteristics. The case studies provided more detailed insight into characteristics of poor applications and the influence of technical circumstances.

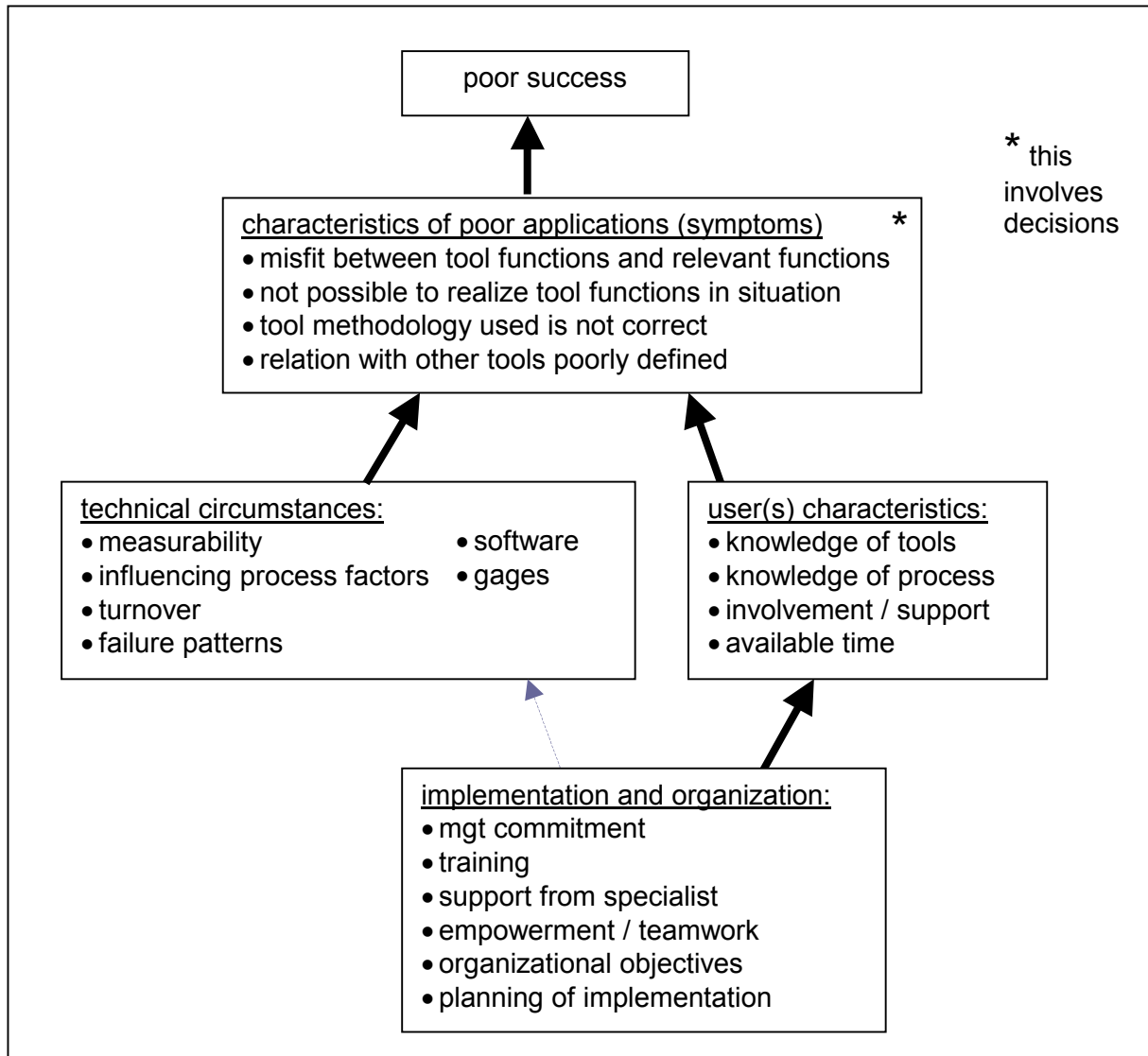


Figure 2.6: Symptoms and causes of unsuccessful applications of quality tools

3 Conceptual framework and research design

This chapter deals with answering the second research question: 'How can the problems in applying quality tools be solved?', and defining detailed research activities/objectives to realize the overall research objective as defined in Chapter 1: 'To support practitioners in making effective use of existing quality tools'.

3.1 Research needed to solve observed problems

In this section we will discuss the second research question. The second research question can be answered from the point of view of a company and from the point of view of research needs. Although the objective of this section is to determine how this research can contribute to solving the problems discussed in Section 2.4, we first discuss what a company can do to solve or prevent problems.

From a company point of view, problems can be (partly) solved by proper organizational activities such as training, support of a specialist, and management commitment. E.g. by intensive training and support from a specialist, understanding of standard tools can be improved. This will enhance the ability of users to define approaches that fit the situation. Without training and support users may lack this ability. The resulting disappointments and lack of confidence can be a cause of poor implementation, applications that are stopped before becoming successful, or no application at all. Besides providing training and support, the company should also make sure that through organizational activities the abilities and effort of the users are stimulated and that sufficient time is available.

One can conclude that, in accordance with the literature discussed in Section 2.2, training is indeed an important organizational factor that can help a company in solving most of the problems observed. However, not only was lack of training reported as a cause of problems, but also the adequacy of training was reported to be a problem [Dale and Shaw, 1991]. Although lack of training is an organizational problem, poor quality of training is not necessarily an organizational problem. The question arises whether the present knowledge in literature on quality tools is sufficient to set up adequate training in order to prevent the symptoms observed.

Since the goal of this research is to provide decision support for the application of quality tools, we will focus on the availability of relevant knowledge on tools presented in textbooks and training programs. The question is whether this knowledge is sufficient, and if not, which knowledge could help in preventing the symptoms observed. When reviewing textbooks and training programs in the field of quality tools, with respect to the symptoms, the following can be observed:

- Training is often tool-oriented and the focus is on the standard methodology of a tool. Little insight is provided into when and how the tool methodology should be

adapted to fit a specific situation. Thus, in non-standard situations, problems with respect to the tool methodology may arise. To compensate this, support from a specialist who can train and support on the job could be of help [cf. Does et al., 1999]. Research could contribute to collect knowledge of how to tailor a tool to a specific situation. However, this type of research lies in the field of development and refinement of single tools, and therefore outside the scope of this research.

- Through the focus on methodological aspects of tools, the goals of a tool are often not discussed explicitly, as a result of which users are not aware of their functions. Little attention is given to indicate in which situations a tool should or should not be used, i.e. in which situations a tool function is necessary. The possibilities of fulfilling these functions in a particular situation and possibilities of using alternative techniques are also not often addressed. Thus there is a danger that the application of a tool becomes a goal in itself although it is not appropriate for the situation. Research could help in clarifying the goals of tools and providing guidelines for selecting suitable tools.
- Many textbooks and courses in the field of quality control and improvement are mono-disciplinary, i.e. they are limited to the tools of a single discipline or program. Little or no attention is paid to the relevance of tools from other disciplines or programs and their relation with the tools at hand. Thus users know are only aware of a limited number of tools, and view tools from various disciplines as separate activities. Furthermore, even within a mono-disciplinary training, little insight is given into the relation between tools. Research could contribute by providing an integrated framework for tools from various disciplines in which the role of a tool within a larger whole, and the relations between tools become clear.

It can be concluded that current knowledge of quality tools is largely on the level of the methodology of (single) tools. This is reflected in training programs and textbooks. With respect to the non-methodological aspects of the application of quality tools, it is less clear that sufficient knowledge is available. The shortcomings observed concern insights into the goals of tools, their relationships (in and outside disciplines) within a larger framework, and the considerations for selecting certain tools in a specific situation. The objective of the second part of this research will, therefore, be to address these issues. Based on the answers to the second research question, two objectives were formulated. In Sections 3.2 and 3.3 respectively these goals are explained in more detail. The goals derived from the second research question are:

- First: determine underlying goals of tools and build a functional framework, i.e. an integrated structure based on goals of relevant tools (from various disciplines).
- Second: determine which factors influence the applicability of tools and provide guidelines for selecting tools from the functional structure.

Although organizational causes do play an important role, they will not be the focus of the second part of this research. However, this does not mean that this area should not be the subject of further research: despite the attention given to these problems things still go wrong. In Section 6.6 the main observations and conclusions concerning organizational factors are discussed.

3.2 Functions of quality tools, the need for structure

The first objective of the remaining part of this research is to build a functional structure, based on the functions (goals) of quality tools. From the exploratory research we conclude that there are five reasons for using functions in providing knowledge for the application of quality tools:

- Functions allow determination of the necessity to apply a certain tool.
- Functions make it easier to understand when and why a tool is applicable.
- Functions give a better understanding of which techniques can be seen as alternatives in executing a function.
- Not all relevant activities for controlling and improving processes are covered by formal tools. It is better, therefore, to look at functions of techniques to get a complete overview.
- Functions give a better understanding of relationships between techniques. E.g. how to use a particular tool in combination with other tools. Thus it also enables integration of tools from various disciplines.

By providing them with knowledge of the functions of tools, users can be supported in making more effective use of existing quality tools. Using the metaphor of a toolbox, the current situation concerning quality tools resembles a toolbox in which various tools are placed in a disorderly way. At best there are a number of separate toolboxes containing tools from one discipline or program. The first step towards making more effective use of these tools would be to define one integrated toolbox and to divide it into sections containing similar tools. The functions or goals of a tool can be used to define the structure of these sections. Thus groups of alternative tools are defined and insight is given into their function. Using the metaphor of a toolbox, various kinds of screwdrivers and spanners could be grouped in a section based on their function: fastening with nuts and bolts, and screws; various glues could be grouped in another section based on their function: fastening with glue. Together they could be put in one part of the tool box because they have a common goal, namely fastening. Within the functional structure the sections should also be arranged in a logical way, so that the coherence becomes clear.

Note that functions of tools can be formulated on multiple (hierarchical) levels. On a high level, for instance, the functions of tools can be divided into process control and process improvement. Within the area of process control, (sub)functions would be controlling process output and controlling process factors (see Section 2.2). When functions are defined on a more detailed level, the groups of tools within each function will become smaller. The functional structures should be detailed enough to support the selection of tools, but should not become too detailed and thus impractical.

As illustrated in Section 2.3, a tool may have multiple functions. E.g. a Control Chart can be used for three functions: process control, process analysis and product

assurance. Thus it is possible that a certain tool will appear in more than one place in a functional structure.

The functional structure does not only help to make more effective use of *existing* tools: having a functional structure will also support users in determining how to react to new tools that are developed. Using the framework, one can determine whether new tools are completely new or resemble existing tools. The relations with other existing tools can also be determined. From a scientific point of view, it may be interesting to observe gaps and overlaps within the framework in order to find opportunities for the development of new tools and new applications of existing tools.

By trial and error, people may gain experience and implicitly discover some of the sections in the tool-box. To stimulate this, one can encourage the intended user to try harder and provide more time to find out which tools can best be used. However, this is inefficient and there is a danger that users become disappointed or continue with daily practice before they are able to gain insight into the contents of the toolbox. Therefore it is preferable that the necessary knowledge on functions of tools is provided (through improved training).

The next step in making more effective use of a toolbox would be to define guidelines for determining which sections and which tools to use in a certain situation. This is the second goal, described in the next section.

3.3 Contingency factors: the applicability of tools

As the case studies in Section 2.3 show, there is not a single best practice for selecting relevant functions and tools from a functional framework. Various situational characteristics influence the way tools within the functional framework should be selected; these characteristics are called contingency factors (see e.g. [Dessler, 1976] for a reference in the field of organization theory, or [Melan, 1998] for a reference in the field of quality management). Therefore the second objective of the remaining part of this research project is to find contingency factors and to provide guidelines for choosing tools within the functional framework.

Contingency factors influence the selection of tools in two ways. Firstly, contingency factors determine the necessity of fulfilling a certain function or tool. This group of contingency factors will be addressed as stimuli. Secondly, contingency factors may influence the possibilities of using a tool in a specific situation. These contingency factors are addressed as constraints. Both types of contingency factor determine whether a tool is applicable in a particular situation. Contingency factors also influence the methodology to be used for a tool. However, this research will not be directed at giving guidelines for tailoring the methodology of a tool to a particular situation.

The case studies reported in Chapter 2 show that various technical circumstances influence the application of quality tools. In Figure 3.1 examples of these contingency factors are grouped into stimuli and constraints. Although in determining contingency factors focus will be on technical circumstances, other types of factors are not excluded beforehand.

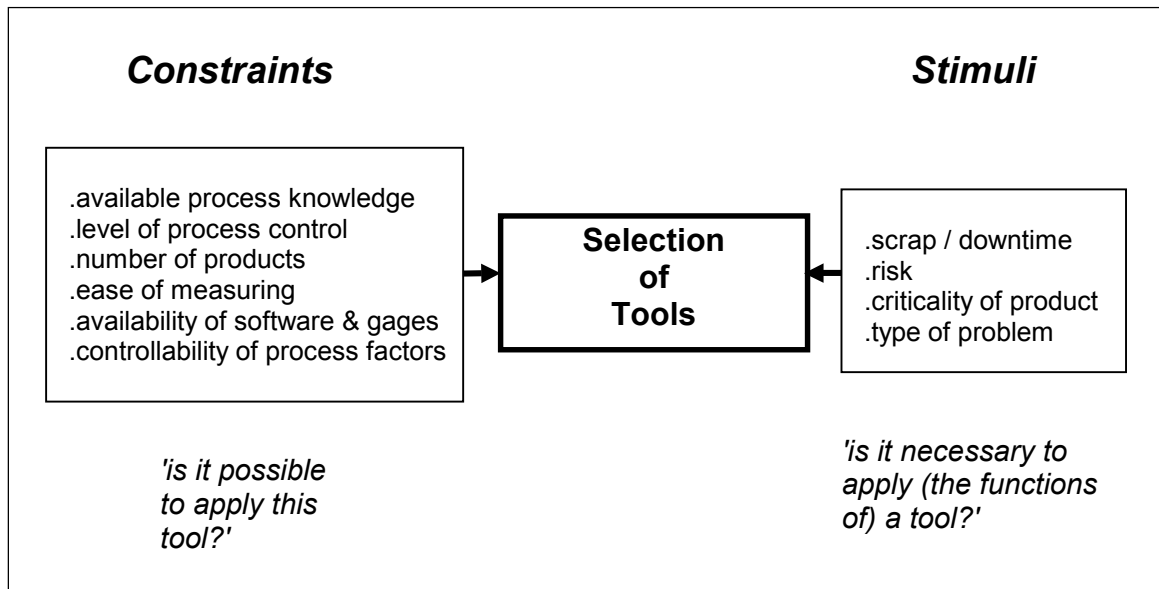


Figure 3.1: Examples of contingency factors that influence tool application

Contingency factors differ in terms of changeability, i.e. situational factors can be relatively easy to change on one hand, or almost impossible to change on the other hand. The changeability of contingency factors can be used when implementing a tool, e.g. management can provide the necessary software or gages to enable the use of a certain tool. However, the changeability also implies that the fit between a situation and a tool is subject to change. Not only external influences change situational factors. Also the application of a tool itself can cause situational characteristics to be dynamic. Therefore, the selection of suitable tools is not a once-only activity, but needs to be evaluated and adjusted over time.

3.4 Conceptual model for decisions in applying tools

The goal of this research is to support practitioners in making effective use of existing quality tools. Based on the answers to the initial research questions, it was decided to do this by providing a functional structure for tools and guidelines for selecting tools in this structure. This knowledge will help users to define a set of tools that fits the particular situation. To prevent the symptoms observed in Chapter 2, users must effectively make four kinds of decision when defining a set of quality tools. The following types of decision can be derived from the problem clusters reported in Section 2.4:

- Determine relevant functions.

- Select suitable tools (to fit function and situation).
- Define proper relations between sets of tools.
- Determine methodology for selected tools (that fits situation).

This research supports the first three decisions listed above. Only the fourth type of decision, concerning methodological problems, is not supported. Apart from providing insight into the goals of a tool, no support on the level of single tools (such as a clarification of the methodology) will be provided. Yet tailoring a single tool to a specific situation requires advanced methodological knowledge, but also an ability to recognize a situation requiring the tailoring of a tool. As such, the results of this research will provide support for decisions on the inter-tool level, i.e. in choosing an appropriate set of tools to improve or control a production process. In Figure 3.2 the various decisions that must be made in order to design/select a successful set of tools are combined into a conceptual model. The decisions supported by this research are marked.

In literature few comparable models were found. Riis et al. [Riis et al., 1997] introduced a conceptual model that considers situational characteristics of an enterprise to determine the optimal (TPM) maintenance profile. However, this model is used to define this profile at a company level and is therefore formulated on a higher level of abstraction. Deslandres and Pierreval [Deslandres and Pierreval, 1991] carried out research on the application of quality tools. They describe a computer application based on a classification of a few formal SPC-techniques. However, they do not give a framework with relationships between functions. Their paper concentrates on the information system rather than the information to be put into the system. Experiences in using this system are not reported.

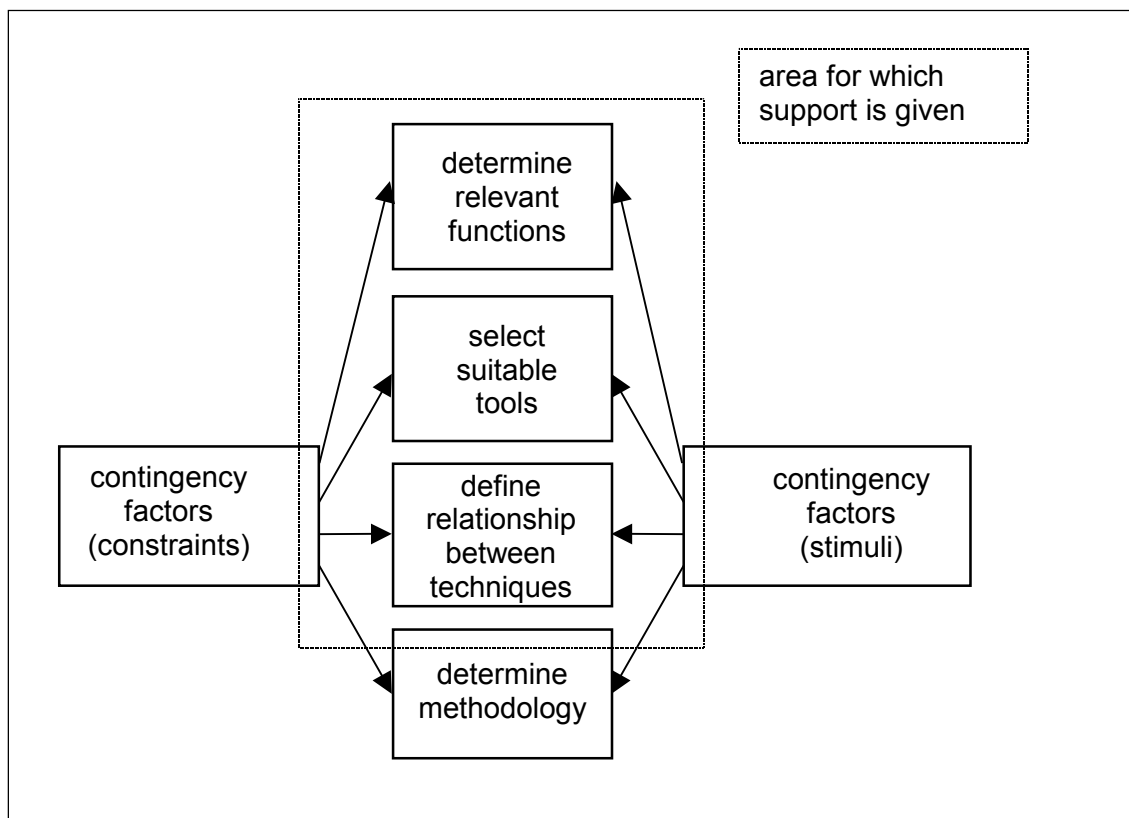


Figure 3.2: Conceptual model for decisions in applying quality tools

Thus the exact form in which knowledge should be provided to support decisions was not specified. It was decided that this research will not be directed primarily at developing of a (software) system. Instead, the research will be focussed on generating relevant knowledge and insight. The exact form in which this knowledge should be presented in order to become effective in practice can be determined afterwards.

In Section 6.5 the possibilities of using the results presented in Chapters 4 and 5 for decision support are discussed in more detail.

3.5 Research method for second part

The second part of this research aims at finding functional structures and contingency factors for quality tools. As for the first, exploratory part of this research, a method had to be defined for collecting relevant knowledge to achieve these goals. Three options were considered:

- survey among companies applying tools,
- case studies among companies applying tools,
- review of literature on quality tools and applications.

Concerning the first goal (building a functional framework), it appears to be unnecessary to collect new empirical knowledge on the application of tools. Although exploratory cases can be used to provide insight into relevant functions in practice, it is likely that functions can be derived from analyzing methodological descriptions of tools and practical experiences as reported in literature. Integrating these functions will be based on logical considerations.

Concerning the second goal (deriving contingency factors), multiple case studies were considered as a research instrument. It would concern an extension of the case studies that are part of the exploratory research. However, since the goal of this research is to study a large set of tools (complete toolbox), it would be nearly impossible to gain direct empirical knowledge within the time span of this research project. The following problems were encountered when considering multiple case studies:

- long throughput time of implementation of a tool in practice,
- deriving contingency factors for the whole range of process control and process improvement tools would require studying the application of multiple tools in various environments, without knowing in advance which environments should be chosen,
- when studying the effect of tools in a certain situation it can be hard to isolate the influence of contingency factors from other factors such as the support and effort of users.

Questionnaires were considered as a more efficient alternative for case studies. However, the drawbacks discussed in Section 2.3.1 (e.g. lack of detail, giving desirable answers, lack of understanding of own problems) are even more serious when finding

contingency factors. Problems in isolating the influence of contingency factors and other factors can also be expected when using surveys. (An illustration of these problems can be found in research by Mann and Kehoe [Mann and Kehoe, 1993, 1994]. This research was based on a survey and structured interviews among leading companies. An example of the type of questions was asking whether or not a certain tool is applied. Since a higher manager was often the respondent, this type of study does not provide insights on the level of the actual application of tools. Mann and Kehoe suggest the use of case studies to get more detailed information [Mann and Kehoe, 1994]).

Based on the above considerations it was decided to use a combination of literature review (to collect experience in the application of single tools or tools from one discipline reported by others), and insights from the exploratory case studies (to experience mechanisms and contexts of applications in business practice for some tools). One could argue that using existing literature as a main source of information would not bring much additional knowledge. However, this research is intended to improve the *accessibility* of the vast amount of knowledge on quality tools spread throughout the literature. By using the framework of functions and contingency factors when reviewing literature, the (scattered) descriptions and experiences reported can be used, logically combined and analyzed to generate knowledge for decision support. Thus this study is based on a synthesis of existing experiences, rather than collecting new experiences (see quote [Maddox, 1999]). In line with this, the goal is not to improve the functionality of single tools but to provide better insight so that more effective use can be made of the existing functionality of multiple (coherent) tools.

3.6 Structure of Chapters 4 and 5

Chapter 4 will address tools in the area of process control, whereas Chapter 5 deals with tools for process improvement. Although process control and process improvement are treated separately, in practice there is a strong relationship between these two main functions. Process controls are one of the possible outcomes of an improvement project; in other words, it may be necessary to use improvement tools before controls can be defined. In Chapter 5 this relation is addressed in more detail.

In each chapter, the field of relevant tools will be described first, based on a review of literature (completed with relevant insights from the exploratory case studies). This description serves as an inventory of tools and elements that can be used for the functional framework. Subsequently, the main differences and overlaps of the reviewed tools are discussed. On the basis of this discussion, the functional framework is derived and explained. Then the main differences in terms of contingencies are explained and guidelines for selecting tools from the functional framework are given. Each chapter is concluded with a discussion of the possibilities for using the framework and general conclusions.

3.7 Scope of tools and processes considered in this research

Although the area of quality control and improvement has spread to non-production areas within companies and also to non-production companies, this research focuses on production environments. We will consider discrete production, i.e. parts production and assembly processes, because in this type of production various disciplines can be observed and the overlap of different disciplines is clearly visible. This research considers tools as applied to a single production process, i.e. with one output point. Although such a process may be part of a series of interrelated production processes, the application of quality tools will not be studied on this higher level. Tools will not be studied on the level of a single tool, but on the operational level, i.e. on the level of sets of tools that are used to control or improve a production process.

As indicated in Section 2.1, there is a wide range of quality tools. Initially this research was directed at Statistical Process Control tools. It turned out that tools associated with Statistical Process Control were used for other functions than merely the control of production processes. Therefore the scope of the tools considered was broadened. Yet, to ensure that the research goals could be achieved within the time frame of this research project, the scope was limited to process control tools and process improvement tools. Other areas such as new process (and product) design are not considered in this research.

4 Structure and applicability of Process Control Tools

Part of this chapter was previously published in a paper on an integrated approach for process control [Schippers, 1998c].

4.1 Introduction

The starting point of this research was the application of Statistical Process Control (SPC) tools. Thus the work described in this chapter started focussing on structuring SPC tools used to control production processes. SPC traditionally uses output measurements to monitor the stability of a process by detecting the presence of causes of instability, called special causes or assignable causes (see e.g. [Shewhart, 1931] and [Montgomery, 1996]). However, as a result of the trend to strive for prevention instead of detection (see Section 2.1), SPC is shifting from controlling variation in product characteristics to controlling process factors that cause this variation [Scott and Golkin, 1993]. The goal of this shift is to detect and resolve problems in the process before they can lead to disturbances in the product. In some cases statistical tools such as Control Charts can be used to control process factors. An example is using a Control Chart to monitor the concentration of a tin bath when making diodes [cf. Does et al., 1999, p. 99]. However, Chapter 2 shows that in other cases alternative tools, such as a periodical maintenance check and automated controls, are used to achieve process control. Since these tools are part of disciplines other than SPC, the scope of the tools under study was broadened.

It turns out that the control of production processes is not only the subject of Statistical Process Control (SPC) but also of other disciplines such as Total Productive Maintenance (TPM) [Nakajima, 1988], Automated Process Control (APC) [Stephanopoulos, 1984], and Poka-Yoke [Shingo, 1986]. In this research we focus on these disciplines, because they are the most well-known and frequently used disciplines directed at process control. Although each discipline has a specific approach to process control, there is a great deal of overlap between these disciplines because of their common goal: to control disturbances in a production process. Despite this overlap, these disciplines are traditionally separated, both in science and in business practice.

In practice each discipline is often initiated by separate departments: SPC by the quality department and production; TPM by the maintenance department; APC and Poka-Yoke by the engineering department (cf. [Palm, 1990] for SPC and APC). In these cases efforts to improve control tend to be limited to tools from one of these disciplines, or where controls from different disciplines are used, they are often not related to each other. This may result in single, or separate parallel mono-disciplinary applications. Since the tools from various disciplines are partly overlapping, but also partly additional alternatives, this situation is not desirable. E.g. limiting oneself to the

tools of SPC implies the risk that the ultimate goal is to implement a Control Chart, while tools from other disciplines may be more appropriate.

Also in literature the overlap of process controls did not result in an integrated approach to process control. Although literature from the separate disciplines partly claim the same area, most of the publications from these disciplines (referred to in the next section) hardly mention each other. An exception is the interest in literature on SPC in the field of APC. The integration of SPC and APC has been the subject of several papers [see e.g. Palm, 1990; Box and Kramer, 1992; Montgomery et al., 1994; Montgomery and Woodall, 1997; Box and Luceño, 1997; Göb, 1998]. These papers are largely directed at integrating tools from APC and SPC into one quantitative tool, hereby focussing on the mathematical aspects of integration. Although the usefulness of these efforts is not disputed here, we do not aim to contribute to these discussions and only refer to these papers when characterizing APC and SPC. On the subject of integrating SPC-related techniques and TPM very few papers exist [Jostes and Helms, 1994; Dar-El, 1997]. Since the discussion in these papers is limited to management aspects, we will not refer to them in the remaining part of this chapter.

In this chapter we will derive a functional framework that integrates control tools from various relevant disciplines (first objective), and provide guidelines for selecting tools within the framework (second objective). Based on a review of literature, Section 4.2 describes the main tools and functions of the four disciplines, and discusses typical ways in which functions are fulfilled. Section 4.3 summarizes the results of Section 4.2 in order to discuss the overlap and differences. In Section 4.4, the Integrated Process Control model is derived as a functional framework (for process controls) that supports an integrated approach to process control. In Section 4.5, the factors that determine the selection of controls are discussed. In Section 4.6, these factors are translated into guidelines for selection of tools. Section 4.7 discusses the results of this chapter.

4.2 Review of literature on tools for process control

The common goal of SPC, TPM, APC and Poka-Yoke is to reduce and control disturbances in a process. To achieve this, they rely to a great extent on defining activities for monitoring and adjusting production processes. These activities are defined as 'process control tools' or in short 'controls'. This section describes the controls of the four disciplines, based on a review of literature. The goal is not to give a full description of these controls, but to address their functions, the typical ways of fulfilling these functions, and their strengths and limitations. In Subsection 4.2.5, the role of changing process and product specifications as an alternative to controls from these disciplines is discussed briefly.

4.2.1 SPC controls

The three basic SPC control tools are the Control Chart, the Out of Control Action Plan (OCAP) and the Process Capability Study (PCS) (see Section 2.1). The main goal of SPC controls in production is to achieve product quality by controlling the stability of the underlying process.

The Control Chart can be used to monitor the stability of a process. In SPC, a stable process is defined as a process with only common (process inherent) causes of variation, resulting in a stable variation pattern with a predictable outcome of one or more charting characteristics (see also Appendix 3 for a further discussion). Typically these characteristics are the location (e.g. mean) and a spread (e.g. standard deviation) around this location. Although the name of the tool suggests otherwise, the Control Chart is merely a monitoring tool: it gives a signal in the case of an unstable process. If the process is unstable, it is assumed there are special causes of variation that are not process-inherent; this will be detected as an 'out of control'. A Control Chart can be used to monitor a measurable process factor (e.g. a tin bath concentration) but in general Control Charts are used to monitor an output characteristic (in most cases a single characteristic is considered).

To monitor the process, samples of product or process characteristics are taken with a certain frequency (e.g. hourly). Statistical rules are used to compare sample means and spread with those expected from a stable process. Through the definition of a stable process underlying the statistical rules, and through the sampling strategy used, the Control Chart allows for variations that follow a (constant) probability distribution. Small shifts in the mean or spread of a process are not always detected. Although, besides the Shewhart Control Charts, more sensitive types of charts, such as CUSUM charts and EMWA charts, have been developed (see [Montgomery and Woodall, 1997] for an overview), out of controls will only be detected by Control Charts in the case of rather large disturbances, that take the form of shifts and trends [cf. Palm, 1990; Göb, 1998]. Research has also led to the development of Control Charts that are less sensitive for certain types of variation, thus allowing variation that follows a certain model (e.g. a known tool-wear trend (see e.g. [Montgomery 1996, p414]), extra batch-to-batch variation [see e.g. [Does et al., 1999]) or autocorrelated data (see e.g. [Wieringa, 1999]). Control Charts are typically used in cases where these disturbances occur with a low frequency.

To actually control a process, a signal from a Control Chart should be followed by an action that identifies and removes the disturbance (i.e. the special causes of variation). SPC typically relies on human action to determine causes of instability and to adjust the process by removing these causes. If the Control Chart is used to monitor the stability of an output characteristic, it is actually used to control a process as a whole (as opposed to controlling a specific process factor). The output characteristic can be influenced by various process factors, e.g. material, machine, tools, machine settings, human factors, et cetera. The Out of Control Action Plan (OCAP, see Section 2.1), can be used to provide guidelines for determining causes and to specify actions. Thus the

control actions can be made more specific for certain important process factors (human interpretation and intervention are still necessary).

Although the Control Chart is often (mis)used to assure product quality (see e.g. Section 2.3), this is not the primary purpose of the tool, and it is only possible under specific conditions. Since stability of a process does not mean that all products are within specifications, the Process Capability Study (PCS) is used as a supplementary tool (in addition to Control Charts). It is used to determine whether the stable process results in products that fall within the specified tolerances (LSL and USL), i.e. to assure product quality. This is achieved through relating the process inherent variation (based on the individual measurements used for the Control Chart) to product tolerances. This is done off-line, as opposed to Control Charts where the need for action is determined while the process is running. Although not a standard application of the tool, the PCS can also be used for (off-line) control of process variation (see Section 2.3).

In Figure 4.1 a typical application of the SPC control tools is depicted schematically.

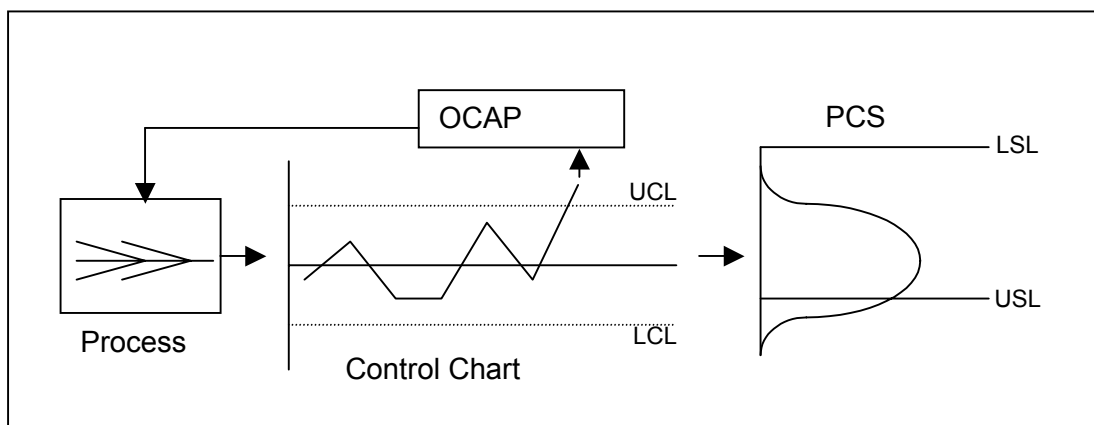


Figure 4.1: Schematic representation of typical application of SPC control tools

Besides the above tools for controlling production processes, SPC also contains a tool that can be used for evaluating a measurement process: the R&R study (Repeatability and Reproducibility study) [see e.g. Does et al., 1999]. The main goal of this tool is to establish and evaluate the variation in a measurement process (compared to the tolerances) in order to ensure that measurements used for e.g. Control Charting are reliable.

Recent publications stress that the power of SPC is not the application of statistical tools, but the 'application' of Statistical Thinking [Hoerl, 1995; Schippers and Does, 1997]. In short, Statistical Thinking is based on the awareness that all work occurs in processes (including non-production processes), that all processes are subject to variation, and that understanding, controlling and reducing causes of variation are the key to improvement. This way SPC becomes a concept that is very broad and that can be used throughout the organization. In this chapter, however, we will only discuss SPC control tools used in production, as described in SPC textbooks (see e.g.

[Montgomery, 1996]). SPC tools used for process improvement (such as Control Charts used for analysis) are addressed in Chapter 5.

4.2.2 TPM controls

TPM [Nakajima, 1988; Willmott, 1993; Riis et al., 1997] is directed at improving the utilization (effective use) of production installations. The utilization is measured with the Overall Equipment Effectiveness (OEE). This OEE ratio measures the reduction of the effective use due to six losses. These losses include losses due to downtime (1: breakdowns, 2: setup and adjustment time), speed related losses (3: idling and minor stoppages, 4: reduced speed), and quality losses (5: defects from running process, 6: defects from startup). The main goal of TPM is to reduce and prevent the six losses by controlling production installations, i.e. the equipment of a production process. To improve the utilization of an installation, TPM concentrates on defining various types of maintenance and cleaning activities for machines and tools. Thus both time-related problems and quality problems, caused by disturbances in machines and tools, are prevented.

Although there is a relation with the control of a production process, the OEE is not considered as a process control, for the following reasons. Firstly, although the OEE is influenced by the level of control of the process, the loss through setup and adjustment time is also influenced by non-process related factors such as production scheduling. Secondly, the quality losses in the OEE are accumulated for all product characteristics and based on a good/bad classification (as opposed to SPC). Thirdly, the OEE is not measured very frequently, typical frequencies being once a week or once a month. Often the OEE is calculated for a series of process steps rather than a single process. Thus, the OEE is typically used on a higher level than the control tools considered in this chapter: it could e.g. be used to monitor the performance of various controls, rather than to actually control a process. Fourthly, although a relevant part of the performance of a process, disturbances related to time-related output performance are not included in this research. (In Section 4.7 we will discuss the issue of time-related performances in relation to process control.)

However, maintenance activities, that also form an important part of TPM, are included in this research as part of the area of process control tools. These activities are used on a lower level than the OEE, i.e. on single machines or machine parts. The actual interventions in the machine or tool can take the form of repair, adjustment or replacement of parts. Of course maintenance is not exclusive for TPM, it is also used outside a TPM program. However, TPM is a popular and recognizable program with elements that are very relevant for the area of process control. Therefore it appears useful to position its controls within the framework to be derived in Section 4.4. Figure 4.2 gives a schematic representation of TPM. The three types of maintenance are discussed below [cf. Willmott, 1993, p.12].

The first type, corrective maintenance (sometimes also addressed as breakdown maintenance), is based on taking actions when one observes that an installation is not working properly (e.g. produces poor products or breaks down). Corrective maintenance is typically used in cases where breakdowns are rare and unpredictable, and the consequences are moderate. It is, thus, based on a measurement of the output of a process. The measurement is often not part of the corrective maintenance procedure itself; the actions taken are directed at machines and tools. Within TPM, corrective maintenance is considered as a reactive (i.e. detection-based) approach, which should be replaced by one of the activities described below.

Another group of maintenance activities is based on periodical intervention in the installation, regardless of the state it is in. This is called preventive maintenance or time-based maintenance. The frequency is based on knowledge of the deterioration pattern of the installation. The chance or influence of deterioration is assumed to become larger in time, i.e. to follow a trend. This deterioration pattern should be adequately known or one should choose a maintenance frequency high enough to prevent disturbances. Preventive maintenance may be appropriate in cases where it is more expensive to determine the exact state of the machine (part) than to repair or replace a part. This approach may also be appropriate in cases where the trend of the disturbance is accurately known, based on experiences in the past. Of course, product tolerances should be wide enough to allow for certain deviation due to the trend.

A third group of maintenance activities is called situational maintenance or condition based maintenance. It is based on knowledge concerning the relation between certain characteristics of the process or product and the magnitude or chance of malfunctioning. Certain characteristics of the installation are measured (periodically) to determine whether actions are necessary (refer to the periodic measurements of powder flow in Case D of Section 2.3.3). The characteristic is compared with a technical specification that represents a condition that does not yet give poor performance, i.e. serves as a warning limit. If the characteristic is outside the warning limit, the installation is repaired or adjusted, thus preventing unnecessary interventions in the process.

Another activity that is part of the TPM approach is maintenance prevention. Maintenance prevention can be achieved by periodical cleaning, lubrication and bolting, or by modification of the equipment, i.e. 'to design out problems' [cf. Willmott, 1993, p12]. Both activities are directed at reducing or removing the deterioration pattern. Periodical cleaning, lubrication and bolting are seen as the task of operators (autonomous maintenance). Maintenance prevention through modification should be part of new product development, but can also be the result of frequent repairs of certain parts of the machine during production. In the case of repeated actions in a certain part of the machine, one may look for possibilities to avoid this, e.g. by using a material or construction that is less subject to wear. Although these one-time changes to the process activities can not be addressed as a control, they are an important alternative. See Section 4.2.5 for a further discussion of one-time changes to the process.

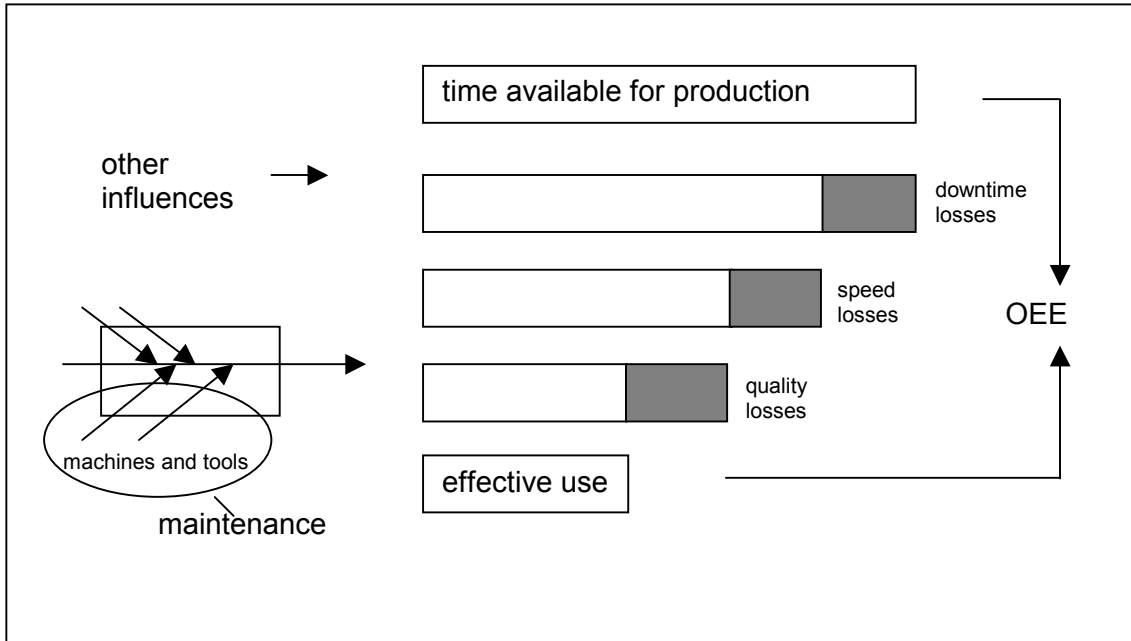


Figure 4.2: TPM OEE and maintenance controls

Like SPC, TPM has become more than a set of tools. It has been transformed into a concept, i.e. a way of managing processes or even production companies [Nakajima, 1988; Willmott, 1993]. The involvement of various departments, especially the involvement of workers on the floor, is an essential part of TPM. In this chapter, we will concentrate on the controls of TPM, i.e. various maintenance and cleaning activities, that are described in TPM text books (see e.g. [Nakajima, 1988]). For a further discussion of organizational factors we refer to Sections 4.7 and 6.6 of this thesis.

4.2.3 APC controls

Automated Process Control (also called Engineering Process Control, EPC) consists of automated feedback and feed-forward loops. The main goal is to compensate for the effect of disturbances in the process, in order to keep the process on target. It is typical for APC that it does not change those factors that are disturbing the process (this as opposed to SPC that aims to remove the causes of disturbances [cf. Palm, 1990]). E.g. in case of disturbances in the material input, not the material but the settings are changed to compensate for this disturbance. To control the process, very frequent or continuous measurements of a product or process characteristic are taken and compared with a target value. The observed variations are compensated by automatic changes (without human intervention) in controllable process factors (i.e. the settings of the process). The necessary actions are determined by an automated controller. To configure the mathematical models in the controller, it is necessary to know the relation between process settings and process output.

APC feedback loops are used most often. Feedback loops can be based on product measurements or on the measurement of process conditions. When a deviating

product is measured, the controller determines a change in the settings of the process that will compensate for this disturbance, in order to ensure that the succeeding products will deviate. This type of feedback is based on (auto)correlation, i.e. the value of a measurement of product number 'n' or a measurement on time 't' is supposed to be (partly) correlated with the next product (n+1) or the measurement on t+1. Thus it is possible to reduce a deviation in 'n+1', based on a deviation found in 'n'.

The speed of alterations in the direction of changes in a characteristic (i.e. upward and downward trends), should be relatively low compared to the speed of measurements and interventions, otherwise the autocorrelation cannot be used. Moreover, the magnitude of disturbances should stay between certain limits to prevent the desired compensation going outside the range of the controller, i.e. the desired change in settings is not technically possible. Through the use of automated on-line or very frequent measures APC can be used to compensate for continuous fluctuations in the mean. The disturbances compensated using APC are typically disturbances in materials, machines, tools and environment. Through the automation of control loops, APC can be used for complex intervention rules, e.g. to deal with dynamic process behavior, to be able to make very frequent changes or to be able to intervene in multiple settings [Palm, 1990].

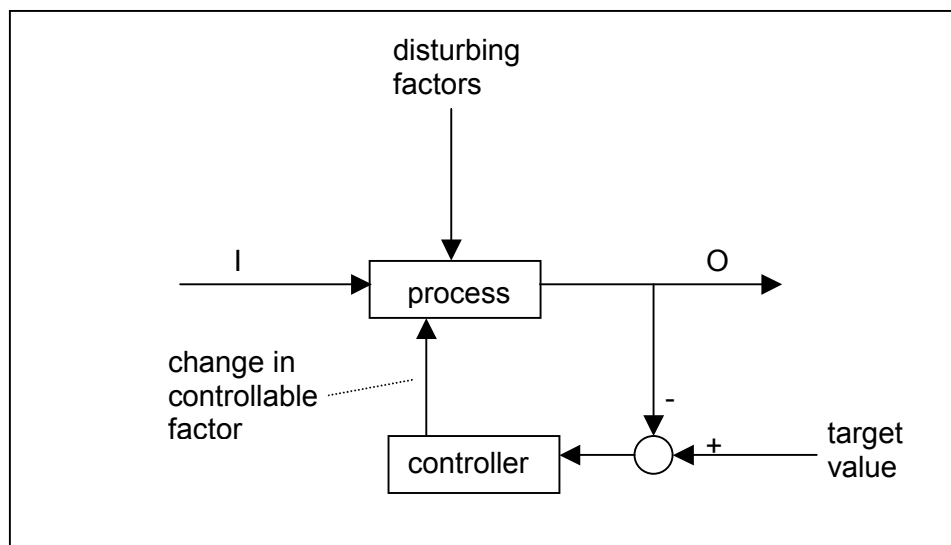


Figure 4.3: Schematic representation of APC feedback loop

Besides feedback loops also feed forward loops are possible; for instance the setting of drying time or oven temperature based on measuring the humidity of material input. When using feed-forward loops it is not only possible to use autocorrelation but also to tailor the settings of the process to a specific input item.

Automated controls are mainly applied in the chemical industry, where variation is often largely auto-correlated and (chemical) process models are present [cf. Stephanopoulos, 1984]. However, automated control loops are also used in production machines for discrete products (part production). APC can be seen as part of a concept with a very broad working field, namely Control Theory (CT). CT also includes control

loops that are not automated, continuous, or directed at drifts of the process mean. In this paper we will consider APC controls as described in standard APC textbooks (see e.g. Stephanopoulos, 1984).

4.2.4 Poka-Yoke controls

Poka-Yoke was popularized by Shigeo Shingo [Shingo, 1986]. Poka-Yoke stands for 'preventing inadvertent errors'. Often it is translated as 'mistake proofing', since the main purpose of Poka-Yoke is to prevent or control disturbances caused by mistakes and omissions of operators. This type of error typically occurs in cases where vigilance and concentration of operators is required, such as assembly processes. The relevance of mistakes (as opposed to problems due to variation) is illustrated by [Hinckley and Barkan, 1995].

The essentials of Poka-Yoke are [Hirano, 1988] :

- *100 % inspection*: Instead of samples or other periodical activities, so that the results of mistakes, which often are incidents, can be detected.
- *Inexpensive solutions*: To prevent high inspection costs, Poka-Yoke typically uses inexpensive solutions. Since mistakes often result in a relatively large deviation, they can be detected without very precise measurements.
- *Direct action if a problem is detected*: To prevent a detection oriented approach that does not pay attention to causes of variation, Poka-Yoke is based on immediate action after a problem has been detected.

There is no real Poka-Yoke methodology. Popular textbooks on Poka-Yoke largely consist of a wide range of examples [e.g. Hirano, 1988]. Poka-Yoke typically deals with human errors such as using wrong parts, omitting operations, wrong positioning (e.g. upside down) et cetera. Poka-Yoke controls can take the form of a device or sensor measuring the process or the product (see Figure 4.4a and 4.4b), but also of a one-time change in the process or the product (as depicted in Figure 4.4c). Poka-Yoke uses inexpensive 'hardware' solutions; thus one should be able to have a 100% check without manual measurements or other activities that require large efforts and continuing attention of operators. The goal of a 100 % check is to be able to detect incidents, which are typically the result of human error.

Poka-Yoke solutions can be process-oriented or output-oriented. Output-oriented Poka-Yoke devices may be solely for product assurance, e.g. a device that filters out poor products without further alarm (See Figure 4.4b). In other cases the goal is to sound an alarm as soon as a poor product is produced, not only to remove or rework this poor product, but also to warn the operator that there was a disturbance in the process that should be removed. In most cases the actions are not prescribed explicitly, apparently because the disturbing factor and the action required to remove the disturbance will be clear (in many cases the disturbing factor will be the operator himself). Thus Poka-Yoke can be used to detect relatively large disturbances or

mistakes. The stability of the process in terms of small changes in mean and variation cannot be monitored or controlled.

A Poka-Yoke solution can also be directed at a specific process factor. Thus it may detect the occurrence of a disturbance and prevent a disturbance in the output of the process. In these cases the action will be directed at this process factor. Although Poka-Yoke is mainly oriented to human-related process factors, examples of Poka-Yoke controls for other process factors can also be found in text books. An example is a Poka-Yoke control that sounds an alarm and shuts down a pneumatic spanner system when the air pressure becomes too low, thus preventing that nuts are not fastened tight enough without being noticed [Hirano, 1988]. Some Poka-Yoke solutions are directed at a special kind of process factor: a process condition, which is rather a state of a running process than a part of the definition of a process. An example would be the detection of the presence of a part in a die. Process conditions are the result of other process factors and cannot be directly acted upon (see Appendix 3).

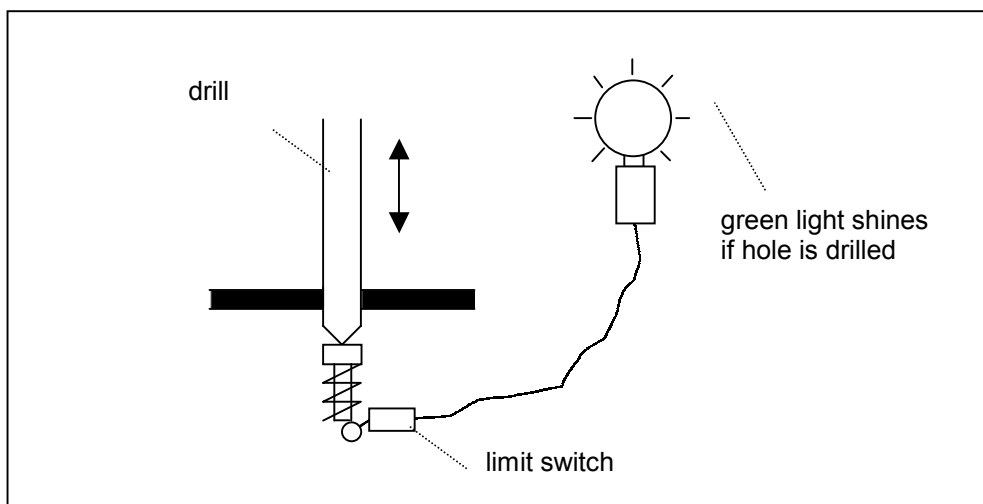


Figure 4.4a: Example of Poka-Yoke control in a drilling process

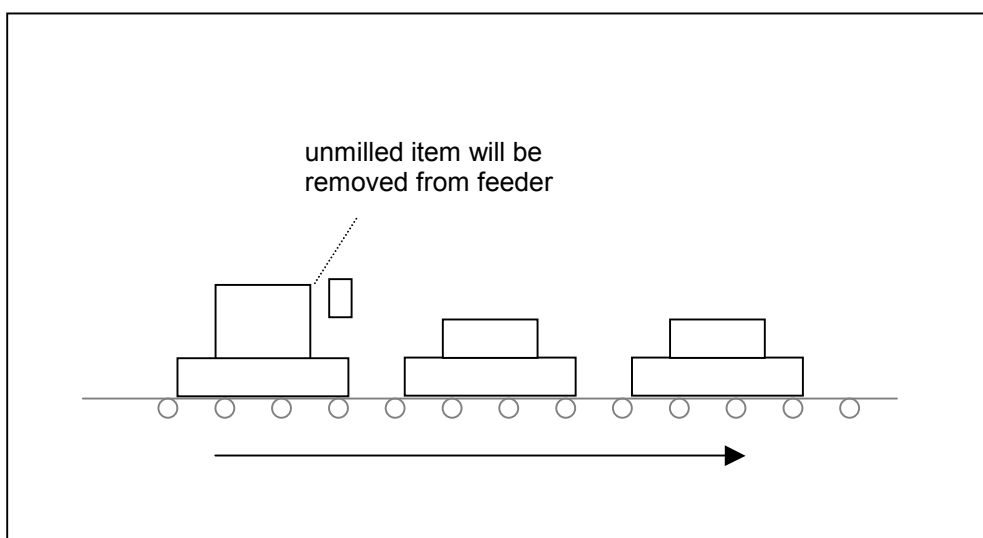


Figure 4.4b: Example of Poka-Yoke for product assurance

There is a group of Poka-Yoke solutions that involves a structural change in a product or a process rather than a control (i.e. an activity that includes a measurement and an action). An example is the change of the holes in the bracket depicted in Figure 4.4c. The role of this type of change is discussed in the next sub-section.

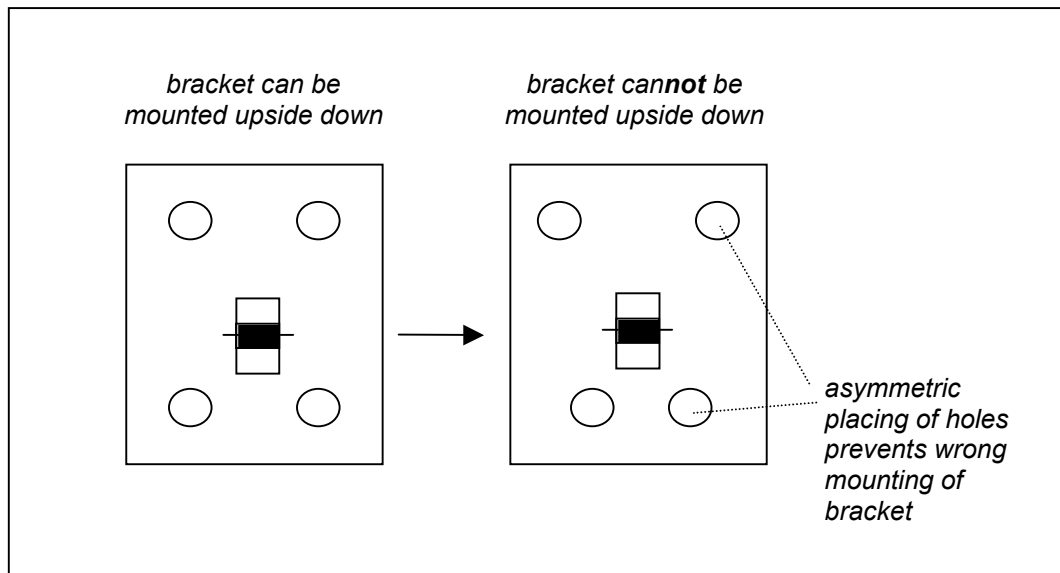


Figure 4.4c: Example of Poka-Yoke irreversible action for bracket

Because of the use of cheap solutions that enable a 100% measurement, Poka-Yoke is (only) able to detect rather large disturbances (which are typically the result of mistakes) such as a *missing* hole instead of a hole with a slightly deviating size. Through the development of sensors that are cheap and more sensitive [cf. Robinson and Miller, 1989], smaller changes may also be detected. Thus the difference with other disciplines becomes smaller. In cases where sensors are used, Poka-Yoke resembles APC controls. Although the (automated) measurement may be the same, there are some differences. One difference is that APC uses a measurement to change (settings of) the process automatically, whereas Poka-Yoke is only intended to stop the process or give a warning, that should be followed by human action. Another difference is that Poka-Yoke is typically directed at incidental shifts or abnormalities (i.e. discrete incidents) whereas APC is directed at autocorrelated fluctuations.

4.2.5 The role of structural changes as an alternative for process controls

The purpose of a control is to reduce or control disturbances in a process. This is achieved by taking measurements from the process and by making adjustments in the case of disturbances. However, a control is not always the optimal means to achieve this goal. An important alternative for using a control is to change the definition (specification) of a process or a product in such a way that the disturbances will not occur or will not influence the output of the process. This type of improvement is called a structural change (also called an 'irreversible action' [cf. Shainin, R.D., 1993]).

Some of the activities within the disciplines discussed take the form of a structural change. For instance, when a machine part is subject to wear, it may be possible to prevent this by producing this part from another material instead of defining a control such as a preventive maintenance scheme (see Section 4.2.2 on TPM). Also the Poka-Yoke solution shown in Figure 4.4c (in which the definition of the product is changed) is an irreversible action. Another example of an irreversible action is to change the standard settings of a process in order to reduce variation (see Chapter 5).

If possible, this type of structural solution is even preferable to a control, since the latter requires continuing effort and attention to measure the process and take feed-back actions. Only those problems that cannot be solved by means of a structural change (for technical or economical reasons) should be controlled using a control tool. Thus one could say that the best way of controlling disturbances is not by using a control tool but by applying a structural change. In the remaining part of this chapter the structural changes are not considered. However, in Chapter 5, both structural changes and controls will turn out to be an important category of solution when improving processes.

4.3 Differences and overlap of process control disciplines

The descriptions in the previous section show that all four disciplines contain control tools, i.e. tools to monitor and adjust production processes. Within the area of process control both differences and overlaps can be observed. This can best be illustrated by characterizing and comparing the application areas of SPC, TPM, APC and Poka-Yoke on certain dimensions. In Table 4.1 the descriptions of the previous section are summarized by characterizing the disciplines considered on four dimensions. It shows that the four disciplines overlap for some dimensions, but differ on other dimensions. (Note that this is only a first characterization of process control disciplines, to illustrate differences and overlap of the disciplines reviewed in the previous section. The remaining part of this chapter contains a more detailed discussion.)

The first dimension used in Table 4.1 refers to the main control functions. Recalling the historical overview in Section 2.1 and the descriptions in the previous section, the main functions are: product assurance, output process control, and control of process factors. As Table 4.1 shows there is a large overlap in the main control functions within the area of process control disciplines. The next section discusses functions of control tools in more detail.

The second dimension concerns the process factors addressed by the controls of a certain discipline. Examples of process factors are material, machine, tools, operators and settings. Table 4.1 shows that, as far as the process factors addressed by each discipline are concerned, there are differences but also overlaps.

Discipline	Control Functions	Disturbances in	Disturbance Types	Measurements (Frequency of)
SPC	controlling process output; controlling process factors; product assurance	all process factors, but not specific	shifts and trends in location and spread	infrequent e.g. hourly
TPM	controlling process factors; controlling process output	machines and tools	longer term trends in the mean, deterministic	low frequency e.g. weekly
APC	controlling process output; controlling process factors	materials, machines, tools and environment	short-term, minor drifts in the mean; autocorrelated	very frequent-continuous e.g. seconds / minutes
Poka-Yoke	controlling process output; controlling process factors; product assurance	all process factors, but especially operators	mistakes / large deviations	continuous

Table 4.1: Overview of application areas of SPC, TPM, APC and Poka-Yoke

The third dimension refers to the type of disturbance typically addressed by a discipline. This depends mainly on the frequency of measurements (which is used as a fourth dimension) and the way the tools within the discipline determine whether a disturbance has occurred and an adjustment is necessary. The disturbance type addressed by each discipline and the related measurement frequency show little overlap. During this research it turned out that there was a need for a clear overview and classification of disturbance types. This led to the discussion of causes and classes of variation presented in Appendix 3. In the remaining part of this chapter we will refer to this appendix when addressing failure patterns.

On the basis of this initial comparison, one can conclude that the controls from each discipline are strongly related and may partly be considered as each other's alternatives or additions. There is a large overlap, especially on the operational level: The outcome of an analysis to improve process control might be a Control Chart (SPC), a maintenance task (TPM), or a sensor (APC or Poka-Yoke). This supports the integrated approach to process control in this chapter. Although not all controls that are used in practice are part of the disciplines discussed, the need to consider them as a coherent set of tools to choose from applies to all relevant controls.

The (set of) tools that should be selected depends on the situation at hand (see Chapter 3). Differences as can be observed in Table 4.1 cause that some tools are more appropriate than others for a certain situation. However, this does not imply that the selection of tools only involves the choice between disciplines. It is quite possible that within a company, or even within a process, tools from more than one discipline should be applied. The selection of suitable tools within a discipline is also not straightforward.

Regardless of the exact circumstances, approaching process control from one discipline implies the danger of sticking to the tools of this discipline and thus not finding the optimal solution for process control. Therefore, when defining, describing or improving the control of production processes, the disciplines should be seen as a coherent set of controls. However, there is no conceptual model that can be used to integrate and structure the large variety of controls. To achieve this, it is necessary to structure the field of process controls.

Recalling the research objectives, the first goal of this chapter is to derive a functional framework for process control tools, in which the relation between various tools become clear. Such a model should be able to position controls of various disciplines, regardless of the type of process. Furthermore, it should give insights necessary to determine to what extent controls are complementary or overlapping. Deriving such a model will be the subject of Section 4.4. The second goal of this chapter is to determine contingency factors for selecting control tools within the framework. This will be the subject of Section 4.5. Both sections are based on a further analysis of differences and overlaps between process control tools.

4.4 Deriving a functional structure for process control tools: the IPC model

To support an integrated approach to process control, we introduce the Integrated Process Control (IPC) model. Since the functions of process controls can be used to group controls and to give insight into their relation (see Section 3.2), the structure of the IPC model is based on functions of process controls.

Although all controls are directed at process control, not all controls are each other's direct alternatives. Thus, within the overall function of process control, there are groups of controls with different (sub)functions. A first categorization of process control functions was given in Table 4.1. Three control functions were distinguished: control of a specific process factor, output process control and product assurance. Although this division is suitable for a first classification of process control tools, it is not suitable as a basis for a functional framework. For this purpose we need a more detailed structure with a clear distinction between the categories. This is explained in the following paragraphs.

Recalling the definition of a control, it is an activity for monitoring and adjusting a process. The distinction between the three above-mentioned control functions appears to be based on differences in the action taken when a disturbance is detected, and differences in the 'point' in the process where measurements are taken. Thus a possibility for obtaining a more detailed and clear distinction is to categorize controls explicitly on these two dimensions (action point and measurement point). This means that the category 'control of a specific process factor' is further divided into categories

for each process factor. Analogously, controls can also be categorized by the point in the process where measurements are taken. Thus the distinction between controls based on output measurements and controls based on measuring a certain process factor can be made.

Based on these considerations it was decided to use the above dimensions as a basis for the IPC model. By using a matrix structure the cells of the IPC model represent a group of controls that takes measurement at a certain point of the process and intervenes (or acts) at a point of the process, which may be - but is not necessarily - the same. The two dimensions are discussed in Sections 4.4.1 and 4.4.2 respectively.

Other dimensions, such as the disturbance type, could have been used as a third or alternative dimension. Using the disturbance type would lead to a division that resembles the division between disciplines. In general, adding a third dimension could make the structure too complex. The two dimensions selected provide insight into the overlap between tools of various disciplines. In addition they also illustrate how a tool can be used for various functions, i.e. various combinations of measurement point and intervention point. Other differences between tools (such as the disturbance type) will be considered as contingency factors (see Section 4.5)

4.4.1 The point where measurements are taken

A process control starts with measurements taken from the process. These measurements can be taken in various 'parts' of the process. The main difference in measurement points is between measuring process factors and process output. These main categories can be further divided. The categories that are used as the rows of the IPC model are listed below. (For further definitions we refer to Appendix 1.)

- incoming material characteristics
 - machine characteristics
 - tool characteristics
 - operator characteristics
 - settings (controllable process factors that can be adjusted)
 - process conditions
 - output product on-line (while process is running regular production)
 - output product off-line (while process is not running regular production)
- In many cases measurements are taken from process output or from the process factor that is known to disturb the process. Yet, also other measurement points are feasible.

4.4.2 The point where actions / interventions are made

Based on the measurements (that are grouped by the previous dimension) the goal of a control is to act in the case of disturbances. In general, adjustments will be made to the cause of a disturbance. However, it is also possible that there is e.g. a disturbance

in material input (which is measured) and that adjustments are made to the settings of a process instead of to the material. Moreover, not all controls include a pre-described intervention for a specific process factor.

The columns of the IPC model represent the different types of adjustments in terms of action point or intervention point. The subjects for actions used in the IPC model are:

- intervening in a specific process factor: the IPC model contains a column for the same process factors as discerned for measurement points, except for process conditions, since it is not possible to influence these factors (directly).
- process control: this column concerns controls with un-predefined interventions in the (whole) process, i.e. the purpose of the tool is to monitor the process in general, in order to signal when adjustments are needed without specifying the actions to be taken for certain process factors in the case of disturbances (interventions are not defined beforehand).
- product assurance: the primary purpose of controls in this column is not to intervene in the process but to verify the conformance of output to product requirements (in SPC terms this is technical control). In the case of disturbances, the primary action will be directed at the output, e.g. by sorting out and scrapping products.

4.4.3 Positioning controls in the IPC model

To illustrate the positioning of controls in the IPC model, first the historical development of SPC-related controls (similar to the developments described in Section 2.1) is used. The changes in time are described and depicted in a schematic representation of the IPC model in Table 4.2. The arrows indicate the change in controls when moving from one situation to another.

- The traditional approach to process 'control' was often product- and detection oriented (product assurance): samples are taken from a batch of products after finishing production (output off-line) (situation A in Cell I8). (Refer to Figure 2.1)
- Using the Control Chart, the next step is to monitor the process by measuring products in samples during production (output on-line) and to compare charting statistics such as means and ranges of these samples with control limits based on a stable process. If samples fall outside these limits the process is out of control and it is therefore stopped to look for causes. However the interventions to be made are not specified. The goal is to control the process as a whole (output control). This is situation B (Cell H7).
- While using Control Charts as in situation B, it may turn out that most of the problems that occur can be related to a few (dominant) process factors, e.g. a deviating process setting, and the deterioration of a machine part. These causes are the input for an Out of Control Action Plan (OCAP), a flowchart to prescribe how to determine and to remove the causes of an out of control situation (situation C in Cells H2 and H6 added to B). In this way the control loop is closed by prescribing interventions for specific process factors. (See also Figure 2.2).

- Although OCAP's allow for a quick removal of causes for out of control situations, the goal should be to prevent failures. Therefore preventive measures can be taken directed at the control of dominant process factors. E.g. the wear of the machine part is controlled by a conditional preventive maintenance scheme that measures the condition of the machine and acts by repairing or replacing parts of the machine (situation D in Cell B2). To prevent problems with the process setting, APC is used to measure material thickness (incoming material) and use a feed forward signal to adjust the setting. Thus a disturbance of a certain process factor is controlled by intervening in another process factor (situation E in Cell A6). (Refer to Figure 2.4 for a schematic representation.)

	material	machine	tools	human factors	environ-ment	settings	process control	product assurance
A	material					E		
B	machine	D				↑		
C	tools	↑						
D	human factors							
E	environ-ment							
F	settings							
G	process conditions							
H	output on-line							
I	output off-line							A
	1	2	3	4	5	6	7	8

Table 4.2: Schematic representation of a roadmap in the IPC model

In the IPC model depicted in Table 4.3, a few illustrative examples of controls from the disciplines discussed (abbreviation between brackets) are given. The examples are placed by the intervention point and measurements points of typical applications found in literature. The examples will be discussed below. Note that some combinations of measurement point and action point are more likely to occur than others. It concerns controls that use on-line output measures, and controls that measure and intervene in a certain process factor. These combinations have been made gray. Some cells of the model might be crossed out because practical controls that fit these combinations of measurement point and intervention point are very unlikely. Examples are cells A7 to F7. These cells would imply a control that measures a process factor (not a process condition) combined with an intervention that is not pre-defined and could apply to all process factors.

SPC-related controls:

- The main use of the Control Chart is based on on-line measurements of output characteristics to monitor the process as a whole (H7). When output measurements are used, the OCAP can be used to prescribe interventions in specific process factors (see H1 through H6).
- Control Charts can also be based on measurements of process factors. One possibility is to monitor process conditions. When this process condition is influenced by various other process factors, the goal will again be to monitor the process as a whole (G7). To prescribe interventions in specific process factors an OCAP can be used (G1 through G6). It is also possible, however, that a process condition can be linked to a dominant process factor. In this case, the Control Chart can be used to control this process factor. In these cases an OCAP will be of less importance.
- Control Charts may also be used based on process factors other than process conditions. For instance to monitor material inputs (A1).
- The main function of the Process Capability Study (PCS) is product assurance based on off-line measurements of output characteristics (I8). However, the case studies in Chapter 2 showed that the PCS can also be used to control the process as a whole based on off-line output measurements (I7).

TPM-related controls:

- TPM maintenance activities focus on intervening in the machine (parts) and tools (Columns 2 and 3). Conditional maintenance may be based on measurements of the machine part or tool itself (B2 and C3), but measurements of process conditions (such as noise level or temperature) are also used (G2 and G3).
- Preventive maintenance is not based on a 'real' measurement of a process factor or output characteristic. Yet the moment of intervention is based on measuring the number of products produced (H2 and H3 or I2 and I3), or the operating time of a machine (part) or tool (B2 and C3).
- Corrective maintenance is typically based on measurement of process output (H2 or H3). These measurements are often not part of a corrective maintenance policy, but may be measurements used for other purposes (e.g. Control Charting).

APC-related controls:

- The interventions of APC controls are directed at controllable settings of the process (Column 6). The measurements used may be on-line output measurements (H6) or process conditions (G6), which implies a feedback loop.
- Measurements may also concern material input (A6) or environment (D6), which implies a feed-forward loop.

Poka-Yoke controls:

- Poka-Yoke controls are used for product assurance based on on-line output measurements (H8), where removing non-conforming products is the only action.
- When the purpose of a Poka-Yoke control is to stop the process as a soon as a non-conforming product is detected, the function is general output/process control (H7).

Yet prescribing an action is not part of the tool (note that an OCAP may be a useful tool in this respect). When the cause of the disturbance is clear, i.e. 'intervention in human factors' the intervention may refer to this specific factor (H5).

- Poka-Yoke tools are often used to monitor a process condition (such as the presence of a part or the depth of a drill). The purpose may again be general output/process control (G7) (when there are multiple causes to be considered), but also specific interventions are possible (e.g. G2 or G3).
- Poka-Yoke may also be used to measure and intervene in material input (A1) by detecting and removing non-conforming parts.

The IPC model shows similarities between tools from different disciplines. Also the various functions for which a tool can be used become clear. Moreover, possibilities for combining tools from various disciplines can be derived. E.g. using an Out of Control Action Plan in combination with a Poka-Yoke control on product output to prescribe the necessary actions in the case of an alarm of the Poka-Yoke device.

		Intervention							
Measurement [point]	material	machine	tools	environment	human factors	settings controllable	process control	product assurance	
A	material sampling (m) control chart (s) poka-yoke (p)					poka-yoke (p) APC feed-forward (a) control chart (s)			
B	machine	preventive maintenance (t) conditional maintenance (t)							
C	tools		preventive maintenance (t) conditional maintenance (t)						
D	environment					APC feed-forward (a)			
E	human factors								
F	settings controllable					poka-yoke (p)			
G	process conditions	OCAP + CC (s) cond. maint. (t) OCAP + CC (s) poka-yoke (p)	cond. maint. (t) OCAP + CC (s) poka-yoke (p)	OCAP + CC (s)	poka-yoke (p)	APC (a) OCAP + CC (s)	control charts (s) poka-yoke (p)		
H	output on-line	OCAP + CC (s) corr.maint. (t) rev.maint. (t) OCAP + CC (s)	corr.maint. (t) rev. maint. (t) OCAP + CC (s)	OCAP + CC (s)	OCAP + CC (s) poka-yoke (p)	APC (a) OCAP + CC (s)	control charts (s) poka-yoke (p)	100% check (m) poka-yoke (p)	
I	output off-line						PCS (s)	PCS (s) sampling (m)	
	1	2	3	4	5	6	7	8	

Table 4.3: The Integrated Process Control (IPC) model with some typical examples (s)=SPC, (t)=TPM, (a)=APC, (p)=Poka Yoke, (m)=miscellaneous

4.5 Contingencies in applying process control tools

To be able to select process control tools it is necessary to know in which situations a certain function (i.e. measurement point and intervention point) is important, and which controls are suitable for this function. In literature, little structured knowledge on these situational factors can be found. Results of the exploratory case studies and the review of literature on various disciplines provide the situational factors listed below. One should note that certain contingency factors are interrelated or may have interacting effects.

1. Presence of a dominant process factor: A process factor is dominant if it is the most important source of disturbances. When a certain process factor is dominant, the interventions of controls tend to focus on this factor. Exceptions are APC controls in which not the disturbing factor but the settings are adjusted. The measurement point of controls will vary: most controls will be based on measurements of the dominant process factor or on an output-measurement, yet other measurement points are also possible. Because of the fact that some disturbance patterns are more likely to occur for certain process factors, the tool to be used can also be influenced, see 4: Disturbance pattern. (Although used in a different way, the term 'dominance' within a process can also be found in [CHRYSLER et al., 1994] and [Juran et al., 1974])
2. Absence of a dominant process factor: If, instead of a real dominant process factor, there are many moderate causes, this may cause a shift to output control and measuring process output. Thus the influence of multiple process factors can be monitored simultaneously. The same shift occurs when a process is immature and there are multiple causes with a considerable impact on variation: in these cases it is not possible to control all these causes separately at the source; output controls and feedback loops can be used instead.
3. Level of process knowledge: If the level of process knowledge is low, controls tend to be output-oriented, in terms of intervention and measurement points. The reason is that specific controls for process factors are not sensible without process knowledge. Furthermore, controls tend to be directed at assurance since, for output control, one also needs process knowledge to determine feedback actions. By using tools for output control, one can aim at gaining new process knowledge: causes can be looked for after detecting a disturbance in the output. In this way the control tool is, in fact, used as an improvement tool. We refer to Chapter 5 for a further discussion on process improvement tools.
4. Disturbance pattern: The pattern of disturbances (e.g. shifts, trends or incidents) is mainly of influence on the selection of a tool within a cell (For definitions and a further discussion of various disturbance patterns we refer to Appendix 3). This applies both to controls that use output measurements as well as to controls that use measurements of process factors. To detect certain disturbance patterns, specific measurement patterns and rules to link measurements to interventions are necessary. The selection of tools is thus influenced. To be able to intervene in the process, a non-stable pattern must be detected. As a result, the disturbance pattern can also influence the measurement point and intervention point of controls. This

may occur when output variation patterns and variation patterns of a process factor are different. In general the output failure pattern will be the same as the failure pattern of the dominant process factor. However, a stable variation pattern in product output may be the result of one or more dominant non-stable variation patterns. Thus it may be impossible to use controls on product output, but controls on dominant process factors may be possible. Sower and Foster [Sower and Foster, 1990], describe a case that is an implicit illustration of this effect.

5. Possibilities to take measurements: Apart from the disturbance pattern there is also the issue of the technical (and as a result also economical) feasibility of measuring process factors or process output. A certain output characteristic may be difficult to measure, but the process characteristic that causes disturbances in this characteristic may be easier to measure, as illustrated in Case D of Section 2.3. Poor measurability of process factors and product characteristics may also result in the use of tools that require relatively few measurements. Thus the measurability determines the selection of tools within a cell. Through the development of accurate, inexpensive and often automated measurement devices, it has become more easy to take measurements [cf. Robinson and Miller, 1989], which enables the use of tools that require more measurements or the use of additional controls, e.g. for product assurance. Note that the economical feasibility of taking measurements not only depends on the measurement but also on the 'budget' for taking measurements. This is discussed in point 9: 'Costs of using controls relative to turnover and costs of poor control'.
6. Possibilities to allow for disturbances / necessity to intervene: The level of technical control of a process, i.e. how well variations (including non-random patterns) fit within tolerances, also influences the selection of tools and the measurement point of tools. When the level of technical control is high it may be possible to allow a trend e.g. due to wear of a machine part until a certain limit is reached. For instance using preventive maintenance or a Control Chart for tool wear [cf. Montgomery, 1996, p414]. When the same trend would immediately lead to products outside specifications, there is a necessity to intervene in the process, e.g. using an APC feedback loop. Thus the level of control influences the selection of a tool within a cell. If the level of variation is low compared to tolerances this may lead to output-directed tools or tools that allow for certain variation patterns.
7. Consequences of poor products / necessity to intervene: The consequences of poor products (and the resulting importance of a 'space' between variation and specifications) also influence the way a certain disturbance pattern should be handled, and the necessity to control certain variation patterns (such as patterns with a low frequency of occurrence or with a low chance of leading to non-conforming products). In cases where the consequences of producing poor products are high (i.e. for safety-critical products), one cannot allow output products near or outside specification limits. As a result, controls for process factors and for process control tend to be combined with controls for product assurance and specific controls for process factors. Also when process demands are pushed higher, it may be necessary to control variation at the source and/or to filter out all deviating products by 100% measuring [cf. Hinckley and Barkan, 1995]. For example, in some cases, SPC tools are not powerful enough to achieve very low defect levels (i.e.

PPM levels). Instead 100% checks may be necessary to assure product quality totally [Robinson and Schroeder, 1990; Osborn, 1990]. More frequent measurements may be necessary to find certain disturbance patterns. Thus it may be necessary to apply controls that can be used to detect and remove causes with a low frequency of occurrence. Conversely, in some situations it may be more efficient to rely on detecting problems in product output than to try to prevent them.

8. Possibilities to intervene in disturbing process factors: The possibilities to intervene in the disturbing process factors (in terms of the technical and economical feasibility) influence the use of process control tools. In some cases it may be difficult or very expensive to intervene in the process frequently. This may result in tools that have a low frequency of intervention (corrective maintenance instead of preventive maintenance). In cases where it is hardly possible to intervene in the disturbing process factor (e.g. unavoidable changes in material input), but interventions in settings are possible, one can compensate for the disturbances instead of removing them, e.g. using APC loops. Thus the possibilities to intervene in the process influence the intervention point and the tool within a cell.
9. Costs of using controls relative to turnover and costs of poor control: Not only do the absolute costs of measurements and interventions influence the application of controls, the costs of using controls should be related to process turnover. A relatively high turnover will imply more financial room for controls, which allows the use of extra controls (both for assurance and process factors) or controls with high start-up costs. A low budget for control (see e.g. Case C in Section 2.3.3) may reduce the number of controls and may cause a shift to output-oriented controls, since the effect of various causes can thus be monitored simultaneously. Besides, in the case of a high turnover the possible losses through poor control are higher, and thus, the consequences of producing products outside specification will be greater (see point 7).

Although in practice other factors such as company policy or customer requirements may be of influence, the above contingency factors will largely influence not only the selection of tools in practice. One can observe that contingency factors can be both stimuli, i.e. factor that determine the necessity to use certain controls, and constraints, i.e. factors that influence the possibility to use a control (cf. Section 3.3). The above list shows that various contingency factors influence the measurement point and the intervention point, i.e. the function or cell within the IPC model (cf. 'determine relevant function' in Figure 3.2), but also the selection of a tool within a cell (cf. 'selection of tools' in Figure 3.2). The relations between various tools (cf. relationship between techniques' in Figure 3.2) are explained by the IPC model.

The goal of finding contingency factors was to provide guidelines for selecting control functions and control tools. The next section discusses possibilities for deriving practical guidelines in order to support the application of process control tools.

4.6 IPC Design profiles for process control systems

The goal of this research is to support practitioners in decisions concerning the application of quality tools. Although the previous section provides insights into contingency factors, for decision support more practical guidelines would be preferable. Preferably, these guidelines should assist practitioners in selecting one optimal set of tools for a specific situation. However, if at all possible, this would be very time consuming and not possible within the time frame of this research. Nevertheless this section aims to illustrate how the IPC model and contingency factors can be translated into more practical guidelines. Based on knowledge of the main contingency factors, the IPC model can be used to prescribe 'scenarios' or 'design profiles' containing a set of controls that are likely to fit a certain 'typical' situation. For this purpose the contingency factors of the previous section are clustered into steps for deciding which tools to use. In this way, the user can select a group of tools that can be considered for the situation at hand. Note that these guidelines support the user while leaving the decision to the user.

One of the most important factors that influence the set of functions and controls to be used is the dominance of certain process factors. Although there is no strict link between the dominant process characteristic and the discipline to be used, Table 4.1 shows that the attention for a certain process factor partly characterizes the control disciplines considered. The dominance of one group of process factors will imply the use of controls that are specifically directed at these factors. Often there is also a relation with the type of disturbances that this process factor generates. Thus, it may be helpful to provide users with tools that can be used for a process with a certain dominant process factor as a first indication.

There is still a large set of tools that can be used when a certain process factor is dominant. Therefore we need other contingency factors to guide the user when selecting relevant functions and suitable tools. Table 4.1 shows that the type of disturbance is also an important distinctive factor. Not all tools are able to detect and adjust certain disturbance types (see also Appendix 3). Thus we can group the tools suggested for controlling disturbances in a certain process factor by the disturbance pattern for which they can be used.

The above two contingency factors limit the number of potential tools, but there are additional factors that influence the selection of tools, such as the measurability of a process and the possibilities to intervene in the process. These factors are not yet taken into account. However, for each failure pattern, controls can be suggested for various functions within the model. Based on considerations such as ease of measurement and possibilities to intervene in the disturbing process factor, users can e.g. decide whether to use output directed controls or controls directed at a certain process factor.

Thus contingency factors are combined into design profiles. Each design profile consists of an IPC model filled with a set of tools that can be used for a type of process which is linked to a dominant process factor. In addition, for each design profile, a table is supplied which suggests a set of tools for a certain disturbance type (described in terms of specific disturbances that can occur in the process factor at hand). Each tool suggested is listed in the IPC model and a reference to the related cell (function) is given. As an illustration of the form and contents of design profiles, in Appendix 4, design profiles for the following dominances are presented:

- Machine and tooling dominant process.
- Material and component dominant process.
- Operator dominant process.

Further development and testing of design profiles in practice is subject for future research.

To use the design profiles, one should first determine from which process factor a disturbance originates, do that the design profile for a certain process factor can be selected. Secondly, one needs to know the disturbance type, in terms of the pattern of disturbance. If this is known, the set of tools suitable for this type of disturbance can be selected from the table. The selection of a tool from this set is left to the user, whereby the remaining contingency factors and specific circumstances should be considered. Thus, the IPC model and design profiles do not specify the exact tool methodology, but support the user in selecting the right tools for the right functions.

Discussion of research results in this chapter

The first goal of this chapter was to derive a functional framework for process controls. This resulted in the IPC model. The IPC model gives insight into the overlap and relations between control tools of various disciplines. Furthermore, the IPC model shows the various ways to apply a certain tool in terms of functions within the model. It can be used in training on process control tools, e.g. to give an overview of controls from several disciplines and their functions. In this way it becomes apparent that some controls have more or less the same goal and can be seen as alternatives. The most important implication for business practice is that using the IPC model ensures that relevant controls from various disciplines are considered and, if necessary, combined as a coherent set of controls. The IPC model supports such an integrated approach when describing, analyzing or prescribing the control of a production process. These activities will be used when improving the control of existing production processes (see Chapter 5) or designing a control system for a new process.

The IPC model also has implications for process design activities. The task of the design department should be to define not only the product and the process but also the controls of the process. One should not wait for the actual production start-up to define controls. This also prevents the development of products and processes that are difficult to control. The IPC scenarios mentioned above can be used as design profiles

for controls. Again, the most important implication is that relevant controls of various disciplines are considered and, if necessary, combined as a coherent set of controls. The application of quality tools in design activities and the use of IPC scenarios are subject for further research (see Section 6.7).

The second goal of this chapter was to provide guidelines for selecting control tools from the framework. The contingency factors discussed in Section 4.5 and the design profiles discussed in Section 4.6 provide these guidelines. Referring to Figure 3.2, the guidelines provide support for determining relevant functions, selecting suitable tools, and partly also for defining relations between tools. However, the guidelines do not provide a 'one-on-one' solution for a specific situation. The ultimate decision to select certain tools remains a task of the user. Also determining the exact methodology of a tool (e.g. the type of Control Chart or APC feedback loop) is left to the user. As stated in Chapters 1 to 3, the latter is not within the scope of this research since there is a vast amount of knowledge on the tool level.

The research described in this chapter was focussed on the control tools of various disciplines. Yet these disciplines, in particular SPC and TPM, are more than a coherent set of tools. The implementation and application of tools within these disciplines is part of a program, which consists of both a methodological part (including a coherent set of tools) and an organizational part (including guidelines for e.g. implementation and management of the tools). See e.g. [Does et al., 1997] for SPC, and [Willmott, 1993] for TPM. Concerning the implementation of both SPC [Does et al., 1997] and TPM [Riis et al., 1997; Willmott, 1993], authors stress the importance of organizational aspects such as management commitment, operator involvement and empowerment, training, and implementation management. An implementation program should assure that attention is given to these aspects, since achieving an effective control of production processes is more than choosing the right controls. This is in line with the observations in Chapter 2. For a further discussion on organizational aspects we refer to Section 6.6.

The above discussion on implementation programs may give rise to the question whether the integrated approach to process control resulting from the IPC model should result in a new integrated discipline for process control. Although this is subject to further research, the implication of the IPC model is not that companies that are running an SPC or TPM program should abandon this or start up additional mono-disciplinary implementation programs. Starting from a mono-disciplinary program and considering all relevant controls using the IPC model will already result in a better approach to process control. Future research may result in a special implementation program for IPC.

Since this research is focussed on quality tools, the output of a process was defined in terms of characteristics of the product produced. As a result, in Section 4.2 the OEE of TPM was positioned outside the scope of this research. Yet the discussion on TPM showed that there is a relation between quality and time-related aspects of process output. In fact, poor control of a process can result in both quality and time-related problems. For example, when SPC and Poka-Yoke are used effectively, this can result

in frequent stops of the process when a problem is signaled. Although the yield of the process is not lowered in terms of product quality, the uptime of the process is lowered. Thus disturbances in the process factors do not only lead to disturbances in product output characteristics but also to disturbances in time-related output performance such as reduced speed and breakdowns of machines. Future research could be directed at including time-related performance in process controls. This issue is addressed in the directions for further research in Section 6.7.

Although this chapter is directed at improving the use of tools for process control, one should bear in mind that the application of controls is not a goal in itself. The goal is to reduce and control disturbances in a process. As noted in Section 4.2.5 in some cases the best solution for controlling disturbances and thus controlling output variation is not to apply a control tool, but to define a structural change. Such a one-time change in the definition of the process can be much more efficient. In fact, if possible this type of change, which structurally removes disturbances or removes the influence of the disturbances on the process, is to be preferred. Structural changes are a logical consequence of the trend to prevent disturbances instead of detecting and removing them as described in Section 2.1. Although structural changes are not part of the IPC model, they do play an important role when looking for improvements. The relevance of defining both structural changes and controls as part of activities to improve a process will also become clear in Chapter 5.

5 Structure and applicability of Process Improvement Tools

The main part of this chapter has been previously published in a paper on variation reduction strategies [de Mast, Schippers, Does and van den Heuvel, 1999].

5.1 Introduction

The historical overview in Section 2.1 showed that besides tools used to control production processes, another group of quality tools is used for improving production processes. The research described in this chapter was directed at finding functional structures and contingency factors for these process improvement tools (analogous to the approach used in the previous chapter).

In literature various improvement tools can be found, varying from (simple) qualitative tools such as fishbone diagrams, to (complex) quantitative tools such as Design of Experiments. In this chapter we will limit our scope to quality tools used for process improvement. Although some of the tools discussed in this chapter are also relevant in design of new products and processes, in this research we start from the situation of an existing process during the manufacturing stage, in which the variability of a process causes poor product quality. (Note that this implies that the process to be improved is already selected.)

The common goal of the improvement tools considered is to reduce the variability of a process by identifying causes of variations and generating preventive actions. Preventive actions can take the form of a structural change of the process (or the product) or defining a process control activity (described in Chapter 4). The variability of a process can take the form of both stable, random variation patterns (addressed as a state of statistical control in SPC), but also time-dependent, non-stable patterns of variation (referred to as variation resulting from special causes). Both types of variation may be subject of improvement. Since there is a lack of clear, broadly accepted definitions in this respect, Appendix 3 discusses and defines variation types and causes in more detail.

A large variety of tools can be used to find causes of variation and to define improvements. In most cases it is not sufficient to use a single improvement tool. While in the area of process control multiple tools are used simultaneously (e.g. to control various process factors), process improvement tools are typically used in a coherent sequence. Upon reviewing process improvement tools in literature, it showed that various pre-defined sequences could be found, containing a wide range of (partly overlapping) tools. These sequences are presented as stepwise approaches for improvement, or even larger (company wide) improvement programs. Although these

sequences may be applicable in other areas than process improvement, in this chapter we will refer to them as process improvement strategies. They are defined as:

A coherent series of steps aimed at reducing the variability of a process by identifying the factors that affect variation and generating improvement actions.

An improvement strategy has some characteristics of the functional structure that is to be derived in this chapter. However, it showed that strategies found in literature differ in terms of their functionality and the tools used for certain functions. Also the terminology used differs between strategies. Yet, in general, these strategies (especially those having a 'trademark') are presented as a generally applicable strategy, which users are expected to adopt as 'package deals'. Little insight is given into the limited applicability of this package. Therefore it was decided to consider the existing improvement strategies as a basis for deriving a more generic functional framework for process improvement tools.

Upon reviewing literature, we composed a list of process improvement strategies that are well defined methodologies, which are generally applied in practice, and which have proven to be successful. We were able to find four variation reduction strategies that comply with these requirements. One of the sequences found in literature is a stepwise approach to implement SPC [cf. Does et al., 1999]. The other selected strategies are Taguchi's methodology [cf. Ross, 1996], the Shainin System [cf. Shainin, P.D., 1993; Shainin, R.D., 1993] and Six Sigma [cf. Harry, 1997; Harry and Lawson, 1992]. Note that apart from SPC, the disciplines discussed in the previous chapter are not mentioned in the list. The reason is that they lack a similar stepwise approach for identifying causes of variation and generating preventive actions.

The strategies that have been selected are described and reviewed in Section 5.2. Section 5.3 gives an initial discussion of the differences and overlaps of the four strategies. In Section 5.4 a functional framework for integrated process improvement (the Integrated Process Improvement Model or IPI model) is derived and explained. The IPI model can be seen as the cumulation of the various approaches that are presently available. Section 5.5 discusses the main contingency factors in applying process improvement tools and provides guidelines for selecting functions and tools when using the IPI model in practice. The discussion of the research results and directions for further research in Section 5.6 concludes this chapter.

5.2 A review of existing process improvement strategies

Below the four strategies considered in this chapter are briefly described. All four strategies are presented as a stepwise approach. Some strategies are presented as a series of steps including a set of tools, while others are described in terms of the rationale behind each step. The content of each strategy, i.e. the steps that it consists

of and the goal of each step is briefly described. The listed references were used as a source of information for determining the content of each strategy.

5.2.1 10-step approach for implementing SPC

Although the term SPC is also used in senses encompassing a larger scope of quality tools (such as Design of Experiments), we focus here on a stepwise approach for implementing on-line SPC [Wetherill and Brown, 1991] in industry, provided by Does et al. [Does et al., 1997 and 1999]. This approach is used by multidisciplinary teams, mainly consisting of operators and process engineers. Hence, SPC exploits techniques that are easily comprehended. Intentionally, the implementation of SPC is company wide. Besides the stepwise approach, Does et al. [Does et al., 1997 and 1999] also provide an organizational framework for company-wide implementation.

The primary goal is to bring a process in a state of statistical control, i.e., having a stable and predictable level of variation in its output. This objective is attained by detecting and removing special causes of variation that lead to a non-stable variation. The reduction of 'process inherent' variation is not the main intention of on-line SPC. This is reflected in the emphasis on qualitative analyses and observational analyses (i.e. using quantitative data from regular production). Controlled experimentation to reduce process inherent variation is hardly used. The distinction between process inherent variation due to common causes, and variation due to special causes is operationalized in the Control Chart (see Appendix 3 for a further discussion).

SPC is concerned with controlling a process rather than with a single output characteristic. Therefore the approach starts with describing the process (Step 1), its cause and effect relations (Step 2), and prioritizing the most problematic cause and effect relations using an FMEA (Step 3). Thus the main problems of the process are selected based on existing knowledge of the process, present within the team. The tools used are of a qualitative nature. Steps 2 and 3 are also used to identify possible causes of the most important problems based on current knowledge of the process. Through exchange of relevant knowledge in Steps 1 to 3, the team may already be able to define improvement actions (Step 4).

It is very well possible that the current knowledge of team members is not sufficient to find causes of problems and define effective improvements. Therefore the next step in the strategy is to use measurements of the process for further quantitative analyses (Step 5). If possible one should use existing data which was gathered in the past (but not yet effectively used). If measurements are not available, one can decide to collect new measurements. Measurements are collected and analyzed using simple problem solving tools in order to find causes. As a result of this step, the team should be able to define improvements and decide which measurements should be used for the Control Chart (in Step 7).

However, before using the Control Chart, a measurement analysis is used to ensure that the measurements used as input for the Control Chart are reliable (Step 6). After this the goal is to use the Control Chart (Step 7) to make an initial analysis of measurements from the process and calculate control limits (called a Phase 1 Control Chart). Before one can calculate control limits for operational control, one should search for instabilities that are the result of special causes. After detecting a special cause of variation, the actual cause of disturbances should be determined and prevented by improvements (Step 4). After removing special causes, control limits are calculated and the Control Chart is used to monitor and maintain stability of the process (Step 2). To be able to actually control the process, the Control Chart is combined with an OCAP. The OCAP is drawn up in Step 8 'Out of Control Action Plans'

After implementing the Control Chart as a monitoring tool, the capability study is used as a tool to validate the effect of improvements (Step 9). The final step of the strategy (Step 10: certification), is used to audit the improvements made and ensure that the improvements are maintained and re-audited in the future.

5.2.2 Taguchi

Genichi Taguchi invented and promoted various methodologies and concepts for improving products and processes, such as the Taguchi Loss Function and three phases in (re)designing products and processes (viz., system design, parameter design and tolerance design). Furthermore, he introduced an alternative experimentation methodology, using orthogonal arrays (OA's). Also the simultaneous optimization of both the mean and variation, and the use of 'outer arrays' to evoke variation through noise factors is typical for the Taguchi methods. Taguchi, an engineer himself, uses a vocabulary that is typical for engineers and which differs to some extent from the statistical vocabulary that is used in traditional quality control. Having a certain degree of refinement without being too mathematical, the methodology should be readily understandable to engineers. We refer to [Taguchi, 1986] for a discussion of Taguchi's methodologies. Although the adequacy of the methodology has been the subject of much debate among statisticians [c.f. Nair, 1992], the approach is popular in business practice.

As an operationalization of Taguchi's methodologies and concepts we consider a stepwise strategy described by Ross [Ross, 1996], as applied to production processes. This approach is built around Taguchi's quantitative experimentation methodology. Ross stresses the importance of the planning phase of experimentation, which is reflected in a number of steps for planning experiments. Yet the initial steps in the strategy are still a preparation for experimentation, rather than steps directed at finding causes of disturbances and improvements.

The first step of the method 'State the problem(s) or area(s) of concern' (Step 1) aims to clearly describe the problem. The importance of a technical understanding of the

problem is stressed. The next step 'State the objective of the experiment' (Step 2), aims to determine the required situation based on e.g. customer requirements of competitive benchmarks. In Step 3 'Select the quality characteristic(s) and measurement system(s)', the quality characteristic to be measured as experimental output is determined. This characteristic should preferably be a continuous variable instead of an attributive measure, since the latter requires substantially more measurements. If possible attributive data should be converted into variable data. The second activity in this step is to define the measurement system (measurement tool, method and people). An R&R (Repeatability and Reproducibility) study is recommended.

Step 4 'Select the factors that may influence the selected quality characteristic(s)' is presented as an essential step in the method. It aims at making a list of factors to be evaluated during the experiment for their effect on the quality characteristic. Missing an essential factor in the experiment would not result in positive information. Various qualitative tools (Brainstorming, Flowcharting and Fishbone diagrams) are presented as means to collect and structure to current knowledge. The next step 'Identify control and noise factors' (Step 5), aims to list the factors to be studied, divided into factors that can be changed or influenced in practice (controllable factors) and factors that may vary in practice, but cannot be changed (noise factors).

In Steps 6 to 11 the experimental design is set-up (Step 6 'Select levels for the factors'; Step 7 'Select appropriate orthogonal array(s); Step 8 'Select interactions that may influence the selected quality characteristic or go back to Step 4'; Step 9 'Assign factors to OA(s) and locate interactions'), the experiment is conducted (Step 10 'Conduct test described by trials in OA(s)) and the results are analyzed (Step 11 'Analyze results of the experimental trials'). Experiments are designed in such a way that the effect of factors on both the mean and variation can be studied. Typical for the Taguchi approach is to deliberately evoke variation by using an Outer Array (e.g. to change settings of noise factors) instead of through replication of measurements from one run.

If necessary more than one experiment is used to achieve the objective stated (screening experiments, sequential experimentation). The ultimate goal is to select the optimal values of parameters, i.e. values that result in a desired mean and variation of the quality characteristic. If variation reduction is the goal, the process parameters are chosen such that the process is made robust against variation in the 'noise parameters' (refer to parameter design or robust design [Taguchi, 1986; Lucas, 1994; Vining and Myers, 1990]). In Step 12 'Conduct confirmation experiment' new data are gathered to validate whether the selected values of the factors give achieve the expected results. If variation cannot be sufficiently reduced using parameter design, tolerance design [Taguchi, 1986] is exploited to accomplish a further reduction in variation (this is not a formal step in the method).

5.2.3 The Shainin System

Dorian Shainin put several techniques – both known and newly invented – in a coherent stepwise strategy for variation reduction in a manufacturing environment. This strategy is called 'the Shainin System' (which is trademarked). It contains elements from SPC, traditional DoE and engineering methods for problem solving (such as component swapping). Part of the strategy is popularized by Bhote [Bhote, 1991]. The system has been described in various papers [Shainin, P.D., 1993; Shainin, R.D., 1993]. Both Shainin, but especially Bhote present the Shainin System as a superior alternative to SPC and Taguchi methods. This lead to some critical assessments of tools from the Shainin System [cf. Ledolter and Swersey, 1997a and 1997b]. Since elements of the Shainin System are legally protected as Service Marks and some methods are rarely discussed in literature, it is difficult to obtain a detailed view of some of its parts.

The Shainin System is built around a set of 'ready-made' quantitative tools that are easily understood and applied, hereby refraining from more advanced techniques. The system and its tools are clarified using a popular vocabulary (featuring concepts as *Red X* and *Homing in Strategy*). Through this simplicity, and the integration of tools for technical problem solving, the system is appealing to people with a technical background and limited knowledge of statistics. Qualitative tools, which are found to be 'subjective' [Shainin, P.D., 1993], are not used.

The Shainin System starts from the viewpoint that 'There is no such thing as random variation' (i.e. every variation has a cause), and that 'For any process there will always be one root cause of variation that is larger than any of the others (the Red X) [Shainin, R.D., 1993]. This implies that, also in situations where a process is in statistical control, variation is assumed to be caused by a few major causes (see Appendix 3). Starting from a problem in the output of a process, the objective of the strategy is to select the one, two or three dominant causes of variation (called the Red X, Pink X and Pale Pink X, respectively) from all possible causes (the X-es). Below the steps of the Shainin System are briefly described. (Note that the steps in the Shainin System are not numbered.)

The system starts with defining the project: 'problem definition' (Step 1). The basis for selecting the problems to address should be customer enthusiasm or quality costs. The problem should be defined in terms of a measurable quality characteristic. The next step in the system is intended to ensure that an effective measuring system is available: 'establish effective measurement system' (Step 2). The tools in this step can be used to transform attribute data into variables data (Visual Scoring Transform and Resistance Limit Transformation) and to measure variation in the measurement system through using Isoplots. Isoplots are found to have several advantages over traditional R&R studies.

The next step 'generate clues' (Step 3) is presented as the heart of the system. It aims to find the most important causes using a 'homing in' method consisting of statistical analysis tools. In this way, the list of suspect variables is reduced step by step, thus zooming in on the Red X. Various tools can be used. The main tool is the Multi-Vari chart. For further clue generation also Concentration Diagrams (for within-piece variation), Paired Comparisons (piece to piece variation) and Component Search (for assemblies) can be used. This first reduction of possible factors in this step is based on data from regular production. Once the number of suspect variables has been reduced to a manageable number (5 to 20 according to [Bhote, 1991]), the factors to be studied using experiments (Step 5) are listed: 'List suspect variables' (Step 4).

'Statistically Designed experiments' (Step 5) are only used after reducing the number of suspect variables, since gathering data using designed experiments is expensive. If the number of suspect variables after Step 3 is still relatively high (5 to 20), Variables Search is used to further reduce the number of variables. This tool is presented as a better alternative to fractional factorials (for a discussion of this matter see [Ledolter and Swersey, 1997]). Only after the number of variables has been reduced to 4 or less, a full factorial is used to estimate the magnitude of the effects of these factors and their interactions. The 'Rank Order ANOVA' is suggested as an alternative way for analyzing the results of the experiment. After the Red X has been found, the 'B versus C' tool (Step 6) is used to confirm that the Red X was found, based on a small number of products produced under the current (C) and better (B) condition. If after this step the Red X has not been found, one should return to Step 3. If the Red X found with the full factorial is an interaction, the next step is 'Optimize interaction' (Step 7). This step is not described in detail in the referred sources. Apparently it aims to select the best levels for the individual factors in order to 'use' the interaction.

Once the Red X, and possibly one or two Pink X's are found, the next step is used to determine 'Realistic Tolerances' (Step 8) for these X's. For a range of values of the Red X, products are produced. A scatterplot of the X-values against the value of the product characteristic is used as input for a Tolerance Diagram. From this tolerance diagram the optimal value of the Red X and the allowable tolerance around this value are determined. The next two steps should ensure that these tolerances are controlled. If possible this should be achieved through an 'Irreversible Corrective Action' (Step 9), i.e. a structural change to the product or process. However, if this is not possible one should use 'Statistical Process Control' (Step 10), to control the Red X during the production process. For this purpose the Shainin System suggests Precontrol. It is an alternative for traditional control charting. Although the purpose is to control the Red X, many examples of the Precontrol Chart are based on measurements of the output characteristic. See e.g. [Shainin, R.D., 1993] who only refers to measuring 'pieces' (i.e. products) as input for Precontrol. The final step 'Monitor Results' (Step 11) is not described in detail in one of the referred sources. Apparently its purpose is to monitor process performance in time.

5.2.4 Six Sigma

Six Sigma [Harry, 1997] is a philosophy for company wide quality improvement. It is developed and promoted by Motorola and based on the insights of traditional SPC and DoE. The program is characterized by its customer driven approach, by its emphasis on decision-making based on quantitative data and by its priority of saving money. The selection of projects is based on these three concepts. Six Sigma is a legally protected program. Consequently, it is not possible to discuss all elements in full detail.

The Six-Sigma program is a complete program for company wide quality improvement, encompassing methods for analyzing the customer's wishes and for selecting the problems having the highest priority. The program is set-up in a way that it can be applied to a range of areas, from manufacturing to services. The implementation and application in the organization are coordinated by so-called Champions and Master Black Belts. Projects are conducted by Black Belts and Green Belts, who are selected from middle management and trained intensively. Virtually all known quality tools are somehow mentioned or listed within the 8-book set on the Vision of Six Sigma [Harry, 1997]. The tools range from Control Charting to design of experiments, and from robust design to tolerance design, even some of the tools from the Shainin System are mentioned. Yet, being centered on the Six-Sigma concept, the program has a strong emphasis on experimentation to achieve improvements.

An important part of the Six Sigma program is a 'Breakthrough Strategy' for process improvements, also addressed as the Inner MAIC loop (MAIC stands for Measure, Analyze, Improve and Control). It is 'specifically designed to lead a Black Belt to significant improvements within a predefined process' [Harry, 1997]. It tackles problems in four phases: Measurement (selecting one or more product characteristics), Analysis (benchmarking the key product performance metrics), Improvement (identification of the major sources of variation; establishment of performance specifications for the key process variables) and Control (documentation and monitoring of the new process conditions). The Breakthrough Strategy is part of an embracing strategy – the Outer MAIC-loop –, which comprises the strategical coordination of improvement projects, e.g. the selection of processes to be improved. Since the Inner MAIC-loop complies with our definition of a variation reduction strategy, it is this part of the Six-Sigma program that is considered in this chapter.

The breakthrough strategy starts with selecting a Critical to Quality Characteristic (Step 1), which should be a measurable characteristic. In Step 2 performance standards for this characteristic are defined based on benchmarking. This is succeeded by validating the measurement system (Step 3) to ensure that the measurements used in the next steps are reliable (mainly in terms of repeatability and reproducibility, but also in terms of accuracy and stability) The current performance of the (critical to quality) characteristic is assessed (Step 4). Based on a relatively large number of samples, both short-term capability (related to within sample variation) and long-term capability (overall variation including between sample variation) are calculated. Also various

'standardized' performance measures are calculated, which are typical for Six Sigma (e.g. Z-score and DPMO). The idea is to use these standard metrics company-wide in order that comparisons can be made. After this the objectives to be met after improvement are set (Step 5).

Step 6 'Identify Variation Sources' uses both qualitative tools, such as FMEA's [Harry, 1997, p.23.2], and quantitative based on data from regular production such as Multi-Vari charts [Harry, 1997, p.24.2]. The purpose is to identify causes that should be subject for further analysis, using experiments. In case the number of potential causes resulting from the previous steps is still relatively high (i.e. larger than 8), the next step 'Screen potential causes' (Step 7) exploits experiments (fractional factorial designs) to find factors that influence the (mean or variance of the) output characteristic under study.

In Step 8 'Discover variable relationships', the key process variables are identified by way of designed experiments. The relationships between the relevant causes and the output characteristic are determined and optimal values are determined. Various types of experiments and analyses are used, depending on the level of knowledge and the complexity of the process. Based on the 'model' derived from the experimental results, in Step 9 'establishing operating tolerances' tolerances are defined for X's, taking shifts and drifts of a magnitude of 1,5 sigma into account. The measurement system to be used for controlling the X-es is validated in Step 10 'Validate Measurement System'. Step 11 'Determine Process Capability' is used to determine the capability of the X-es using typical Six Sigma metrics. In Step 12 'Implement process controls' various types of Control Charts can be implemented to control the dominant factors. After completing the 12 steps of the Inner MAIC loop, the improvements are audited and reviewed as part of the outer MAIC loop.

5.3 Differences and overlap of process improvement strategies

The description of the four improvement strategies shows that the strategies under consideration are partly overlapping, but also partly of a complementary nature. Below the main differences and overlaps are briefly discussed. Note that this is only a first comparison of the contents of the four strategies. The next section presents a more thorough comparison of phases, steps and tools.

Strategy	Main Phases	Type of tools / information	Improvement types	Typical user
SPC	<ul style="list-style-type: none"> • Planning • Analysis & Improvement • Control 	<ul style="list-style-type: none"> • qualitative • observational quantitative 	stabilization	multidisciplinary teams (operators and engineers)
Taguchi	<ul style="list-style-type: none"> • Planning • Analysis & Improvement 	<ul style="list-style-type: none"> • qualitative • quantitative experimental 	optimization	(production) engineers
Shainin	<ul style="list-style-type: none"> • Planning • Analysis & Improvement • Control 	<ul style="list-style-type: none"> • observational quantitative • quantitative experimental 	(stabilization) optimization	(production) engineers
6 Sigma	<ul style="list-style-type: none"> • Planning • Analysis & Improvement • Control 	<ul style="list-style-type: none"> • qualitative • observational quantitative • experimental quantitative 	optimization	middle managers and specialists (black belts)

Table 5.1: Differences and overlaps in improvement strategies

Within the four strategies similar steps can be discerned. These steps can be grouped into phases that can be seen as the main functions within the strategies. Each strategy starts with a planning or problem definition phase (Planning). After this the process is analyzed to identify causes (Analysis) and actions are defined to improve the process (Improvement). Finally actions are defined to monitor the process after improvement (Control). In the second column of Table 5.1 the main phases in each strategy are listed. It shows that, all improvement strategies start with a planning phase followed by a phase for analysis and improvement, three of them contain a Control phase.

Besides the above overlap, also differences can be observed, especially with respect to activities related to analysis and improvement. Recalling the definition of a variation reduction strategy, we note that this is the core of variation reduction, in which factors of influence are identified, the most important factors are selected, and in which preventive actions are generated.

The first difference concerns the type of data (and tools) used to identify causes of variation. These are: qualitative data, observational quantitative data and quantitative data gathered using experimentation. (Using observational tools is also referred to as passive data collection, whereas experimentation is referred to as active data gathering.) Table 5.1 shows that there are some differences in the data used within each strategy. In the SPC strategy no experimental data is used, whereas the Shainin strategy does not use qualitative data. From the original strategies it can be observed that one first uses qualitative tools, then uses observational quantitative tools (from regular production), if necessary followed by (designed) experimentation tools.

The second difference that can be observed concerns the type of improvements (problems) addressed by each strategy. The SPC strategy aims at stabilizing a process, i.e. finding and removing factors that cause a process to be in-stable (see Appendix 3) and thus bringing a process in a state of statistical control. The other strategies are mainly concerned with optimizing a process, i.e. finding and intervening in factors that influence the mean and/or the level of (stable) variation in a process. (Note that in the Shainin system the difference between stable variation and non-stable variation is found to be irrelevant or even non-existing). The Six-Sigma approach implicitly starts from a stable process; it does not focus on eliminating causes of disturbances as part of the improvement process. Also after improvements the process is allowed to shift 1.5 sigma, since preventing this is considered to be hardly possible in practice. This matter is also discussed by Tadikamalla [Tadikamalla, 1994].

The two differences observed above are related, i.e. observational tools play a dominant role in stabilization and experiments are dominant in optimization. Yet there is no strict one-on-one relation. The next section addresses this in more detail.

Apart from the differences in steps and tools (i.e. functionality), also differences in the organizational goal and implementation approach can be observed. This is e.g. reflected in the users that typically apply each strategy, and the organizational framework used for implementing the approach. The most right column in Table 5.1 lists the typical user(s) of each strategy. Since organizational aspects are not the main issue in this chapter, this matter is further addressed in Section 5.6.

Returning to the functionality one can observe that the Six Sigma strategy appears to be the most complete. Therefore it was considered as the basis for a functional framework. Yet, it was found unsuitable for the following reasons: despite the fact that almost all known improvement tools are somehow listed in one of the eight books [Harry, 1997], the Six Sigma strategy does not cover all of the steps encompassed in the other strategies, especially concerning stabilization. Besides, the Six Sigma approach uses a quite rigid (trademarked) approach using specific tools and terminology, whereas the goal of this research is to provide a more generic framework. Therefore, in the next section, the phases and steps of all four strategies will be used as the building blocks of a generic functional framework: the Integrated Process

Improvement (IPI) model. The IPI model should give insight into the overlapping and complementary parts of the strategies.

Recalling the research objectives, the first goal of this chapter is to derive a functional framework for process improvement tools in which the goals and relations of various tools become clear. It should give insights to determine to what extent functions and tools from various strategies are complementary or overlapping. Deriving this model (the IPI model) will be the subject of Section 5.4. The second goal of this chapter is to determine contingency factors for selecting improvement functions and tools within the framework. This will be the subject of Section 5.5. Both sections are based on a further analysis of differences and overlaps between process improvement steps and tools.

5.4 The IPI model, a functional framework for process improvement

In this section we shall derive the Integrated Process Improvement model, as a functional framework for process improvement tools. It is a cumulation of the functions of the separate strategies. In order to make this cumulation, we followed the line of action described hereafter.

Although all of the selected strategies can be found in literature in the form of a stepwise approach, the presentations are not in similar terms. Some strategies are presented as a series of actions including a set of tools, whereas others are described in terms of the rationale underlying each step. Therefore for each strategy the underlying functions of its steps were determined. Thus the steps of the four strategies could be compared and combined. While identifying corresponding functions from different strategies, we obtained a collection of generic steps (i.e. functions), which are the building blocks of the Integrated Process Improvement model. Due to differences between strategies, the original order of steps within each strategy could not be maintained. Therefore, a logical order for the generic steps had to be determined.

For a first ordering of steps the main phases indicated in Table 5.1 were used. These phases were: planning, analysis and improvement, and control. A structured approach to process improvement should in some form or another encompass the activities in these three phases. However, in comparing the steps of the four strategies and generating a sequence of generic steps, it showed that the activities to analyze the process and the activities to improve the process were mixed, i.e. were not grouped into two separate and consecutive phases. One reason appears to be the fact that qualitative and observational tools are used before experimentation because gathering data through experimentation is generally more expensive than using data from regular production. The second reason is that improvements to stabilize a process should normally precede improvements to optimize the process, since experimentation

requires a stable process or at least a process that can be kept stable in time during the experiment. In the previous section we already noted that for stabilization one typically uses observational data.

As a result the activities to identify causes and defining improvements are split and rearranged into two separate phases (Phases 2 and 3). Although the division between these phases largely coincides with the division between stabilization and optimization, the separation between Phases 2 and 3 is actually based on using observational and experimental tools (and data). Thus Phase 2 has a dual goal: both stabilizing the process and identifying factors as a preparation for experimentation in Phase 3. For the determination of the final order of generic steps within these phases, additional considerations played a part that are based on logic concerning the interdependency of steps.

Below we describe the steps of the Integrated Process Improvement model in more detail. For each phase first the logical considerations underlying the ordering of steps within this phase are clarified. Next the steps are discussed in more detail. For each step a brief description of the generic goal is given, the corresponding activities in each strategy are listed, the main differences and gaps are briefly discussed and typical tools are listed. Numbers between brackets indicate the original order of steps within each strategy. An asterisk (*) indicates an activity that is part of a strategy but not a formal step. In cases that a step of a strategy covers more than one generic step, this is indicated adding suffixes a and b. For a detailed description of the listed tools we refer to the references given in the previous section.

5.4.1 Phase 1: Problem definition

An improvement project should start with a phase in which the problem to be tackled is defined and the improvement activities are planned and prepared. This is acknowledged by all of the strategies under study. Therefore, the first phase is concerned with defining the problem to make it suitable for (quantitative) analyses. The logical order within this phase is as follows: the problem is defined (Step 1.1); the problem is related to a measurable characteristic (Step 1.2); it is determined how this characteristic will be measured (Step 1.3); the current performance is measured (Step 1.4); the objectives as compared to the current performance are set (Step 1.5).

Step 1.1 Select and define problem. The goal of this step is to determine and prioritize the problem. The corresponding steps of the strategies are:

SPC: *Process description (1); Cause and Effect analysis (2a); Risk analysis (3a)*.
Using these tools important characteristics in the process are identified and prioritized.

Taguchi: *State the problem(s) or areas of concern (1)*. The problem to be improved is selected based on e.g. customer complaints or Quality Function Deployment critical items.

Shainin: *Define the project (1a)*. The problem to be addressed is selected based on quality costs and customer enthusiasm.

Six Sigma: *Select CTQ (Critical To Quality) characteristic (1a)*. Projects are typically selected using benchmarking and a thorough baseline analysis. Customer satisfaction (preventing customer complaints) and money savings are the leading principles.

The effort and tools in this step depends on the clarity of the problem. Typical tools in this step include Pareto analysis, Process flowcharting, Cause and Effect analysis, and Quality Function Deployment (QFD).

Step 1.2 Translate problem into measurable characteristic. This step involves specifying the metric that is used to measure the selected characteristic. Thus the performance of the process can be determined objectively and one can use quantitative analysis tools in the improvement process.

Taguchi: *Select the quality characteristic(s) and measurement system(s) (3a)*. This step includes identifying a (measurable) performance characteristic, which should preferably be a continuous variable.

Shainin: *Define the project (1b)*. Translating the problem into a measurable characteristic is not a separate step in the Shainin system. Yet the importance of variable data (instead of attributive data) is stressed as part of Step 1. A service-marked tool is suggested to transform attributive data into variables data (the Visual Scoring transform) [Shainin, R.D., 1993].

Six Sigma: *Select CTQ (Critical To Quality) characteristic (1b)*. The performance of a characteristic is related to a defect rate (Defects Per Million Opportunities or DPMO), which in turn is translated to a Z-metric, which is a typical Six Sigma metric.

Translating the problem into a measurable characteristic is not one of the steps of the SPC strategy. Yet the strategy implicitly assumes that a measurable characteristic is defined. All strategies stress the importance of using a continuous (variable) measurement (instead of an attributive measurement). Most strategies start from continuous data as a basis for using quantitative tools.

Step 1.3 Define and validate measurement system. The goal of this step is to ensure that measurement systems that are used for the collection of quantitative data in the next phases, are reliable. Moreover, based on this evaluation, measurement error can be eliminated as one of the potential sources of variation.

SPC: *Measurement analysis (6)*. An R&R study is used to evaluate the variation of the measurement system (note that the original order of steps is different).

Taguchi: *Select the quality characteristic(s) and measurement system(s) (3b)*. It is determined how the selected characteristic will be measured. The measurement system is assessed using an R&R study. If necessary, the accuracy and precision of the measurement system are improved.

Shainin: *Establish effective measuring system (2)*.

Six Sigma: *Validate measurement system (3)*.

All strategies stress the importance of a proper measurement system. In general one concentrates on the variation or precision of a measurement system (repeatability and reproducibility), yet the performance of the measurement system also includes accuracy, linearity, and stability. Typical tools to be used are gage R&R study and calibration.

Step 1.4 Assess current performance. The performance of the current process is assessed.

Six Sigma: *Establish product capability (4)*, both short-term (i.e., process inherent variation) and long-term (including shifts and drifts).

Only the Six Sigma strategy features a step with this goal. Yet this is an essential part of defining the problem (i.e. the difference between the current and the desired performance of the process). The performance can apply to both the variation and mean. Taking into account the SPC approach, the assessment of current performance would also include assessing whether the process is stable.

Step 1.5 Define objectives. The objectives that are to be met after the improvements are established are set.

Taguchi: *State the objective of the experiment (2)*: The performance level required when the experiment is complete is stated in 'general' terms. The three main categories are: lower the best, nominal the best and higher the best.

Six Sigma: *Define performance standards (2); Define performance objectives (5)*. Benchmarking is used to find a competitor that is 'Best-in-Class'. The difference between the current performance and the Best-in-Class performance is assessed (gap-analysis). Ambitious objectives are set (*stretch goals*). The goal can either be to change (center) the mean or reduce the variance of the selected output characteristic.

The performance analysis in the previous phase is a basis for defining objectives. The objectives can be both reducing variation and changing the mean of the process. Following the goal of the SPC approach, stabilizing the process may also be the objective.

5.4.2 Phase 2: Identification and stabilization

After going through the definition phase, the core of the improvement strategy as described in the introduction of this section starts here. In the first two steps of this phase, those factors that possibly have a significant effect are identified. First qualitative tools are used (Step 2.1), after this quantitative tools are used to analyze data from regular production (Step 2.2). Steps 2.1 and 2.2 have a dual goal: the first goal is to analyze the process in order find causes of instability of the process. This may be a goal in itself, as stated in the previous phase, but it is also a prerequisite for using experiments in Phase 3 (since experimentation requires a process that is stable or can be kept stable during experimentation). The second goal is to identify factors that should be studied in the experiments. Since experimentation is relatively expensive, a pre-selection of relevant factors should take place in this phase. As a result of this dual goal, in the last two steps, the selected causes are dealt with, removing the disturbances (Step 2.3) and the process parameters that should be subject for experimentation in Phase 3 are listed (Step 2.4).

Step 2.1 Qualitative identification of variation sources. Using qualitative tools, the process is analyzed to generate clues about variation sources, hereby exploiting existing knowledge of people involved in the process.

SPC: *Cause and Effect analysis (2b); Risk analysis (3b)*. Apart from indicating the most important characteristics of the process (Step 1.1), these techniques are also used to indicate and prioritize the important variation sources for the selected characteristic.

Taguchi: *Select the factors that may influence the selected quality characteristic(s) (4)*. Process knowledge that is present with a group of people, associated with the product or process, is utilized.

Six Sigma: *Identify variation sources (6a)*.

Note that qualitative tools are not used in the Shainin System. Shainin explicitly rejects identification of possible sources on the basis of expert insights in favor of identification based on measurements (Step 2.2) [Shainin, R.D., 1993]. Tools that are frequently used in the other strategies include Ishikawa diagrams, logbooks, risk analysis (FMEA), brainstorming and process mapping.

Step 2.2 Quantitative identification of variation sources. In this step quantitative tools are used to analyze both existing and newly collected data from regular production. The goal is to analyze the structure of variation in the characteristic under study and relate it to (potential) causes.

SPC: *Measurements (5); Control Chart (7a)*.

Shainin: *Generate clues (3a)*. Using tools such as multi-vari study, component search and paired comparisons, classes of causes that are not likely to contain the important causes are eliminated, thus homing in at the dominant variation sources.

(Note that, although qualitative tools are found unsuitable, the quantitative nature of paired comparisons can be doubted.)

Six Sigma: *Identify variation sources (6b)*.

The structure of the variation in the process may reveal *symptoms* of several sources of variation, thus providing clues on where important factors can be expected. Symptoms that show in the variation structure might include: shifts, drifts, outliers, and mixture patterns but also variance components (see Appendix 3). One can also directly link certain factors to the structure in the variation (e.g. by multiple regression).

Tools that can be used in this step are: Control Charts, ANOVA, multi-vari chart, correlation study, regression, histogram, run-chart, concentration diagram, component swapping study, analysis of means.

Step 2.3 Eliminate disturbances. The goal of this step is to eliminate or reduce disturbances, i.e. factors that cause the process to be unstable. This can be achieved by defining a structural (irreversible) change in the process in (e.g. technical changes or adjustments to working procedures) or by the introduction of controls. Defining and implementing structural changes is the subject of Step 4.1, whereas defining and implementing controls is the subject of Step 4.2.

SPC: *Improvement actions (4)*. The goal of this step is to define improvements to stabilize the process.

Shainin: *Generate clues (3b)*. Often, clues are so eminent that an important variation source can be pinpointed and no further experimentation is necessary.

The elimination of disturbances is an explicit activity within the SPC strategy. Apart from this strategy only the Shainin System appears to eliminate disturbances. Yet, in the Shainin System, no difference is made between stabilizing and optimizing the process. From the discussion of the Six-Sigma strategy in the previous section it can be concluded that identifying and removing causes of disturbances is not a goal within this strategy.

If one cannot control (or eliminate) disturbances one may aim at reducing their influence by changing the parameters of a process. This is subject for experiments in Phase 3.

Step 2.4 List process factors (for Phase 3). After removing causes of disturbances, the remaining process factors are listed as input for the next phase.

Taguchi: *Identify control and noise factors (5)*. This step aims to list the factors to be studied, divided into controllable factors and noise factors.

Shainin: *List suspect variables (4)*.

Although only the Shainin system contains an explicit step to list process factors to be used for experimentation, also the Taguchi and the Six Sigma strategy use a list of factors identified in Phase 2 as input for the next phase. Since experiments are not exploited in the SPC strategy, no corresponding steps can be found.

5.4.3 Phase 3: Experimentation for optimization and assigning tolerances

This phase has the list of identified process factors put together in Step 2.4 as its input for further analysis using experiments. After the vital few among these factors are distinguished, their effect onto the response is modeled using a designed experiment. Hence, it is necessary that the list of process parameters is complete, which means that all factors that are not in the list either have a minor effect on the response or are (kept) constant during the experiment.

The order of the phase is dictated by the following dependencies: if necessary the number of (important) factors is further reduced using a screening experiment (Step 3.1); for the most important an experiment is set up to model their effect the product characteristic under study (Step 3.2); the estimated model is interpreted to find optimal settings (Step 3.3); in these optimal settings the adequacy of the model is validated and the effectiveness of the improved settings is assessed (Step 3.4); if necessary operating tolerances are established (Step 3.5).

Step 3.1 Experimentation for screening. If necessary, the number of factors is reduced conducting a simple experiment. Experimentation consists of the phases: set-up experiment, conduct the experiment, and analyze the results.

Taguchi: *Initial screening experiment (5-11*)*. Although conducting a screening experiment is not a formal step of the Taguchi method, it is suggested to start with a screening experiment (low resolution) in case many factors have to be studied. After this an additional experiment can be set up for further analysis (sequential experimentation).

Shainin: *Statistically designed experiment: variables search (5a)*. For the sake of selecting the dominant factors out of a list of 5 to 20 factors, Shainin proposes an elimination technique called variables search. See [Ledolter and Swersey, 1997b] for a discussion.

Six Sigma: *Screen potential causes (7)*. A low-resolution experiment is used to reduce the number of factors to be studied in the next step.

A screening experiment can also be used to find relevant factors, in case one could not do this using observational data. (In the Taguchi strategy the screening experiment has a similar goal). Typical tools are: fractional factorial designs, effect plot.

Step 3.2 Experimentation to model effects. Either the screening experiment is augmented or a new experiment is set-up. The measurements are analyzed, which yields a model that describes the process.

Taguchi: *Set up and conduct experiment, analyze data, interpret results (5-11)*. In the Taguchi methodology this involves separating the factors in control and noise factors (5), selecting levels for the factors (6), selecting the appropriate orthogonal array(s) (7), selecting interactions that may be of influence (8), assign factors to orthogonal array(s) and locate interactions (9), conduct tests described by trials in the orthogonal array(s) (10) and analyze the results of the experimental trials (11a).

Shainin: *Statistically designed experiment: full factorial (5b)*. A 2^k -factorial experiment is conducted to estimate the effects of the important factors.

Six Sigma: *Discover variable relationships (8a)*. Various types of experiments are used to model the effect of the identified factors on the output characteristic. Popular experimental designs used are factorial designs, the central composite design and the Box-Behnken design. Concepts from response surface methodology [Box and Draper, 1987] are also exploited.

The experimental designs and analysis tools vary, also within each strategy. The design and analysis depends on e.g. the goal of the experiment. This matter is further addressed in Section 5.5.

Typical design tools are: factorial designs, orthogonal arrays, central composite design, Box-Behnken design, designs for robust design. Analysis tools: linear models [Searle, 1971], analysis of variance [Montgomery, 1997].

Step 3.3 Selection of optimal values for parameters. From the estimated model optimal settings for the relevant parameters are selected. Optimal here means: bringing the response on target and/or minimizing variation in the response.

Taguchi: *Analyze results of the experimental trials (11b) (parameter design)*. Typically for Taguchi experiments, the dispersion is modeled using Signal to Noise ratio's (S/N-ratios). The parameters that affect the S/N-ratio are set to minimize this measure, whereupon the parameters that affect the process' location but not the S/N-ratio are used to bring the process on target.

Shainin: *Optimize interaction (7), Realistic tolerances (8a)*. Realistic tolerances are used to fine-tune the optimal values of the Red X.

Six Sigma: *Discover variable relationships (8b)*.

Which values are optimal depends on the objective set in Step 1.5. By selecting optimal settings various types of variation problems can be solved. Typical tools are contour plots, calculus (to analyze the model), response surface methodology [Box and Draper, 1987] and robust design (see [Lucas, 1994; Vining and Myers, 1990]).

Step 3.4 Verify optimal settings. By means of additional runs the correctness of the optimal settings, and thus the correctness of the model are assessed.

Taguchi: *Conduct a confirmation experiment (12)*. This is done to demonstrate that the chosen settings do provide the predicted and desired results. If not additional experiments are necessary.

Shainin: *Better vs. Current (B vs. C) (6)*. This is a non-parametric test for assessing improvement. For this purpose a relatively small number of products is produced under the current and the improved (new) conditions.

Note that the aim of the 'B versus C' tool is primarily to verify the importance of the Red X (optimal settings are determined in the next step of the strategy). The Taguchi approach is more precise in verifying optimal settings; a confidence interval for the resulting from the optimal settings is derived (based on previous experimentation), and used to verify the predictive accuracy of the model. In the Taguchi approach also the effectiveness of the optimal settings is assessed in the confirmation experiment in order to determine whether additional experiments are necessary.

Step 3.5 Define tolerances for X-es. If the selection of optimal settings is not possible or does not result in the required performance, one can define tolerances for controllable factors causing variation in the response. This is called tolerance design [Evans, 1974/1975].

Taguchi: *Tolerance design (*)*. The relationship of the variance of the parameters to the variance of the response is established, whereupon appropriate tolerances can be set. In Taguchi's methodology this requires a new experiment.

Shainin: *Realistic tolerances (8b)*. For a range of values of the Red X, 30 products are produced in a random order and a scatter plot of the response versus the dominant process parameter is drawn. A tolerance parallelogram is used to determine tolerances for the Red X.

Six Sigma: *Establish operating tolerances (9)*. A 'region of optimal performance' in the design space is selected, providing preliminary tolerance limits for the important parameters. This is based on the model of the relations between process factors and the response.

From the above descriptions one can observe that tolerances are used in two ways. Firstly to further reduce the variation in a process by controlling causes of variation (in the Taguchi approach). Secondly to determine allowable deviations around an optimal value of a process factor (as in the Shainin approach). In the latter case, the optimal values will be selected based on the optimization of the mean. In general new (experimental) data are required to define tolerances. The tolerances can be achieved by either applying a control (to be defined and implemented in Step 4.2) or be defining a structural change in Step 4.1 (e.g. using a different kind of material with less variation).

5.4.4 Phase 4: Control and assurance

Based on the results of the previous phases one can define structural changes (Step 4.1) or implement controls, both for the output of a process and for the process parameters (Step 4.2). The effects of the improvements (Steps 2.3, 3.3, 3.4, 4.1 and 4.2) can be validated (Step 4.3). If the result does not meet the objectives set in Step 1.5, a return to a previous step is required. If the effects are satisfactory, the improved situation is assured, which concludes the project (Step 4.4). An auditing plan is developed in order that the improvements can be hold on to.

Step 4.1 Define and implement structural changes.

Shainin: *Irreversible corrective action (9)*. In the Shainin system irreversible corrective actions are a preferred alternative to controls (as defined in the next step). It concerns structural changes to the process or the product that do not require 'any active control efforts'. In this step it is assessed whether irreversible actions can be used to obtain the desired nominal value and variation in the Red X. If the Red X can change its values during production, statistical process control (10) is needed.

Also other strategies do not exclude this type of improvements. Yet the role of structural changes as a preferable alternative to controls is only stressed by the Shainin System, resulting in a specific step. Stressing the importance of structural changes as alternatives to controls complies with the observations in Section 4.2.5. Limiting oneself to controls may result in improvements that are less effective and more effective than structural changes. Structural changes involve changes in the concept or parameters of the process (or product).

Step 4.2 Define and implement controls. Controls are defined to control disturbances (Step 2.3) and variation sources (Step 3.5). In this step, the controls defined in Steps 2.3 and 3.5 are set up and implemented. The potential sources of disturbances and relevant parameters for optimization are controlled. Also the response may be monitored to detect disturbances.

SPC: *Control Chart (7b); Out of Control Action Plan (OCAP) (8); Control Plan (*)*. The OCAP gives structured directions in cases that the process is out of control. Disturbances are logged and these logs are analyzed. Thus, continuous improvements are instigated. The control system is laid down in the Control Plan.

Shainin: *Statistical Process Control (10); Positrol (*)*. Shainin advocates the use of Precontrol [Ledolter and Swersey, 1997a] instead of Control Charts. Positrol is provided as a technique for managing control of process factors.

Six Sigma: *Validate measurement system for the parameters (10); Implement process controls (12)*. The tolerance limits for the parameters are tightened in order to 'buffer' against the measurement error. Also, the difference between short-term variation and long-term variation is taken into account.

It may be clear that the IPC model and design profiles of Chapter 4 should be used in this phase (see also Section 5.6). This implies that control 'toolbox' contains a wider range of tools than those used in the strategies considered. The controls defined in this step can be both output oriented and process factor oriented (X-es). The output-oriented controls can be used to monitor the performance in terms of an important output characteristic, while the process factor-oriented controls can be used to control important (dominant) process factors. These controls form an integrated control system, which can be laid down in a Control Plan or Positrol plan.

Step 4.3 Validate effect of improvements. It is assessed whether the improvements accomplished by the elimination of disturbances (Step 2.3), parameter design (Step 3.3) and tolerance design (Step 3.4) are sufficient.

SPC: *Process capability study (9)*. The process capability study is based on data from Control Charts in the previous step. Thus also the stability of the process can be assessed.

Shainin: *Monitor results (11)*.

Six Sigma: *Determine process capability (11)*. Typical Six Sigma metrics are used.

It concerns performance over a longer time, including the effectiveness of structural changes and controls defined in Steps 4.1 and 4.2. Thus the effects of improvements are measured under real production circumstances. Typical tools used in this step are: process capability study, process capability indices, and tests such as t-tests, F-tests, non-parametric tests.

Step 4.4 Assurance / Auditing. To assure that improvements are not lost after a period of time, the performance of the process and its control system are periodically inspected. In addition, the periodical assessment of the process performance provides documented evidence showing the product's quality level.

SPC: *Certification (10)*. The process (step) is evaluated every three months and audited every year.

Six Sigma: *Audit and review (*)*. The project is reviewed by a Master Black Belt as part of the outer MAIC loop.

In Table 5.2 the steps of the generic strategy and the corresponding steps of the four strategies are summarized. Thus the main differences and overlaps of the four strategies are visualized. Although the sequence of steps in the IPI model is a logical one, it should not be interpreted in a rigid way. Firstly, iterations between steps and phases are likely to occur. E.g. results of a certain step can lead to an iteration to a previous step. Secondly, it is very well possible that not all steps are required to achieve the improvement objectives. E.g. after removing disturbances, one can go to Phase 4 in order to assess whether these improvements are sufficient to reach the

desired objectives. The selection of steps and tools within the IPI model and the influence of contingency factors are discussed in the next section.

	SPC	TAGUCHI	SHAININ	SIX-SIGMA	Functions
Phase 1: Problem definition	Process description (1) Cause and Effect analysis (2a) Risk analysis (3a)	State the problem(s) or area(s) of concern (1)	Define the project (1)	Select CTQ characteristic (1a)	1.1: Select and define problem
		Select the quality characteristic(s) and measurement system(s) (3a)		Select CTQ characteristic (1b)	1.2: Translate problem into measurable characteristic
	Measurement analysis (6)	Select the quality characteristic(s) and measurement system(s) (3b)	Establish effective measuring system (2)	Validate measurement system (3)	1.3: Define and validate measurement system
				Establish product capability (4)	1.4: Assess current performance
		State the objective(s) of the experiment (2)		Define perform. standards (2) Define perform. objectives (5)	1.5: Define objectives
Phase 2: Identification and stabilization	Cause and Effect analysis (2b) Risk analysis (3b)	Select factors that may influence the selected quality characteristic (4)		Identify variation sources (6a)	2.1: Qualitative identification of variation sources
	Measurements (5) Control Chart (7a)		Generate clues (3a)	Identify variation sources (6b)	2.2: Quantitative identification of variation sources
	Improvement actions (4)		Generate clues (3b)		2.3: Eliminate disturbances
		Identify control & noise factors (5)	List suspect variables (4)		2.4: List process factors (for ph. 3)
Phase 3: Experimentation for optimization and assigning tolerances		Initial screening experiment (*)	Statistically designed exp.: variables search (5a)	Screen potential causes (7)	3.1: Experimentation for screening
		Set up & conduct experiment, analyze results (6-11)	Statistically designed experiment: full factorial (5b)	Discover variable relationships (8a)	3.2: Experimentation for optimization
		Select optimum levels (parameter design) (11b)	Optimize interaction (7) Realistic tolerances (8a)	Discover variable relationships (8b)	3.3: Selection of optimal settings
		Conduct a confirmation experiment (12)	Better vs. Current (B vs. C) (6)		3.4: Model verification
		Tolerance design (*)	Realistic tolerances (8b)	Establish operating tolerances (9)	3.5: Define tolerances for process factors
Phase 4: Control and assurance			Irreversible corrective action (9)		4.1: Define structural changes
	Control Chart (7b) Out of Control Action Plan (8) Control plan (*)		Statistical process control (10) Positrol (*)	Validate meas. system (10) Impl. process controls (12)	4.2: Define and implement controls
	Process capability study (9)		Monitor results (11)	Determine process capability (11)	4.3: Validate effect of improvements
	Certification (10)			Audit and review (*)	4.4: Assurance / Auditing

Table 5.2: Steps of the four selected strategies and the Integrated Process Improvement model.

5.5 Contingency factors in using the IPI model

Since the IPI model is an integration of four existing improvement strategies, it encompasses a broad range of steps. This does not imply that for every problem all steps are equally relevant. Firstly, it is very well possible that some steps can be completed quickly, whereas others require more effort. Furthermore, not all steps (functions) may be necessary to obtain the desired improvement. Below we discuss the main factors that influence the relevancy of a step and the choice of tools within a step.

- *Variation pattern of product characteristic / type of problem:* If the primary goal of the improvement project is to reduce variation in the process, and the process turns out to be in-stable, the analyses in Phase 2 become of great importance. Stabilizing the process may already lead to the desired result, thus removing the necessity of steps from Phase 3. On the other hand, if the process is stable, the activities in Phase 2 are limited to identifying factors related to variance components and parameters that affect variation.
- *Nature of disturbances / Type of variation pattern of process factor:* In case of an unstable process, the disturbance pattern (see Appendix 3) determines which observational analysis tool to use in Step 2.2.
- *Type of cause system / Existence of dominance causes of variation / Common causes or special causes:* When using experiments, variation due to common causes can be 'collected' using simple (random) replication. In case of dominant causes, variation can also be evoked, e.g. using outer arrays as in the Taguchi methodology. In case the dominant factor is time-dependent, the only way to obtain a representative and comparable (noise) cause system for all trials is evoking causes to change.
- *Nature of factors with largest effect on mean or variation / variation sources versus parameters:* The strategies considered in this chapter do not explicitly discriminate between factors that are actual *sources* of variation and factors that only influence the amount of variation. The term 'variation cause' is used for both types of factors (see Appendix 1). The factor with the largest influence on variation can be of both types. The type of factor determines the possibilities to define certain types of improvements in Phase 3.
- *Possibilities to control or eliminate variation sources:* Those variation sources that cannot be (economically) controlled during production are addressed as noise factors. In case the dominant variation source is a noise factor, one can only reduce variation by reducing the influence of variations in this factor on the output characteristic considered. This can be achieved by using an experiment to determine optimal values of controllable factors (this is called parameter design). Also when variation sources are not known (i.e. when variation is caused by a large number of relatively small chance causes or common causes), the only solution may be to reduce their influence.
- *Possibilities to make structural changes:* If the parameter found to be important during experimentation is a setting of the process, the possibilities to make

structural changes may be larger rather than cases where this parameter is related to e.g. a hardware characteristic of a machine or tool.

- *Maturity of processes:* In more mature processes emphasis is often on optimizing the process (i.e. tackling stable variation), rather than on stabilizing the process. Besides this, an elaborate qualitative analysis is mostly at hand. This implies that, in case of a mature process, the first two phases in the strategy can generally be completed quickly. From this one can conclude that the main area of applicability of the SPC strategy is in relatively immature processes in which many disturbances occur, whereas the Six Sigma strategy is especially applicable in mature processes.
- *Level of process knowledge:* Extensive formalized process knowledge, for instance gained from earlier empirical analyses, enables a quick completion of the first two phases. On the other hand, if the level of process knowledge of the user(s) is low, the possibilities to use qualitative tools (Step 2.1) is limited and one has to gather new observational or experimental data to gain insight into the process. The level of process knowledge also influences the design of experiments used in Phase 3. The level of process knowledge is likely to be related to the above-mentioned maturity of the process.
- *Complexity of a process:* In case of a complex process, the number of possible factors is larger and more effort is required in Phases 1 and 2. Both to identify and remove causes of disturbances, and to reduce the number of possible factors for analysis using experiments. The complexity of a process also influences the number and design of experiments.
- *Presence of interactions and non-linear effects:* In case of interactions between process factors, it may be hard to identify these factors using observational data. The presence of interactions and non-linear effects also determines the experimental design to be used. On the other hand a non-linear effect in a certain process factor enables the selection of optimal values of this process factor in order to reduce the effect of its (uncontrolled) variations (see e.g. [Ross, 1996, p. 213]).
- *Possibilities to use experiments:* In some cases there are hardly opportunities to perform experiments because it is not possible or strongly not desirable to interrupt production. In these cases one has to concentrate on observational data to find sources of variation. (Note that EVOP, which is not included in one of the strategies, can be used to experiment during production [Box and Draper, 1969].)

Note that some of the tools within one step are so much alike that selecting one of them is a matter of preference instead of suitability. However, preferences of the user may influence the selection of tool when it comes down to differences in skills or background. For example, Taguchi uses concepts such as signal-to-noise ratios whereas in Six Sigma uses the variance to quantify dispersion. As a result Taguchi's tools are easier adopted by engineers, whereas Six-Sigma tools are more appealing to people with a mathematical background. Another example concerns the skills of the intended user: The techniques that are used in, e.g., the Shainin System and the approach to implement SPC do not require an extensive statistical training, whereas

some of the techniques that are used in the Six Sigma program assume advanced statistical skills. In case the intended users lack advanced skills, one may choose less complicated tools.

In general it can be concluded that besides contingency factors related to characteristics of the process or the product, also organizational characteristics, such as the skills and background of the intended user, are of influence on the selection of steps and tools. Since this is not the focus of this research, this matter is addressed briefly as part of the discussion in the next section.

5.6 Discussion

This chapter shows there are both differences and overlaps between process improvement strategies found in literature. The Six Sigma strategy appears to be the most complete strategy, it covers a broad range of coherent steps. Yet Six-Sigma has a strong focus on optimization and lacks attention for activities to stabilize the process. The functionality of the four strategies was compared and integrated into a logical functional structure: the Integrated Process Improvement (IPI) model.

The IPI model consists of four phases with 18 steps that form a logical order of activities and tools when improving a process. It starts with the formulation of the problem and ends with controlling an improved situation. The structure provided by the framework reveals the coherency among separate improvement steps and tools and visualizes the functions of various tools. (Note that some of the essential steps of the IPI model are not related to a formal tool, but include a non-formalized activity). The IPI model presented in Table 5.2 allows to visualize the main differences between the four improvement strategies considered in this study in terms of functionality. Especially the complementary nature of stabilization and optimization and the related steps becomes clear.

One can observe that the Integrated Process Improvement model is a generic framework containing a wide range of steps. As a result, not all steps will be equally important for each problem. However, using a generic framework for process improvement has the advantage of providing a common language. The selection of steps, the amount of effort put in each step, and also the selection of tools in each step is influenced by contingency factors. In Section 5.5 the main contingency factors were discussed. These contingency can also be used to understand part of the differences between the original strategies. Apparently the differences in functionality were (deliberately or unintentionally) originated to suit particular circumstances.

As indicated in the description of Step 4.2, the IPC model and design profiles should be used when defining controls. The analyses in Phases 2 and 3 will provide insight into contingency factors such as the dominant process factor and its disturbance pattern. Thus one can select (a set of) appropriate controls from the IPC model. Although the considered strategies focus on the use of statistical controls, also non-

statistical controls should be considered (as illustrated in Chapter 4). Note that the use of the IPI model does not necessarily result in the use of a control to solve the observed problems. A structural change may be an effective and efficient alternative for the use of controls.

The insights presented in this chapter should support practitioners from industry in understanding and selecting suitable improvement steps and tools and use them in a coherent way. Besides this, it is the starting point for further research concerning the use of the IPI model as a generic (functional) strategy for process improvement. Directions for further research to expand and improve the IPI model for this purpose are discussed in Section 6.7.

Besides the functional differences between the strategies under study, there are also differences in the implementation strategy and organizational purpose for implementation. Apart from the intended user, these differences are also reflected in the objective and the scale of the project, which can range from solving a specific problem to bringing about organizational change. The discussion of variation reduction strategies in Section 5.2 shows some differences in this respect. Taguchi, and to some extent also the Shainin System, are more or less used as ad-hoc approaches for problem solving, whereas SPC and Six Sigma are intended to be organization-wide quality improvement programs. SPC is used in a team-approach, which is partly focussed on empowering operators. Six Sigma, however focuses on middle management and specialists as the black-belts.

The possibilities and necessity to integrate a strategy based on the IPI model with an organizational framework is subject for further research. It may be clear that an effective improvement approach requires more than using the right steps and tools: the organizational problems observed in Chapter 2 also apply to improvement tools. Since especially the SPC program and the Six-Sigma program pay attention to this aspect, the comparison and evaluation of the different organizational approaches used appears to be an interesting subject for further research. For a further discussion of organizational factors see also Section 6.6.

6 Discussion and conclusions

This chapter discusses the research findings with respect to the initial research questions and objective (Sections 6.1 to 6.6). In addition directions for further research and recommendations for related research objectives are given (Section 6.7).

6.1 Causes of poor success

The first part of this research was concerned with finding answers to the initial research questions posed in Chapter 1. The first research question was: 'What are the main causes of problems in applying quality tools successfully?'. The second research question was: 'How can the problems in applying quality tools be solved?'. Concerning the first research question, the exploratory research reported in Chapter 2 indicates that the main causes reported in literature are of an organizational nature. Lack of management commitment, lack of training/skills, lack of involvement of operators, and lack of understanding of tools and concepts are the main causes of poor success as reported in literature. Yet, when taking a closer look at these causes, not all differences in the degree of success can be explained by organizational factors. Besides, organizational factors appear to be related to technical problems. These technical problems concern finding a fit between the production process at hand and the quality tools used.

The causes of problems reported in literature apply to tools in general and to all types of processes. This is largely the result of studying problems on a company level. To be able to study technical problems, problems should be differentiated for different types of processes and different tools. Therefore, case studies were used to study problems on a more detailed level. The case studies confirm the importance of organizational causes, but also provide additional insights with respect to the influence of technical circumstances. It shows that technical circumstances do not only lead to differences in tool methodology, but may also lead to selection of alternative tools (instead of one of the popular tools considered), or may even result in a situation where a tool with a similar function is not applied.

The discussion of the literature review and case studies shows that not all problems are the same in terms of the resulting symptoms. Symptoms may be caused by multiple causes and one cause may be influenced by another (sub) cause. Various types of symptoms and causes and their relations were modeled. The model is depicted in Figure 2.6, which is reprinted in a condensed form as Figure 6.1.

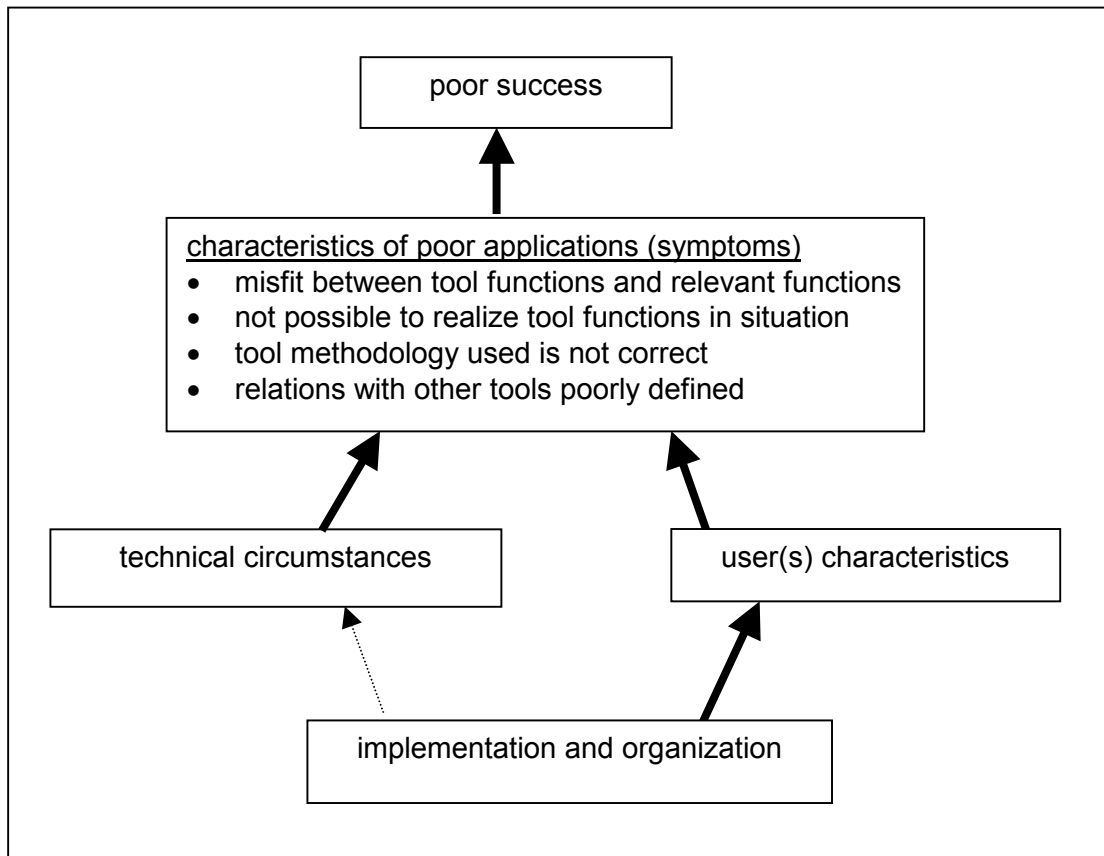


Figure 6.1: Symptoms and causes for unsuccessful applications of quality tools

Part of the problems is related to a poor fit of the tools used and the situation at hand. Although organizational factors are likely to influence this, in some situations it may be harder to find a good fit between a tool and the situation at hand. Thus technical circumstances can place higher demands on the abilities of the user. One might conclude that this is due to a lack of suitable tools, but this is not confirmed by the research results.

6.2 Possibilities for solving problems: research requirements

The goal of answering the second research question was to determine how the second part of this research could generate knowledge that supports practitioners in making effective use of existing quality tools. From Figure 6.1 it can be concluded that, in order to prevent the observed symptoms, users must be able to effectively make four types of decisions when defining the approach to be used. These decisions involve:

- Determining relevant functions
- Selecting suitable tools (to fit function and situation)
- Defining proper relations between sets of tools
- Defining tool methodology fit for situation

The quality of decisions can be improved by organizational measures, e.g. to stimulate the user to try harder. Another possibility would be to provide extensive training. This research, however, questions whether present knowledge in literature on quality tools is sufficient to set up adequate training in order to prevent the problems observed. In Section 3.1 it is concluded that current knowledge on quality tools, which is reflected in training and textbooks on this subject, is largely on the level of the methodology of single tools and often focuses on the tools of a single discipline or program. Especially on an inter-tool level there is a lack of knowledge. The deficiencies observed concern insights into the goals of tools, the relations of tools (in and outside disciplines) within a larger framework, and the considerations for selecting certain tools in a specific situation. Providing this type of knowledge is essential to support decisions that have to be made when applying quality tools.

Based on these shortages the following goals were derived for the second part of this research project.

- First: determine underlying goals of tools and build a functional framework, i.e. an integrated structure based on goals of relevant tools (from various disciplines).
- Second: determine which (contingency) factors influence the applicability of tools and provide guidelines for selecting tools from the functional structure.

Thus the second part of this research can be characterized as a contingency approach on the inter-tool level, which starts from the functions of tools. It supports part of the decisions involved when applying quality tools, as indicated in Figure 6.2.

The above focus does not imply that proper implementation and management of tools and proper tool methodology are considered to be of little importance. It should be clear that providing knowledge on functional structures and contingency factors will not solve all of the observed problems. Yet the aim of this research is to address a relevant aspect of the observed problems that gets relatively little attention in literature.

Based on the exploratory research described in Chapter 2, the remaining part of this research was aimed at finding functional structures and contingency factors for process control and process improvement tools respectively.

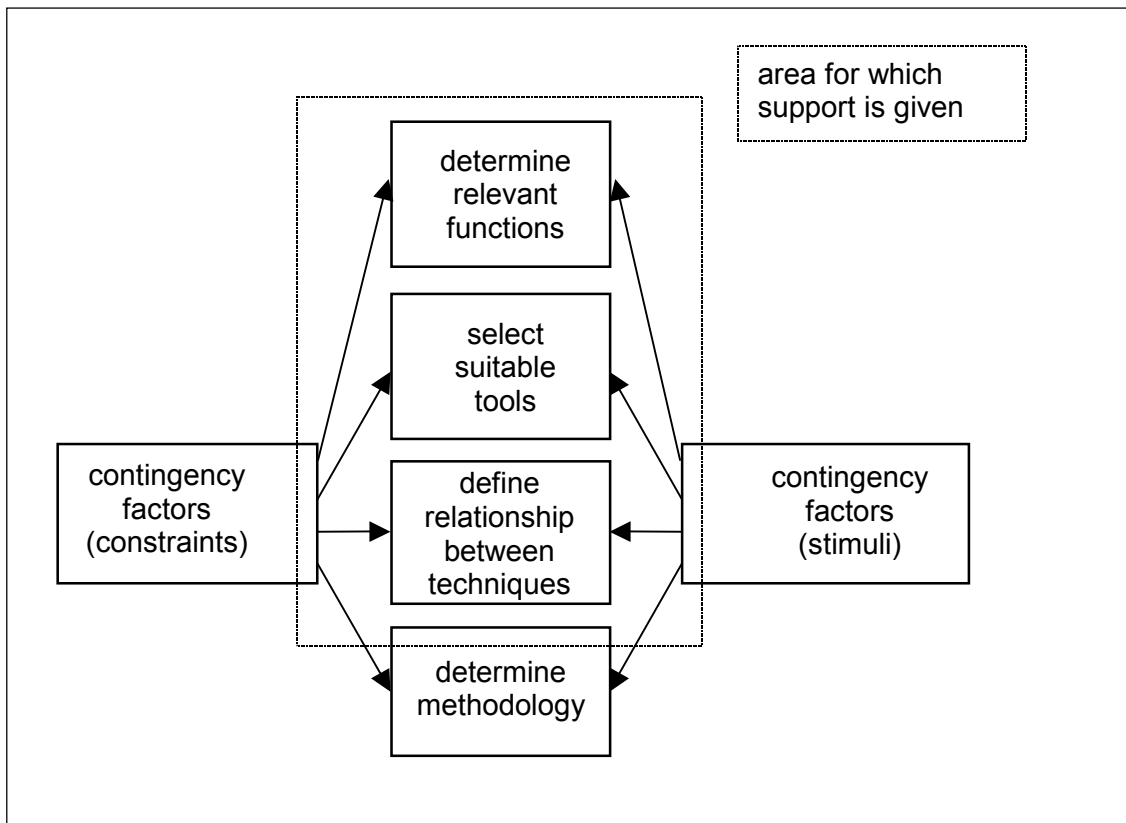


Figure 6.2: Conceptual model for decisions in applying quality tools

6.3 Functional structures

Chapters 4 and 5 demonstrate that using the functionality of tools is a suitable way to compare and relate quality tools. Thus a functional structure for quality tools can be used for decision support. The review of tools in both areas confirmed the existence of more or less separate disciplines (with respect to process control) or programs (with respect to process improvement). Through the integration of tools from various disciplines in one functional structure, users are enabled to consider these tools as a coherent toolbox

The functional structures illustrate that tools may have various functions. Examples are the Control Chart as both analysis tool and control tool in the IPI model or various functions of Poka-Yoke solutions in the IPC model. Also the necessity of applying multiple tools becomes clear. Note that the process control tools (discussed in Chapter 4) are merely used in parallel, whereas process improvement tools (discussed in Chapter 5) are typically used in a sequence.

Although control tools and improvement tools were treated separately in Chapters 4 and 5 respectively, there is a strong relation between the two types of tools. An

improvement project may result in defining controls for dominant process factors (Step 4.1 and 4.2 of the IPI model). In defining and selecting these controls, the IPC model and design profiles can be used. Another relation arises when improvement actions are initiated based on measurements used for control. Use of the Control Chart as a tool for both control and improvement is an illustration of this relation.

6.4 Contingency factors

The functional models derived in Chapters 4 and 5 respectively, can be seen as generic 'toolboxes' from which a user can select a set of tools for a specific situation. The advantage of a generic toolbox is that it provides a common framework for approaches to be used in various situations. Yet contingency factors influence both the necessity and the possibilities for using certain functions or tools in a certain situation. Providing knowledge on contingency factors will support the user in selecting functions and tools. Although contingency factors may be of an organizational nature, in this research we focussed on technical contingency factors.

The main contingency factors for selection of process control tools are related to the dominance of certain process factors, the type of disturbance in this factor, and various factors related to the possibilities and necessities for taking measurements and making interventions. To provide a more practical form of decision support, the contingency factors for process controls were used to derive examples of scenarios or design profiles for process controls.

Concerning the selection of functions (steps) and tools for process improvement, the main contingency factors are related to the nature of the problem to be solved in terms of the type of cause system leading to the disturbance and the pattern of the resulting disturbances. Also the level of knowledge present is of influence on the selection of steps and the amount of effort to be put in the selected steps.

Only part of the differences between the original disciplines and programs can be explained by these contingency factors, which confirms the relevance of integration.

6.5 Use for decision support

The overall research goal was to provide decision support for the application of existing process control and improvement tools. The results of this research should help practitioners in choosing the right tools and applying them in the right (coherent) way. Although the precise form of such a system was not clear, a 'pigeon-holing' - system that would prescribe one specific set of tools based on an input of situational characteristics would be the most elaborate form of decision support. The findings of

this research do not support in this 'one on one' way. Firstly, generating knowledge on this level for the whole relevant field of control and improvement tools is hardly possible within the time frame of a Ph.D.-research. It would require quantifying and balancing all relevant contingency factors. Secondly, it is not desirable to aim at this form of decision support since judgement of the user remains necessary to fine-tune the approach used to a specific situation. It is doubtful whether it is possible to consider all factors of a specific situation, without judgement of the user. Thirdly, providing the user with a set of tools (although suitable for the situation) without insight into goals and considerations for selecting these tools can lead to a tool-oriented approach, in which the application of the tool becomes a goal in itself.

The type of decision support provided by the results of this research does not guarantee that the optimal tool will be selected, but it will increase the chance that suitable tools will be selected, used for the right purpose and in the right context. Nevertheless the intelligence of the user is still required to make the right decisions in applying quality tools. The results of this research support the user when making these decisions through:

- Providing a framework including the most relevant tools instead of a limited set of tools from one discipline or one improvement strategy.
- Providing insight into alternatives to choose from and guidelines for choosing tools.
- Providing insight into the goals of tools within a broader framework of process control or process improvement.

Without these insights, the application of quality tools is not necessarily doomed to fail. In time, users may acquire similar insights by 'trial and error' or 'learning by doing'. However, by providing knowledge on functions and contingency factors the learning curve may be improved. Thus the chance of success is enlarged and the risk of a negative attitude towards certain tools, due to unsuccessful 'trials' is lowered.

For quality professionals the contents of this thesis may be accessible, but for other users, such as operators and engineers, the results of this research have to be translated into a more practical form. To become effective in practice, the results of this research should be used as input for training (both classroom training and training on the job). Firstly, training should be less mono-disciplinary: an integrated approach covering the whole area should be used. Secondly, in addition to the mere methodological aspects of tools, training should provide insight into goals of tools and relations between tools. The IPC model and the IPI model can be used for these two purposes. Thirdly, training should give insight into the limited relevance and applicability of tools by providing contingency factors and design profiles. Further work will be aimed at transforming knowledge from this research into practical applications. The implications for further research are discussed in Section 6.7.

As concluded from Chapter 2, however, the ultimate success is not only dependent on selecting the right tools. The implementation and management of tool applications is also essential. The main conclusions concerning these organizational factors are presented in Section 6.6.

6.6 Relation with organizational factors

Although this research is not focussed on organizational factors, their importance should not be ignored. Making effective use of quality tools requires more than being able to select a suitable tool. Factors such as the commitment and involvement of people are also essential. Although part of the acceptance depends on the (perceived) quality of the tool, the implementation and management of tools have a large influence. (Refer to the summary of organizational factors in Section 2.2.)

Experience in applying quality tools shows that organizational factors are essential for success. As a result, programs such as SPC, TPM and Six Sigma consist of both a methodological and an organizational part, not only to ensure acceptance of tools, but also to enlarge the amount of effort that can be put into quality control and improvement. Furthermore, the communication between various people involved is essential. Therefore a multidisciplinary team-approach should be used, in which various groups (such as operators, design engineers and maintenance engineers) are represented.

The findings of this research support the use of multi-disciplinary teams when improving processes. Firstly, this ensures that all relevant existing knowledge of the process can be used. Secondly, both technical and quantitative analytical skills may be required in the project, which implies the involvement of people with different backgrounds. Thirdly, various types of improvement may be the 'expertise' or task of a certain discipline or group of people (e.g. maintenance engineers, process engineers, development engineers, quality engineers or operators). Yet the ultimate outcome of the project, i.e. the type of improvement action necessary to reach the objective, can not be predicted beforehand.

Implementing an approach for quality control and improvement in an organization requires a long-term effort. As a result, the drive of a (recognizable) discipline or program, such as SPC, TPM, or Six Sigma may be necessary to obtain commitment and to facilitate organizational change. However, adapting only one of these programs may cause a limited scope on process control or process improvement tools, resulting in sub-optimal solutions. On the other hand, it would be confusing to launch or use multiple programs simultaneously. In practice, the launch of a new program is often not linked to existing programs and attention for these old programs diminishes. As a result, people in the organization who have put a lot of effort into

adopting the previous program, become skeptical and assume it is just another program that will blow over in a few years.

This brings up the question whether the IPC and IPI model should ultimately result in a new program for process improvement and control. Based on this research one can conclude that methodological (i.e. functional) integration into one program is possible. However, future research is necessary to determine the possibilities and desirability of integrating the organizational parts of various programs. At this moment, the most important organizational implication for practice applies to training. In fact this research underlines the importance of (the right type of) training as an organizational factor for success. If an organization does not provide opportunities for training in both methodological and functional aspects, the results of this research cannot become effective.

6.7 Directions and recommendations for further research

This section will address directions for expanding the research described in this thesis and give recommendations for future related research.

1. Further development of the IPC and IPI model, contingency factors and scenarios through application in practice.

Future research will be directed at practical application of the results of this research. Experience of using the IPC and IPI model in practice could be used for further development of these models, the contingency factors and scenario's. Also experience in using the material for educational purposes will enable its further development. The possibilities of developing the IPI model as an improvement strategy (with the IPC model included in the final phase) should be assessed. Also the necessities and possibilities of providing an integrated organizational framework should be addressed.

2. Possibilities to use the IPI model for Continuous Improvement.

The improvement strategies described in Chapter 5 take the form of improvement projects. However, following the philosophy of Continuous Improvement (CI), improvements should not stop after the end of a project. Of course one can define a new project after completing the former, but preferably the IPI model should also support a more continuous approach. The analysis of data from regular production (e.g. Control Charts used for output control, or scrap data) as used in Phase 2 of the IPI model can function as a continuous activity that may give rise to further analysis and definition of an improvement project. The use of the model in this sense is a subject for further research. A discussion on the relation between CI and quality tools has been published in [Schippers, 1998b].

3. *Structure and applicability of quality tools in design of products and processes.*

The scope of this thesis was the control and improvement of existing production processes. This does not mean that process improvement of new processes, and defining the control of new processes as part of design activities, is considered to be less important. The opposite is true. Yet, to ensure that the research activities would fit within the throughput-time of a Ph.D. research, it was decided that this area would not be considered. The application of process improvement tools in this area is a subject for further research. A starting point for extending this research in this direction may be process development and in particular process release.

4. *Higher level control loops: selection of processes to be improved and monitoring of processes after improvement.*

The IPI model presented in Chapter 5 starts from a process that is selected for improvement. It includes steps for selecting the parameters to be studied in a process, but it does not provide tools for selecting processes to be improved. Information on quality performance in companies is often not suitable for locating problem processes and main causes of problems in a process. Information is often gathered for administrative purposes. Thus the selection of processes to be improved in relation to the use of process control and improvement techniques could be a subject for further research. Related to this is monitoring the performance of a process after improvement. Both activities can be seen as part of higher-level control loops. To prevent suboptimization on one aspect of performance, this would involve not only the use of quality metrics such as scrap and rework, but also the use of time-related and financial metrics. Note that this subject is closely related to activities in the 'Outer MAIC' loop of the Six Sigma program.

5. *Integration of quality and time aspects in process control and improvement.*

In the IPC model presented in Chapter 4, the time-performance of a production process (in terms of breakdowns and setup-times) was not included in the performance that was considered to be influenced by the control of a process. Yet it is quite possible that downtime is a result or even an alternative indication of quality problems. For instance in cases where a machine is shut-down when a defective product is produced, the effect in terms of quality will be low (one product) but the effect in terms of time may be much higher (for instance 1 hour downtime in which a few hundred products might have been produced. Up to now, few quality tools have been designed or used for time-related performance aspects of process output. Further research could be directed at assessing opportunities for integrating time (non-logistical) and quality performance in process control. Related to this is the issue of using time-related performance measures as a starting point for process improvement.

7. *Application of quality tools in recovery processes.*

Although the application of various quality tools in the area of production has received considerable attention, this is certainly not the case for a new and growing area of 'production': recovery. It concerns various processes to recover products, parts or materials from discarded goods, such as disassembly, cleaning, shredding and separation. The application of quality tools is relatively unexplored in this area. Further research could address the possibilities of applying process control and improvement techniques to remove and prevent disturbances that are typical for this type of production and the necessity of modifying traditional tools for this area. An initial review of opportunities for using quality tools in this area has been published in a paper by Melissen and Schippers [Melissen and Schippers, 2000].

8. *Application of process control and improvement techniques for product reliability.*

Current tools for controlling and improving processes often start from problems in a product characteristic that can be measured as soon as the product is produced (such as a dimension or a function of this product). However, in current markets not only the quality of the product on the moment of delivery is relevant, but also the quality over time, i.e. the reliability during product use, is becoming of growing importance [Sander and Brombacher, 1999]. Traditionally the area of reliability is mainly focussed either on detailed behavior of components or on system structures consisting of ideal components. A subject for further research would be: Can current quality tools and the underlying concepts of variation thinking and process thinking be applied to monitor and improve processes in terms of the reliability of the products produced?

This subject will have a strong relationship to product development, since a product that passes product assurance activities, but fails during use may imply the use of the wrong specifications or even the wrong characteristics when controlling or improving processes. Analyses of field information will be necessary to address this problem.

9. *Managing process knowledge for process control and improvement.*

This research shows that knowing the relations between process factors and product characteristics is essential in controlling and improving production processes. The collection, representation and 'storage' of this knowledge is not only relevant as part of an improvement project. The management of process knowledge between projects is also necessary. Firstly, in order to prevent that it disappears when employees move to other functions or companies. Secondly, to allow other people to learn from past experience. This issue is discussed in a paper on the use of the 'process matrix', which is a tool for analyzing and describing production processes [Schippers, 1999]. Further research will be directed at the further development and use of this tool in the area of process control and improvement.

Appendices

Appendix 1: List of definitions

Appendix 2: List of acronyms

Appendix 3: On causes and classes of variation

Appendix 4: Design profiles (scenarios) for process control

Appendix 1: List of definitions

Below the definitions used in this thesis will be clarified. Note that the definitions used in literature are not always equally interpreted. As a result the definitions in this thesis partly deviate from the ones used in some of the referred literature. Definitions marked with an asterisk (*) are further explained, e.g. to motivate deviations from regular definitions.

Assignable cause:

See 'Special cause'.

Chance cause:

See 'Common cause'.

Common cause:

A process factor with contributes to the process inherent variation.

**Often a common causes is seen as having (a continuous) and minor influence on the output of a process, typically occurring as a part of a system of common causes, and resulting in a stable variation pattern. The above definition is based on the fact that it is (accepted to be) inherent to the process. Thus it is used as the opposite of a 'special cause'. Common causes are also addressed as 'chance causes'. See Appendix 3 for a further discussion.*

Consistent cause:

A process factor with a continuous, time independent influence on the output of a process, i.e. with a stable variation pattern.*

** This term is used by Shainin [Shainin and Shainin, 1988], as an opposite of a 'transient cause', to address whether a process factor has a continuous equal influence (consistent cause) or an influence that varies over time (transient cause). Note that a consistent cause may be both a variation cause (with a stable variation pattern) and a process parameter.*

Contingency factor:

A characteristic of the situation at hand that influences the applicability of a tool.*

**See e.g. [Dessler, 1976] or [Melan, 1998] for a related reference. Contingency factors are also addressed as 'situational factors'.*

Controllable factor:

A process factor of which the value can (practically) be set or influenced.*

**The term controllable factor is promoted by Taguchi. It is used in conjunction with the term 'noise factor'.*

Disturbance:

A deviation from a stable variation pattern.*

**See stable variation pattern*

Dominant process factor:

A process factor with a dominant influence on the output of a process.*

**Often a special cause is also seen as a factor with a dominant influence. Yet in the Control Charting context a dominant cause may be process inherent or acceptable and thus not addressed as a special cause. Therefore a separate definition is used. See 'special cause'.*

Effect:

The change in the location or spread of a product characteristic as a result of a change in a process parameter.*

**This term is generally used in the context of designed experiments.*

Function of a quality tool:

A goal of applying the activities of a tool.*

**Note that in this thesis the function of a tool is used in conjunction to its methodology (its primary goal) and not to address organizational goals such as 'empowering operators' or 'stimulating decision making based on quantitative data'.*

In statistical control:

A state of the process referring to a series of realizations that follow a predetermined statistical model, which implies that the realizations are predictable (within limits).*

**If a Control Chart is used to monitor the conformance of realizations to this model, statistical control implies that the process shows no out of control situations. This definition implies that statistical control depends on the predetermined model, and does not always imply a 'stable variation pattern'.*

Noise factor:

A process factor of which the value cannot be (practically) set or influenced.*

**The term noise factor is promoted by Taguchi. It is used in conjunction with the term controllable factor. A noise factor may refer to a factor that is not known, and as a result cannot be set or influenced. Note that it may be possible to set or influence a noise factor under special (laboratory) conditions.*

Process:

A combination of factors that are of influence while producing a specified product. (based on [ANSI, 1990, p.820])*

**Often processes are defined as: 'a collection of mutually related resources and activities, which transforms input into output'. Yet in this thesis, the inputs of a process are considered as part of the factors within a process that are of influence and thus can be the subject of control or improvement. Therefore a deviating definition is used.*

Process condition:

A special type of process factor, referring to a characteristic of a running process, which is the result of various other process factors and cannot be directly acted upon.*

**An example of a process condition is powder flow in case D, which is the result of various other factors such as the nominal setting of the powder flow, the state of the tubes and the state of the pistol. (Section 2.3). See also 'process factor'.*

Process control tool:

An activity to monitor and/or to adjust a process in the manufacturing stage.*

**A process control tool is also addressed as a 'control' or 'control tool'*

Process definition:

A description of the target value and tolerances of the process factors.

Process factor:

A characteristic related to a part of the process (such as machine, materials, tools, settings, operator, and environment) that may influence the output of a process.

**A process factor may be both a 'variation cause' and a 'process parameter', see corresponding definitions. A process factor may be denoted as 'X_i'.*

Process improvement strategy:

A coherent series of steps aimed at reducing the variability of a process by identifying factors that affect variation and generating improvement actions.*

**See Section 5.1*

Process improvement tool:

An activity used to identify, remove or optimize the influence of process factors on a product characteristic.

Process inherent variation:

Variation which is considered to be acceptable or to some extent unavoidable, and can be described by a statistical model.*

**If the statistical model is used as a basis for a Control Chart, process inherent variation can be defined as variation that will not lead to an out of control signal of the Control Chart.*

Process parameter:

A process factor of which a change in the nominal value will result in a change in the level of variation or the location of an output characteristic.*

**See variation cause for a discussion on this definition.*

Process setting:

A class of process factors of which the (nominal) value can be deliberately changed to a certain value during production without large costs, and which is not subject to change due to other factors.*

**In general a process setting concerns a process factor that was intended to enable operators to manipulate or fine-tune the process, e.g. the temperature settings of a furnace, the speed of a drilling process or the focus distance of a lasercutting process. See 'process factor'.*

Process variation:

The deviations in the value of a product characteristic over a certain period of time.

Product characteristic:

A relevant characteristic of the product produced by a process.*

**A product characteristic may be denoted as 'Y' or 'Y_i'.*

Product definition:

A description of the target value and tolerances of the product characteristics.

Quality tool:

An activity that follows a certain methodology aimed at controlling or improving the quality of products or processes.

Special cause:

A process factor which causes a process to be not in statistical control.*

** The Control Chart is used as a basis for an operational definition of a special cause. In literature often definitions are used that also refer to the magnitude of the influence of a special cause (see 'dominant cause'), but also to the fact that the influence of a special causes varies in time (see 'transient cause'), and the*

fact that it can be (economically) identified and removed, since it is considered not inherent to the process. Special causes are also addressed as 'assignable causes'. For a further discussion see Appendix 3. A special cause is used as an opposite to a 'common cause'.

Stable variation pattern:

A variation pattern in which the individual realizations are mutually independent and follow a fixed probability distribution.*

**Depending on the model that is used as a basis for a Control Chart, a state of statistical control may equal a stable variation pattern. The standard model used in textbooks equals the above definition. Yet, in practice, it will be hardly possible or desirable to obtain a process that totally matches a stable variation pattern. See Appendix 3 for a further discussion. See also 'variation pattern'.*

Stable process:

A process that displays a stable variation pattern, for a certain product characteristic.*

**See the discussion of 'stable variation pattern'.*

Transient cause:

A process factor with a changing, time dependent influence on the output of a process, i.e. with a non-stable variation pattern.*

**This term is used by Shainin [Shainin and Shainin, 1988], as an opposite of a 'sustained cause', to address whether a process factor has a continuous equal influence (a consistent cause) or an influence that varies over time (transient cause).*

Variation cause:

A process factor of which the values vary in practice, and of which reducing this variation would lead to a reduction in the variation in a certain product characteristic.*

**The term variation cause or 'variation source' is used to address a group of factors of which the variation can be controlled in order to reduce variation, as opposed to a group of process factors, called 'process parameters', of which changing the nominal value can be used to reduce variation in a certain product characteristic. Note that a process factor can be both a process parameter and a variation cause. E.g. in case of material thickness, the nominal value can be set (process parameter), but in practice fluctuations in the actual value may occur (variation source).*

Variation pattern:

A series of changes in the realizations of a process factor or product characteristic over time.

Appendix 2: List of acronyms

ANOVA	ANalysis Of VAriance
APC	Automatic Process Control
AQL	Acceptable Quality Level
CI	Continuous Improvement
CT	Control Theory
CtQ	Critical to Quality
DoE	Design of Experiments
DPMO	Defects Per Million Opportunities
EFQM	European Foundation for Quality Management
EPC	Engineering Process Control
FMEA	Failure Mode and Effect Analysis
IPC	Integrated Process Control
ISO	International Standardization Organization
LCL	Lower Control Limit
LSL	Lower Specification Limit
MAIC	Measure Analyze Improve Control
OCAP	Out of Control Action Plan
OEE	Overall Equipment Effectiveness
PCS	Process Capability Study
PPM	Parts Per Million
QFD	Quality Function Deployment
R&R	Repeatability and Reproducibility
SPC	Statistical Process Control
SQC	Statistical Quality Control
TPM	Total Productive Maintenance
TQM	Total Quality Management
UCL	Upper Control Limit
USL	Upper Specification Limit
WCM	World Class Manufacturing

Appendix 3: On causes and classes of variation

1. Introduction

In literature concerning the control and reduction of variation, various names are used to denote different types of causes and classes of variation. A number of terms that are often used (in literature on SPC, APC and DoE) is listed in Table A3.1. (Terms that are used as opposites are listed in the same row.) Upon using these terms for this research, it turned out that 1) they are not mutually exclusive and 2) various interpretations of the same term can be observed in literature 3) many terms are related to using Control Charts, whereas in this research there is a need to define causes and classes of variation independent of a tool or discipline. This appendix aims at providing a clear framework and categorization of causes of variation and the resulting types of variation. Both Chapters 4 and 5 refer to this appendix for a clarification of variation causes and classes. Refer to Appendix 1 for definitions of terms used in this appendix.

Term	'Opposite'	Reference
in statistical control	out of control	Shewhart, 1931
process inherent variation		Shewhart, 1931
stable system of causes		Shewhart, 1931
chance causes	assignable causes	Shewhart, 1931
unknown causes	known causes	Shewhart, 1931
common causes	special causes	Deming, 1986
random variation	systematic variation	Cowden, 1957
controlled variation	uncontrolled variation	Wheeler and Chambers, 1986
background noise		Montgomery, 1996
noise factors	controllable factors	Taguchi, 1986
consistent cause	transient cause	Shainin and Shainin, 1988
stable process	unstable process	Moen, Nolan and Provost, 1991
noise	signal	Wheeler, 1993

Table A3.1: Examples of terms used to address classes and causes of variation

2. The meaning of the term 'in statistical control'

The term 'in statistical control', which was introduced by Shewhart [Shewhart, 1931], is a central term. The concept of statistical control and the distinction between common and special causes of variation, is broadly accepted within the quality profession. However, upon reviewing literature, it shows that the term statistical control is interpreted in various ways. Thus one particular series of observations from

a process (a variation pattern) may be addressed as either in or out of statistical control.

The original definition of a process that is in statistical control (for a certain characteristic of the process or its output), is that 'differences in the qualities of a number of pieces appears to be consistent with the assumption that they arose from a constant system of chance causes' [Shewhart, 1931, p.146]. Montgomery translates this in 'a process that is operating with only chance causes of variation present' [Montgomery, 1996, p.130]. The 'constant systems of chance causes give rise to frequency distributions' [Shewhart, 1931, p.133], i.e. outcomes that follow a fixed probability distribution. Shewhart introduced the Control Chart as a tool for determining whether a process is in statistical control (i.e. the realizations of a certain characteristic follow a fixed probability distribution). The Control Limits of the Control Charts are statistical limits that indicate whether outcomes can be assumed to match a certain probability distribution. The original Shewhart Control Chart assumes that short-term variation is equal to long-term variation. Thus to calculate the control limits the within-sample variation is used.

According to Shewhart, variation within these limits should be left to chance: If the value of a characteristic changes in a certain direction, there is a large probability that within a few products, the values will change to the opposite direction. Thus interventions would only lead to larger variations. When observations fall outside these limits, the process is said to be 'out of control' and 'looking for assignable causes is worthwhile' [Shewhart, 1931, p.148]. The 'worthwhile' criterion is based on economic criteria. Identifying and removing chance causes is considered to be too expensive. As suggested by Deming, 'chance causes' are nowadays often addressed as 'common causes', whereas 'assignable causes' are addressed as 'special causes', thus stressing that common causes are considered to be inherent to the process [Wheeler and Chambers, 1986, p10].

The above shows that the main distinction made concerns two classes of processes: 1) a process with only common causes that is in statistical control, 2) a process with common and special causes that is thus not in statistical control. In literature various statements have been made concerning each of these classes. Below we will give some examples.

Statistical control / common causes:

- Common causes should be left to chance because they can only be removed by making basic changes to the process [Juran, 1988, p.24.3].
- Common causes are inherent to the process [Montgomery, 1996, p.130].
- Common causes form a system of 'many small, essentially unavoidable causes' [Montgomery, 1996, p.130].
- Variation due to common causes is the result of a 'large number of small independent causes' leading to random variation [Cowden 1957, p.2].
- Common causes form a constant cause system [Cowden, 1957, p.225].

- A process (or a system) that has only common causes effecting the outcomes is called a stable process or said to be in a state of statistical control [Nolan and Provost, 1990].
- In a stable process, the cause system for variation remains essentially constant over time [Nolan and Provost, 1990].
- They are continuously present with an equal influence over time [Does et al., 1999].
- 'Any unknown cause of a phenomenon will be termed a chance cause' [Shewhart, 1931, p.7].
- 'A process will be said to be in control when, through the use of past experience, we can predict, at least within limits, how the process will behave in the future' [Shewhart, 1931, p.25; quoted in: Wheeler, 1993, p.24].
- Variation due to common causes is consistent over time [Wheeler and Chambers, 1992, p13].
- One should cease to ask for explanation of noise [Wheeler, 1993, p.118].

Out of control / special causes:

- Their influence is generally large when compared to background noise [Montgomery, 1996, p.131]
- Their influence varies in time [Does et al., 1999]
- *Various statements that refer to the opposite of statements made for statistical control/common causes*

Thus we see that several terms listed in Table A3.1 are associated with 'statistical control'. However there appears to be some ambiguity around the exact meaning of these terms. Furthermore, some authors do not agree with this classification. Below some examples are discussed.

An example of a deviating use of the terms 'statistical control' and 'common causes' can be found in Batson [Batson, 1994]. Batson discusses various variation components (and related causes), within a process that is in statistical control. However, part of these variation components and causes will lead to changes in levels of mean or variation, and are used by other authors as typical examples of special causes of variation that will be detected by a Control Chart. Yet Batson refers to them as common causes that can be modeled by a probability distribution with a (fixed) variance. Examples are shipment to shipment variations of materials used in the process, day-to-day and within day variations of operators, and variation due to wear of tools.

Another ambiguity concerns the linking the 'statistical control' to the terms 'process inherent variation' and 'stable process' and by using the Control Chart as a way to define what is statistical control (cf. [Nolan and Provost, 1990]: 'The Control Chart is the means to operationally define the concept of a stable process.'). The problem is that some variation patterns (such as a trend in the mean due to tool wear in a turning process) are considered to be process inherent, although they do not result

from a stable chance system. This has led to the introduction of special Control Charts that will not detect these patterns as an out of control caused by an assignable cause. An example is a Control Chart that is corrected for known tool-wear trends [cf. Montgomery, 1996, p.414]. Also the introduction of other types of Control Charts, such as the \bar{X} -R Control Chart with limits based on moving ranges [see e.g. Does, Roes and Trip, 1999], are the result of the observation that in practice some variation patterns, which are not stable (i.e. time-dependent) are apparently process-inherent. Thus, the terms common causes, assignable causes, and process inherent variation are depending on what variation pattern one accepts. However, through this the classification 'stable process' also depends on what is accepted and not solely on the variation pattern observed (i.e. the same variation pattern may be addressed as either in statistical control or not in statistical control).

A third point of discussion concerns the fact that variation due to common causes is assumed to be process inherent and thus unavoidable without fundamental (and costly) changes in the process. As a reaction to this Pyzdek [Pyzdek, 1990] states that 'there is no such thing as a common cause'. By using the terms 'in statistical control', 'common causes' and 'process inherent causes' as a synonym, the impression is given that a process that is in statistical control can only be improved by fundamental changes in the process. It may even introduce the belief that 'common variation has no cause'. The examples given by Pyzdek illustrate that all this is not true: also stable variation can be caused by characteristics of the process that are not inherent to the process and not hard to change. We agree that every variation has a cause, i.e. is caused by some parts of the process (process factor). Yet, although the alternative classification suggested does challenge the traditional one and stimulates the search for causes of variation, it does not give a framework for variation types and causes as needed in Chapter 4 and 5 of this thesis.

Also [Shainin and Shainin, 1988, p.24.6] state that 'random variation' (i.e. a stable variation pattern) is not necessarily caused by common causes, i.e. many small causes that are inherent to the process and hard to remove without making fundamental, costly changes to the process. Shewhart suggests that major causes of variation will be detected as assignable causes, but this is doubted by [Shainin and Shainin, 1988, p.24.6]. They state that 'Shewhart's assignable cause was a transient Red X'. However, Shainin and Shainin show that the major causes of variation (called Red X's) do not only take the form of transient causes (causes of which the influence changes in time). They show that a stable variation pattern of a product characteristic may also be largely caused by a dominant process factor with a stable variation pattern (called a consistent red X). Unlike the common causes of Shewhart, this type of process factor is not necessarily hard to find and remove. As a reaction to the traditional view, R. Shainin [Shainin R.D., 1993] states: 'There is no such thing as random variation..'. From another publication it can be concluded that 'random' here refers to the 'mathematical definition of random-without a cause' [Shainin and Shainin, 1988, p.24.3]. Thus, what is meant is that there is no variation that is not caused.]

3. The need for clear definitions

As a result of the above it seems necessary to disconnect the terms 'in statistical control' and 'stable process'. The term 'stable process' should be used to address a product characteristic or process characteristic, of which the individual realizations follow a stable variation pattern. Thus the term stable process can be used to address a process that displays a variation pattern that does not contain a signal that can be used to intervene in this process. A stable variation pattern is defined as a variation pattern in which the individual realizations are mutually independent and follow a fixed probability distribution (see Appendix 1). Whether a variation pattern is inherent for the process or not, should not change the definition of the term 'stable variation pattern'. One should use the term 'in statistical control' to address variation patterns which one cannot or does not want to control by means of interventions.

Also the terms common causes and special causes should not be used too rigidly. As Cowden [Cowden, 1957, p.2] says: 'This classification of types of variability is for purposes of convenience. It seems reasonable to suppose that with sufficient information all variability could be accounted for'. As mentioned above, also Shainin and Shainin show the dangers of using the term common causes, especially when one supposes that only many small insignificant causes can generate a stable variation pattern (and as a result that a major cause of variation will always be detected as a special cause). Therefore we suggest to use the term special cause in relation to the use of a certain type of Control Chart (as it was intended). To address the level of influence of a factor or the difference between time-dependent or time-independent influences we suggest the use of the terms 'dominant cause', 'transient cause' and 'consistent cause'. See Appendix 1 for a further explanation of these terms.

Starting from the principle that every variation pattern has a cause, below we will categorize non-stable variation patterns and, related types of causes (process factors). In practice these variation types cannot be strictly distinguished. Also the distinction between stable and non-stable variation patterns is a continuous one, i.e. in practice there is no strict limit or dichotomy. Yet this appendix will discuss 'typical' non-stable variation patterns. In doing this we will not start from patterns that appear from sampling a process. Instead we will start from the variation patterns of all (discrete) products produced. The frequency of taking measurements could be the result of the observed pattern, but should not influence this pattern.

4. Patterns and causes of non-stable variation patterns

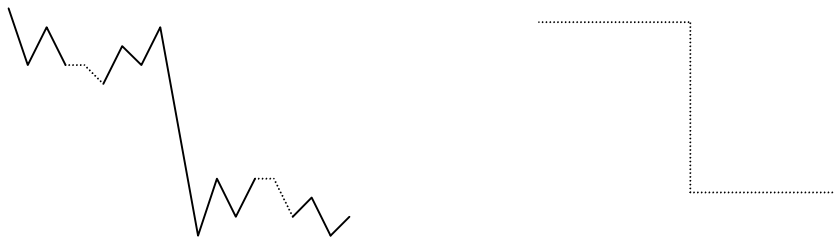
If a non-stable variation pattern occurs, this implies that besides a degree of 'noise' there is a 'signal' that can be used as a basis for intervening in the process, in order to reduce (long term) variation. In case of a stable variation pattern, intervening in the process (in terms of a change in the location) would enlarge variation. To detect non-stable patterns and intervene in the process, one can use the controls discussed in Chapter 4. The type of disturbance will influence the possibilities and effectiveness of a control.

Below we will discuss various types of non-stable variation patterns (also addressed as disturbances) in a product characteristic, i.e. variation patterns of which the probability distribution changes in time. In practice these patterns may occur in combination, when various causes simultaneously influence the considered characteristic. Note that the patterns refer to consecutive individual realizations in a characteristic of a discrete product. Thus the patterns are not depending on the frequency, timing or size of samples, as is the case in discussions of Control Chart patterns in e.g. [Gitlow et al., 1989].

The patterns will be described and examples of causes in practice are given. A simple graphical representation of the variation pattern (individual realizations) will be provided (left-hand side) to illustrate the pattern that may be observed in practice. Besides, the underlying change in the probability distribution is depicted (on the right-hand side).

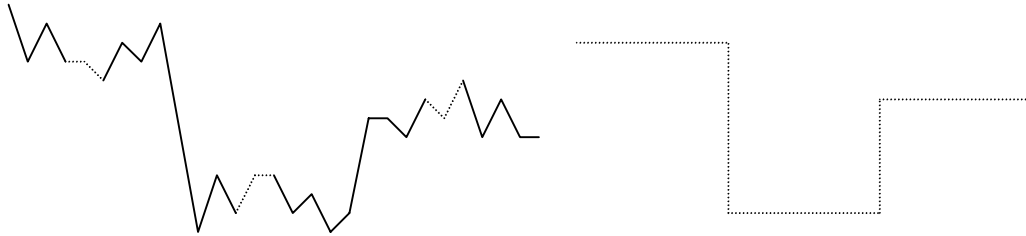
Sustained shift in the mean

The sustained shift [c.f. Montgomery, 1996, p.133] is the typical pattern addressed by a Control Chart. It is a 'step', from a stable process with a certain mean to a stable process with a different mean, that is more or less permanent or persistent (this as opposed to the cyclic shifts). This pattern is schematically depicted in the figure below. A sustained shift may be caused by unplanned changes in the process, such as a part of a machine that breaks down, using a poor batch of materials, or a gauge that is moved by accidentally bumping a part against it.



Cyclic shifts in the mean

A cyclic shift may be caused by causes that are more or less planned to happen with a certain frequency. Examples are using a different batch of materials or a change from the day shift to the night shift.



Sustained drift in the mean

A sustained drift in the mean is a pattern of successive changes in a certain direction that may continue in time or may result in a stable process with a different mean. The pattern of changes may be linear (as depicted), but may also follow a certain curve. This pattern is also addressed as a 'run' [see e.g. Cowden, 1957, p.169]. Wear of a tool or machine part is a typical example of a cause for a sustained drift.



Cyclic drifts in mean

Cyclic drifts take the form of a 'sawtooth' pattern. The mean drifts for a certain period of time and then suddenly returns to a level that is comparable to the original level. This pattern may e.g. be caused by a system that warms up, or may be due to operator fatigue. The drift may follow a linear trend or a curve. (Although the wear of a tool that is periodically repaired or replaced will lead to a tooth saw pattern, the underlying, uncontrolled disturbance pattern is a sustained drift and not a cyclic drift).



Cyclic fluctuations in the mean

This variation pattern emerges when upward drifts are followed by downward drifts thus forming a cyclic pattern. This pattern may be caused by a process factor with fluctuations that are relatively slow, compared to production speed. This pattern may take the form of a real (regular) cycle, but may also be irregular. Montgomery gives an explanation why these patterns occur in production processes: 'Basically, all manufacturing processes are driven by inertial elements, and when the interval between samples becomes small relative to these forces, the observations on the process will become correlated over time.' [Montgomery, 1996, p.375].



Mixture pattern

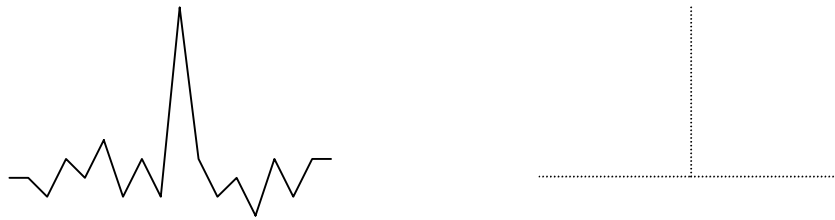
A mixture pattern arises when not every product is generated by the same cause system; not because the cause system changes in time, but because two or more cause systems are working in parallel. This may occur e.g. by using multiple machines to generate a product, or by using a tool (a mould) with more than one positions. Depending on how these products are mixed in time, a mixture pattern will occur. This type of causes is also addressed as positional effects [see e.g. Montgomery, 1996, p.203].



Incidental shift

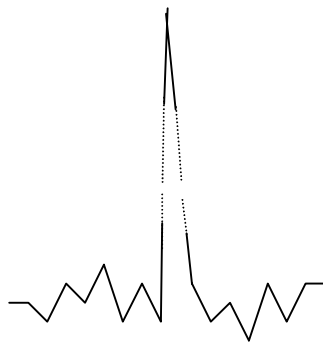
An incidental shift is a sudden change in the process that is lasting for a very short period in time. Although caused by a non-stable pattern in a process factor, the magnitude of the effect can be seen as an extreme value within the (tail of a) fixed probability distribution (see [Hinckley and Barkan, 1995]). This pattern may be caused by an operator mistake, or by a 'dip' in e.g. air pressure or material flow.

Since it is hard to tell whether this is an incidental shift in the mean of the variation, this variation pattern is addressed just as an incidental shift.



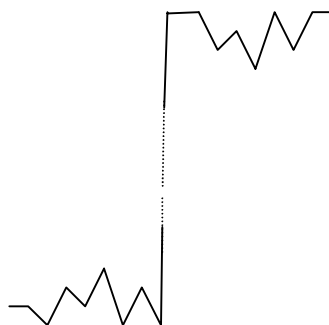
Incidental abnormality

This pattern is comparable to an incidental shift, yet the magnitude of the deviation is far outside the range of values that can be expected from a stable process, i.e. it is a very large deviation, far outside the range of normal operations. Examples of causes of abnormalities are e.g. a missing operation (e.g. a hole was not drilled), an incidental wrong part, or an incidental hitch in the equipment.



Sustained abnormality

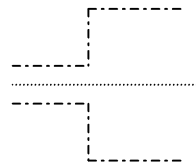
Comparable to the incidental abnormality also the sustained abnormality may occur. The magnitude of deviations is comparable, but the influence is lasting so that the values stays on an abnormal level. This failure pattern is typically the result of a broken machine part, using the wrong tool or using the wrong type of materials.



Apart from non-stable patterns concerning changes in the mean, it is also possible that a non-stable pattern occurs because of changes in spread over time. The above patterns for non-stable patterns in the mean (except for incidental shift and abnormalities), can also be discerned for changes in the spread. Below only two examples will be addressed.

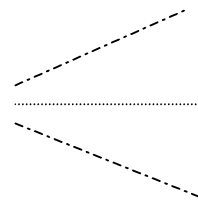
Sustained shift in variance

This shift in variance is typically caused by a shift in the variance of a process factor. Yet it may also be possible that a shift in the mean of a process factor may cause that the variation in the output of a process changes. In the latter case, this will often result in a simultaneous shift in both the location and the spread.



Sustained drift in variance

Analogous to the sustained shift we can also define a sustained drift in variance. The pattern is depicted below.



Appendix 4: Design profiles (scenarios) for process control

This appendix contains examples of how knowledge on contingency factors can be used to make design profiles or scenario's for process control. Note that the scenario's listed here are only intended to be an illustration of the form of the scenario's and the types of information entered. The contents are the result of a first collection of relevant disturbances, tools and functions, and should not be viewed as an operational guide. Although further work will address the completion and testing of the scenario's, a first illustration was considered to be useful in this phase. See Section 4.6 for a further discussion on the use of design profiles.

Dominant process factor: Material/Component

Failure Pattern	Examples	Tool	Cells
sustained shifts in mean	<ul style="list-style-type: none"> • (unknown) change to other supplier • incidental poor batch of materials • sudden change in material flow 	• Control Charts	A1/G1/H7
		• notify batch-change and check	H1/A6
		• incoming Acceptance Sampling	
cyclic shifts in mean	<ul style="list-style-type: none"> • differences in material batches used 	• notify batch change, check and feedback	H1
		• notify batch change, check and feedforward	A6
		• Control Charts (+OCAP)	A1/G7/H7
		• (incoming Acceptance Sampling)	A1
sustained drift in mean	<ul style="list-style-type: none"> • wear process at supplier • deterioration of material stock 	• Control Charts	A6
		• (APC feed forward)	A6
		• (APC feedback)	H6/G6
cyclic drift in mean	<ul style="list-style-type: none"> • <i>not very likely to occur</i> 		
cyclic fluctuations in mean	<ul style="list-style-type: none"> • fluctuations in bulk materials • influence of ambient temperature on materials 	• APC feed forward	A6
		• APC feedback	H6/G6
incidental shifts	<ul style="list-style-type: none"> • poor part in batch 	• Poka-Yoke	A1/G1/H8
mixture patterns	<ul style="list-style-type: none"> • materials from two suppliers 	• Control Chart	A1/H7
incidental abnormalities	<ul style="list-style-type: none"> • unprocessed part in batch • component type A in stead of component type B • double sheet inserted in mould 	• Poka-Yoke	A1/G1/H7
sustained abnormality	<ul style="list-style-type: none"> • wrong type of material batch used 	• Poka-Yoke	H7/H8
sustained shift or drift in variance	<ul style="list-style-type: none"> • deterioration at supplier 	• Control Charts	A1/H7
		• PCS	I1

Dominant process factor: Material/Component

	material	machine	tools	human factors	env.	settings	output control	product assurance
A	material .control chart .sampling .poka yoke					.APC ff .notify+check		
B	machine							
C	tools							
D	human factors							
E	environment							
F	settings controllable							
G	process conditions .OCAP+CC .Poka Yoke					.APC fb	.control chart	
H	output on-line .OCAP +CC .notify+check					.APC fb	.control chart .Poka Yoke	.Poka Yoke .APC sort
I	output off-line .PCS							
	1	2	3	4	5	6	7	8

Dominant process factor: Operator

Failure Pattern	Examples	Tool	Cells
sustained shifts in mean	<ul style="list-style-type: none"> sudden unplanned change in method used 	<ul style="list-style-type: none"> Control Chart + OCAP 	H7+H4/G7+G4
cyclic shifts in mean	<ul style="list-style-type: none"> differences between successive operators/shifts 	<ul style="list-style-type: none"> Control Chart +OCAP training and instructions 	H7+H4/G7+G4 D4
sustained drift in mean	<ul style="list-style-type: none"> <i>not likely to occur</i> 		
cyclic drift in mean	<ul style="list-style-type: none"> operator fatigue 	<ul style="list-style-type: none"> Control Chart +OCAP 	H7+H4/G7+G4
cyclic fluctuations in mean	<ul style="list-style-type: none"> <i>not likely to occur</i> 		
incidental shifts	<ul style="list-style-type: none"> material not adequately positioned 	<ul style="list-style-type: none"> Poka-Yoke 	G4/H4/H7/H8
mixture patterns	<ul style="list-style-type: none"> differences between parallel operators 	<ul style="list-style-type: none"> Control Chart (difference chart) +OCAP R&R study Difference Chart (Control Chart) training and instructions 	H7+H4/G7+G4 I4 H7 D4
incidental abnormalities	<ul style="list-style-type: none"> forgotten operation 	<ul style="list-style-type: none"> Poka-Yoke 	G4/H4/H7/H8
sustained abnormality	<ul style="list-style-type: none"> pile of products processed up-side-down 	<ul style="list-style-type: none"> Poka-Yoke Control Chart +OCAP 	G4/H4/H7/H8 H7+H4/G7+G4
sustained shift or drift in variance	<ul style="list-style-type: none"> 		

Dominant process factor: Operator

	material	machine	tools	human factors	env.	settings	output control	product assurance
A	material			.Poka-Yoke				
B	machine							
C	tools							
D	human factors			.training and instructions				
E	environment							
F	settings controllable							
G	process conditions			.Poka-Yoke				
H	output on-line			.OCAP +CC .difference CC			.control chart .Poka-Yoke	.Poka-Yoke
I	output off-line			.R&R study				
	1	2	3	4	5	6	7	8

Dominant process factor: Machine

Failure Pattern	Examples	Tool	Cells
sustained shifts in mean	<ul style="list-style-type: none"> material bumped into gauge 	<ul style="list-style-type: none"> Control Chart + OCAP 	H7+H2
		<ul style="list-style-type: none"> corrective maintenance (Corr.Maint.) 	H2
cyclic shifts in mean	<ul style="list-style-type: none"> <i>not very likely to occur</i> 		
sustained drift in mean	<ul style="list-style-type: none"> wear of a machine part 	<ul style="list-style-type: none"> preventive maintenance (Prev.Maint.) 	B2/H2
		<ul style="list-style-type: none"> corrective maintenance (Corr.Maint.) 	H2
		<ul style="list-style-type: none"> (modified) Control Chart 	H7
		<ul style="list-style-type: none"> conditional maintenance (Cond.Maint) 	B2/G2
		<ul style="list-style-type: none"> APC feedback (limited) 	H6
cyclic drift in mean	<ul style="list-style-type: none"> warming up of machine 	<ul style="list-style-type: none"> APC feedback 	H6
		<ul style="list-style-type: none"> Control Chart (limited) 	
cyclic fluctuations in mean	<ul style="list-style-type: none"> changes in speed due to variations in power supply 	<ul style="list-style-type: none"> APC feedback 	H6/G6
incidental shifts	<ul style="list-style-type: none"> short hitch in machine 	<ul style="list-style-type: none"> Poka Yoke (limited) 	B2/H7
mixture patterns	<ul style="list-style-type: none"> differences in parallel operating machines differences between positions in a die 	<ul style="list-style-type: none"> Difference Control Chart 	H2
		<ul style="list-style-type: none"> Control Chart+OCAP 	H7+H2
incidental abnormalities	<ul style="list-style-type: none"> short hitch in machine 	<ul style="list-style-type: none"> Poka Yoke 	G2/H7/H8
sustained abnormality	<ul style="list-style-type: none"> breakdown of machine part die broken 	<ul style="list-style-type: none"> Poka Yoke 	G2/H7/H8
		<ul style="list-style-type: none"> Control Chart 	
sustained shift or drift in variance	<ul style="list-style-type: none"> wear of a bearing 	<ul style="list-style-type: none"> periodical process capability study (PCS) 	I2
		<ul style="list-style-type: none"> Control Chart+OCAP 	H7+H2

Dominant process factor: Machine (and tools)

	material	machine	tools	human factors	env.	settings	output control	product assurance
A	material							
B	machine	.Cond.Maint. .Prev.Maint.						
C	tools							
D	human factors							
E	environment							
F	settings controllable							
G	process conditions	.Cond.Maint. .Prev.Maint. .Poka Yoke				APC fb.		
H	output on-line	.Corr.Maint. .Prev.Maint. .OCAP+CC				.APC fb	.control chart .Poka Yoke	Poka Yoke
I	output off-line	.Per. PCS						
	1	2	3	4	5	6	7	8

References

- Akao, Y. (1990), *Quality function deployment: integrating customer requirements into product design*, Productivity Press, Cambridge.
- Al-Salty, M. and Statham A. (1994), "The application of group technology concept for implementing SPC in small batch manufacture", *The International Journal of Quality & Reliability Management*, Vol. 11 No. 4., pp. 64-76.
- ANSI (1990), *Industrial engineering terminology*, Industrial Engineering and Management Press/ Elsevier Science, Amsterdam.
- Banks, J. (1989), *Principles of quality control*, Wiley, New York.
- Batson, R.G. (1994), "Variation reduction strategy for process engineers", *48th Annual Quality Congress Transactions*, ASQC, Milwaukee, pp. 692-698.
- Bhote, K.R., (1991), *World Class Quality*, Amacom, New York.
- Bolwijn, P.T. and Kumpe, T. (1990), "Manufacturing in the 1990's-productivity, flexibility and innovation", *Long range planning*, Vol. 23 No. 4, pp. 44-57.
- Box, G.E.P. and Draper, N.R. (1969), *Evolutionary operation (EVOP); a statistical method for process improvement*, Wiley, London.
- Box, G.E.P. and Luceño, A. (1997), *Statistical control by monitoring and feedback adjustment*, Wiley-Interscience, Chichester.
- Box, G.E.P. and Draper, N.R. (1987), *Empirical Model-Building and Response Surfaces*, Wiley, New York.
- Box, G.E.P. and Kramer, T. (1992), "Statistical Process Control and Feedback Adjustment - A Discussion", *Technometrics*, Vol. 34 No. 3, pp. 251-285.
- Brassard, M. and Ritter, D. (1994), *The Memory Jogger*, Goal/QPC, Methuen, MA.
- Chaudry, S.S. and Higbie, J.R. (1989), "Practical Implementation of Statistical Process Control in a Chemical Industry", *International Journal of Quality and Reliability Management*, Vol. 6 No. 5, pp. 37-48.
- CHRYSLER, FORD and GENERAL MOTORS (1994), *QS 9000 Quality Manuals*, Garin Continuous Ltd, West Thurrock, UK.
- Cowden, D.J. (1957), *Statistical Methods in Quality Control*, Prentice-Hall, Englewood Cliffs, N.J..
- Dale, B.G. and Shaw, P. (1991), "Statistical Process Control: An examination of some common queries", *International Journal of Production Economics*, Vol. 22 No. 1, pp. 33-41.
- Dar-El, E.M. (1997), "What we really need is TPQM!", *International Journal of Production Economics*, Vol. 52 No. 12, pp. 5-13.
- Deming, W.E. (1982), *Out of the Crisis*, MIT Press, Cambridge.
- Deslandres, V. and Pierreval, H. (1991), "Selection of quality methods: the SYSMIQ approach", *Proceedings of the international IFIP TC 5 conference on computer applications in production and engineering*, CAPE, pp. 669-676.

- Dessler, G. (1976), *Organization and Management: a contingency approach*, Prentice-Hall, Englewood Cliffs.
- Dodge, H.F. and Romig, H.G. (1959), *Sampling Inspection Tables, 2nd edition*, John Wiley & Sons, New York.
- Does, R.J.M.M., Roes, K.C.B. and Trip, A. (1999), *Statistical Process Control in Industry*, Kluwer Academic, Dordrecht, The Netherlands.
- Does, R.J.M.M., Schippers, W.A.J. and Trip, A. (1997), "A framework for the application of statistical process control", *International Journal of Quality Science*, Vol. 2 No. 4, pp. 181-198.
- Evans, D.H. (1974/1975), "Statistical tolerancing: the state of the art", part I, II and III, *Journal of Quality Technology*, Vol. 6, pp. 188–195 (part I); Vol. 7, pp. 1–11 (part II); Vol. 7, pp. 72–76 (part III).
- Gaafar, L.K. and Keats, J.B. (1992), "Statistical Process Control: A Guide for Implementation", *International Journal of Quality and Reliability Management*, Vol. 9 No. 4, pp. 9-20.
- Gitlow, H., Oppenheim, A. and Oppenheim, R. (1989), *Quality management: tools and methods for improvement*, 1st edition, Irwin, Burr Ridge, Illinois.
- Göb, R. (1998), "On the integration of Statistical Process Control and Engineering Process Control in Discrete Manufacturing Processes", chapter in: *Advances in stochastic models for reliability, quality and safety*, ed. Von Collani, E. et al., Birkhäuser, Boston.
- Grant, L.G. and Leavensworth, R.S. (1988), *Statistical quality control*, McGraw-Hill, London.
- Harry, M.J. and Lawson, J.R. (1992), *Six sigma producibility analysis and process characterization*, Addison-Wesley, Amsterdam.
- Harry, M.J. (1997), *The Vision of Six Sigma, 8 book set*, 5th edition, Tri Star, Phoenix, Arizona.
- Harry, M.J. (1998), "A Breakthrough Strategy for Profitability", *Quality Progress*, Vol. 31 No.5, pp. 60-64.
- Hinckley, C.M. and Barkan, P. (1995), "The role of variations, mistakes and complexity in producing nonconformities", *Journal of Quality Technology*, Vol. 27 No. 3, pp. 242-249.
- Hirano, H. (1988), *Poka-Yoke: improving product quality by preventing defects*, Productivity Press, Cambridge.
- Hoerl, R.W. (1995), "Enhancing the Bottom-line Impact of Statistical Methods", *ASQC Statistics Division Newsletter*, Vol. 15 No. 2, pp. 6-18.
- Jostes, R.S. and Helms, M. (1994), "Total Productive Maintenance and its link to Total Quality Management", *Work Study*, Vol. 43 No. 7, pp. 18-20.
- Juran, J.M., Gryna, F.M. and Bingham, R.S. (1974), *Quality Control Handbook, 3rd edition*, McGraw-Hill, London.
- Juran, J.M. and Gryna, F.M. (1988), *Juran's quality control handbook, 4th edition*, McGraw-Hill, London.
- Kane, V.E. (1989), *Defect prevention: use of simple statistical tools*, Dekker, New York.

- King, B. (1989), *Better Designs in Half the Time*, Goal/QPC, Methuen, MA.
- Klaus, L.A. (1997), "Motorola Brings Fairy Tales to Life", *Quality Progress*, Vol. 30 No. 6, pp. 24-30.
- Lascelles, D.M. and Dale, B.G. (1988), "A Review of the Issues Involved in Quality Improvement", *International Journal of Quality and Reliability Management*, Vol. 5 No. 5. pp. 77-94.
- Ledolter, J. and Swersey, A. (1997a), "An evaluation of Pre-Control", *Journal of Quality Technology*, Vol. 29 No. 2, pp. 163–171.
- Ledolter, J. and Swersey, A. (1997b), "Dorian Shainin's Variables Search procedure: a critical assessment", *Journal of Quality Technology*, Vol. 29 No. 3, pp. 237–247.
- Levi, A.S. and Mainstone, L.E. (1987), "Obstacles to Understanding and Using Statistical Process Control as a Productivity Improvement Approach", *Journal of Organizational Behavior Management*, Vol. 9 No. 1, pp. 23-32.
- Lochner, R.H. and Matar, J.E. (1990), *Designing for quality: an introduction to the best of Taguchi and western methods of statistical experimental design*, Chapman & Hall, London.
- Lockyer, K.G., Oakland, J.S., Duprey, C.H. and Followell, R.F. (1984), "The barriers to acceptance of statistical methods of quality control in UK manufacturing industry", *International Journal of Production Research*, Vol. 22 No. 4, pp. 647-660.
- Lucas, J.M. (1994), "How to achieve a robust process using response surface methodology", *Journal of Quality Technology*, Vol. 26 No. 4, pp. 248–260.
- Maddox, J. (1999), Quoted in: *Eindhovens Dagblad*, May 14th 1999, p. 3, (in Dutch). May 12th 1999 Sir John Maddox (former Editor in Chief of Nature) visited the Eindhoven University of Technology. In an interview he stated 'Perhaps Scientists should think more and experiment less', referring to the importance of making a synthesis of existing knowledge gathered through experimentation.
- Mann, R.S. (1992), *The development of a framework to assist in the implementation of TQM*, PHD-Thesis, University of Liverpool.
- Mann, R.S. and Kehoe, D. (1994), "The quality improvement activities of total quality management (paper 1)", *Quality World Technical Supplement*, March, pp. 43-56.
- Mann, R.S. and Kehoe, D. (1995), "Factors implementing the implementation and success of TQM", *International Journal of Quality and Reliability Management*, Vol. 12 No. 1, pp. 11-23.
- Mast, J. de, Schippers, W.A.J., Does, R.J.M.M. and Heuvel, E.R. van den (1999), "Steps and Strategies for process improvement", *accepted for publication in Quality and Reliability Engineering International*.
- Melan, E.H. (1998), "Implementing TQM: a contingency approach to intervention and change", *International Journal of Quality Science*, Vol. 3 No. 2, pp. 126-146.
- Melissen, F.W. and Schippers, W.A.J. (2000), "Applying quality tools in the field of recovery processes", *International Journal for Environmentally Conscious Design & Manufacturing*, Vol. 9 No. 1, pp.1-10.

- MIL-STD-105D (1964), *Sampling procedures and tables for inspection by attributes*, Military Standard, U.S. Department of Defense, Government printing office, Washington, DC.
- MIL-STD-414 (1968), *Sampling procedures and tables for inspection by variables for percent defective*, Military Standard, U.S. Department of Defense, Government printing office, Washington, DC.
- Modarress, B. and Ansari, A. (1989), "Quality Control Techniques in U.S. Firms, a Survey", *Production and Inventory Management Journal*, Vol. 30 No. 2, pp. 58-62.
- Moen, R.D., Nolan, T.W and Provost, L.P. (1991), *Improving quality through planned experimentation*, McGraw-Hill, London.
- Montgomery, D.C. (1996), *Introduction to Statistical Quality Control*, 3rd edition, Wiley, New York.
- Montgomery, D.C., (1997), *Design and Analysis of Experiments*, 4th edition, Wiley, New York.
- Montgomery, D.C., Keats, J.B., Runger, G.C. and Messina, W.S. (1994), "Integrating Statistical Process Control and Engineering Process Control", *Journal of Quality Technology*, Vol. 26 No. 2, pp. 79-87.
- Montgomery, D.C. and Woodall, W.H. (1997), "A discussion on Statistically-Based Process monitoring and Control", *Journal of Quality Technology*, Vol. 29 No. 2, pp. 121-162.
- Nair, V.N. (1992), "Taguchi's parameter design: a panel discussion", *Technometrics*, Vol. 34 No. 2, pp. 127-161.
- Nakajima, S. (1988), *Introduction to TPM*, Productivity Press, Cambridge, MA.
- Nolan, T.W. and Provost, L.P. (1990), "Understanding Variation", *Quality Progress*, Vol. 23 No. 5, pp. 70-78.
- Oakland, J.S. and Sohal, A. (1987), "Production Management Techniques in UK Manufacturing Industry: Usage and Barriers to Acceptance", *International Journal of Operations Management*, Vol. 7 No. 1, pp. 8-37.
- Osborn, D.P. (1990), "Statistical power and sample size for Control Charts-survey results and implications", *Production and Inventory Management Journal*, Vol. 31 No. 4, pp. 49-54.
- Palm, A.C. (1990), "SPC versus automatic process control", *Annual Quality Congress Transactions v 44*, ASQC, Milwaukee, WI., pp. 694-699.
- Pyzdek, T. (1990), "There is no such thing as a common cause", *ASQC Quality Congress Transactions v 44*, ASQC, Milwaukee, WI., pp. 102-108.
- Quesenberry, C.P. (1991), "SPC Q charts for start-up processes and short and long runs", *Journal of Quality Technology*, Vol. 23 No. 3, pp. 213-224.
- Riis, J.O., Luxhoj, J.T. and Thorsteinsson, U. (1997), "A situational maintenance model", *International Journal of Quality & Reliability Management*, Vol. 14 No. 4, pp. 349-366.
- Robinson, A.G. and Schroeder, D.M (1990), "The limited role of statistical quality control in a zero-defect environment", *Production and Inventory Management Journal*, Vol. 31 No. 4, pp. 60-65.

- Robinson, S.L. and Miller, R.K. (1989) *Automated inspection and quality assurance*, Dekker, Basel.
- Ross, Ph. J. (1996), *Taguchi Techniques for Quality Engineering*, 2nd edition, McGraw-Hill, London.
- Sander, P.C. and Brombacher, A.C. (1999), "MIR: the use of reliability information flows as a maturity index for reliability", *Quality and Reliability Engineering International*, Vol. 15 No. 6, pp. 439-447.
- Sandorf, J.P. and Bassett III, A.T. (1993), "The OCAP: Predetermined Responses to Out-of-Control Conditions", *Quality Progress* Vol. 26 No. 3, pp. 91-96.
- Schippers, W.A.J. and Does, R.J.M.M. (1997), "Implementing Statistical Process Control in Industry, the role of statistics and statisticians", *Proceedings of the Tempus Workshop: Statistics at universities, its impact on society*. pp. 65-82, Eötvös University Press, Budapest.
- Schippers, W.A.J. (1998a), "Applicability of statistical process control techniques", *International Journal of Production Economics*, Vol. 56-57 No. 1-3, pp. 525-535.
- Schippers, W.A.J. (1998b), "Continuous Improvement: goals, tools and contingencies", *Continuous Improvement: from idea to reality, Proceedings of the 2nd International EuroCINet Conference*, pp. 365-377, Twente University Press, Enschede.
- Schippers, W.A.J. (1998c), "An integrated approach to process control", *Accepted for publication in the International Journal of Production Economics*.
- Schippers, W.A.J. (1999), "The process matrix, a simple tool to analyse and describe production processes", *Quality and Reliability Engineering International*, Vol. 15 No. 6, pp. 469-473.
- Scott, J. and Golkin, K. (1993), "Rapid deployment of automated SPC systems", *Industrial Engineering*, Vol. 25 No. 8, pp. 18-20.
- Searle, S.R. (1971), *Linear Models*, Wiley, New York.
- Shainin, D. and Shainin P.D. (1988), "Statistical Process Control", chapter in: *Juran's Quality Control Handbook*, ed. Juran, J.M and Gryna, F.M., McGraw-Hill, London.
- Shainin, P.D. (1993). "Managing Quality Improvement", *47th Annual Quality Congress Transactions*, ASQC, Milwaukee, pp. 554–560.
- Shainin, R.D. (1993), "Strategies for technical problem solving", *Quality Engineering*, Vol. 5 No. 3, pp. 433–448.
- Shewhart, W.A. (1926a), "Quality Control Charts", *Bell Systems Technical Journal*, Bell Telephone Laboratories, October, pp. 593-603.
- Shewhart, W.A. (1926b), "Finding Causes of Quality Variations", *Manufacturing Industries*, February, pp. 125-128.
- Shewhart, W.A. (1927), "Quality Control", *Bell Systems Technical Journal*, Bell Telephone Laboratories, October, pp. 722-735.
- Shewhart, W.A. (1931), *Economic control of quality of manufactured product*, Van Nostrand Reinhold, Princeton.

- Shingo, S. (1986), *Zero Quality Control: Source inspection and the Poka-Yoke System*, Productivity Press, Stanford, Connecticut.
- Sower, V.E. and Foster, Ph. R. (1990), "Implementing and evaluating advanced technologies: a case study", *Production and Inventory Management Journal*, Vol. 31 No.4, pp. 44-47.
- Stamatis, D.H. (1995), *Failure Mode and Effect Analysis: FMEA from Theory to Execution*, ASQC Quality Press, Milwaukee.
- Stephanopoulos, G. (1984), *Chemical process control: an introduction to theory and practice*, Prentice-Hall, Englewood Cliffs.
- Stephen, W.R. (1993), "Have You Checked Your SPC Program Lately?", *Quality*, Vol. 32 No. 2, p. 41.
- Stratton, B. (1998), "Results: Monstrous. Want some?", *Quality Progress*, Vol. 31 No. 10, pp. 27-44.
- Sullivan, L.P. (1986), "Quality function deployment", *Quality Progress*, Vol. 19 No. 6, pp. 39-50.
- Tadikamalla, P.R. (1994), "The Confusion Over Six-Sigma Quality", *Quality Progress*, Vol. 27 No. 11, pp. 83-85.
- Taguchi, G. (1986) *Introduction to Quality Engineering – Designing Quality into Products and Processes*, Asian Productivity Organization, Tokyo.
- Vasilash, G.S. (1993), "TQM/SPC: Get a buy-in or watch them bug-out", *Production*, Vol. 105 No. 10, pp. 54-57.
- Vining, G.G. and Myers, R.H. (1990), "Combining Taguchi and response surface philosophies: a dual response approach", *Journal of Quality Technology*, Vol. 22 No. 1, pp. 38–45.
- Wetherill, G.B. and Brown, D.W. (1991), *Statistical Process Control; Theory and Practice*, Chapman and Hall, London.
- Wadsworth, H.M., Stevens, K.S., and Godfrey, A.B. (1986), *Modern Methods for Quality Control and Improvement*, Wiley, New York.
- Wheeler, D.J. and Chambers, D.C. (1992), *Understanding Statistical Process Control, 2nd edition*, SPC Press, Knoxville, Tennessee.
- Wheeler, D.J. (1991), *Short run SPC*, SPC Press, Knoxville, Tennessee.
- Wheeler, D.J. (1993), *Understanding variation, the key to managing chaos*, SPC Press, Knoxville, Tennessee.
- Wieringa, J.E. (1999), *Statistical Process Control for Serially Correlated Data*, Ph.D. Thesis, Labyrinth Publication, Capelle a/d IJssel.
- Willmott, P. (1993), *Total Productive Maintenance: the Western way*, Butterworth-Heinemann, Oxford.
- Wood, M. and Preece, D. (1992), "Using Quality Measurements: Practice, Problems and Possibilities", *International Journal of Quality and Reliability Management*, Vol. 9 No. 7, pp. 42-53.
- Wozniak, C. (1994), "Proactive vs. Reactive SPC", *Quality Progress*, Vol. 27 No. 2, pp. 49-50.

Summary

Despite the large amount of literature on techniques for quality control and improvement, there are still many companies who experience problems in the application of these techniques. Some companies do not manage to apply the techniques successfully, others do not even initiate the application of certain techniques. In existing literature it is assumed that these companies are simply lagging behind those who are successful in this area. The reason for initiating the present research was the assumption that it is not simply a case of lagging behind. On the basis of this, two research questions were formulated. Firstly, what are the main causes of problems in applying existing quality techniques? Secondly, how can the problems experienced in applying quality techniques be solved? The goal of this research is to put the answers to these questions in such a form that it can be used to support the effective application of existing quality techniques (see Chapter 1).

To obtain an answer to the above research questions, an overview of the reasons for unsuccessful application of quality techniques was made, based on a survey of the relevant literature and exploratory case studies in a number of companies. The approach and results are described in Chapter 2. (As an introduction to the subject and as a basis for defining the various techniques considered in this research, a short historical description of quality techniques and their area of application is given in Paragraph 2.1.) A study of the literature in which causes of problems in the application of quality tools are mentioned shows that in particular organizational factors are reported. Lack of commitment from management, lack of training and skills, lack of involvement of operators and lack of insight into the techniques and concepts are reported most frequently. However, not all differences in degree of success can be explained by these factors. A group of problems seems to be connected to finding a suitable set of techniques for a specific situation. The case studies confirm the role played by organizational factors, and also give insight into the role played by characteristics of product and process. Furthermore, it appears that there are various types of problems (in terms of symptoms), whereby a number of interconnected causes and sub-causes of both an organizational and a technical nature play a role. Moreover, it turns out that functions of techniques can be used to clarify and describe the problems observed.

The results of both studies are incorporated in a model for causes and symptoms. On the basis of this model, it was determined how this research could contribute to solving the problems observed. Since existing literature is mainly directed at organizational causes, the second part of this research is mainly directed at more technical causes related to a wrong fit of the situation in question and the set of techniques used. The goal of this research is to provide support for a number of decisions when determining the approach to be used. These decisions concern the definition of relevant functions, the selection of suitable techniques, the definition of

relations between techniques and, partly, also the definition of the methodology that will be applied for a specific technique.

On the basis of the above analysis and the ensuing model, two research goals were formulated for the second part of the research. Firstly, determination of the underlying goals of techniques and deduction of a functional framework in which the various techniques can be placed. Secondly, determination of factors which influence the choice of techniques within this framework and, on the basis of this, formulation of guidelines for selecting techniques for a specific situation (Chapter 3).

Subsequently, for two main groups of techniques, viz. process control techniques and process improvement techniques, separate functional frameworks were deducted and factors which were of influence on the choice of technique within these frameworks were determined (Chapters 4 and 5). To this end, an overview of the relevant techniques as used in industry and described in literature was made. On the basis of an analysis of the similarities and differences, the functional frameworks were drawn up and the most important factors influencing selection of techniques were derived. For the group of process control techniques, this information is also incorporated in sets of techniques (scenarios) for specific types of processes (Appendix 4). For each main group, the results of the above research were published in a separate article that was used as a basis for the chapter in question.

In Chapter 4 it turns out that, besides Statistical Process Control (SPC), three other disciplines are relevant for control of (the quality of) production processes, namely Total Productive Maintenance, Automatic Processes Control and Poka Yoke. The control techniques from the four disciplines should be seen as a coherent set of tools from which a choice can be made when designing the control of a process. The point of making a functional framework is therefore not only to structure the tools within a single discipline, but also to integrate these disciplines.

On the basis of a first global analysis of the differences and similarities of the four disciplines, it was decided to use a functional framework with two dimensions. The first dimension concerns the 'place' in the process where measurements are taken (the input of a control). Using this dimension a distinction is made between measurements of the various (groups of) process factors and between on-line and off-line measurements of the output of a process. The second dimension concerns the type of intervention that is carried out on the basis of these measurements and their processing. Here, a distinction is made between interventions in the various process factors, controls with an intervention in the process that was not specified beforehand, and controls that are specifically aimed at ensuring the quality of the output of a process. The two dimensions are combined in the Integrated Process Control Model. The model illustrates the correlation between the tools of the various disciplines. In addition, the various types of application (functions) of a specific control technique become clear.

Chapter 4 also discusses guidelines for selection of functions and techniques within the framework: A number of contingency factors can be indicated. Among other things, these are related to the dominance of a specific process factor, the type of disturbance that this process factor entails and factors that are related to the possibility and necessity of both measurements of and intervention in process or output. To give a more practical content to the goal of decision support, a start was made with drawing up scenarios or design profiles for process control techniques. Depending on the type of process factor that is dominant and the corresponding disturbance pattern, a number of suggestions are given for tools and their function.

The techniques used for improving the (quality of) production processes are gone into in Chapter 5. From an inventory of the relevant literature, it appears that such techniques are often used in the form of a stepwise approach (a set of techniques carried out in a stepwise manner). Besides a stepwise approach for the implementation of SPC, the Taguchi method, the Shainin system and the Six Sigma approach are also widely used. Such stepwise approaches have characteristics of the functional structure to be derived. Despite this, it turns out that there are differences between the steps in the various approaches and the content of each step: there are both overlapping and complementary parts. The existing stepwise approaches are, therefore, taken as a starting point for formulating a (generic) functional framework for process improvement tools.

On the basis of a first comparison of the four step plans considered, a global design of the functional framework was made. The ultimate structure of the framework is derived by determining the underlying functions of the steps in each approach, placing similar steps together (being the steps of the functional framework) and subsequently deciding on a definitive classification and sequence of these steps on the basis of logical considerations. This led to the Integrated Process Improvement Model, which shows the various functions and the relationships of techniques. The most important differences between the four stepwise approaches considered also become clear. In particular, the differences in attention paid to stabilization (in Phase 2) and optimization (in Phase 3) of processes, and the dual role of qualitative and observational quantitative techniques in the second phase of the model becomes apparent.

The functional framework thus drawn up can be seen as a generic model. Such a model has the advantage of using the same framework for various improvement projects. There are, however, situational factors that influence the choice of steps (and tools) within the framework. The most important factors are concerned with the nature of the problem to be tackled, the amount of process knowledge present and, partly connected to this, the possibility and necessity for using certain types of techniques.

As conclusion, the results of the research are discussed in the light of the original research questions and research goals (Chapter 6). Although the area chosen for special attention in the second part of the research would seem to point at research into a less important part of the cause of problems, the results of this research contribute concrete possibilities for tackling organizational problems. In particular, the results of this research could be incorporated in training methods in order to diminish the problems observed in the areas of training in and knowledge of techniques.

The thesis is concluded with recommendations for further research in relation to the subject investigated here.

Samenvatting (summary in Dutch)

Ondanks de grote hoeveelheid literatuur op het gebied van technieken voor kwaliteitsbeheersing- en verbetering zijn er nog steeds bedrijven die problemen hebben bij het toepassen ervan. Sommige bedrijven lukt het niet technieken met succes toe te passen, anderen beginnen niet eens aan het toepassen van bepaalde technieken. In de bestaande literatuur wordt er vaak van uit gegaan dat deze bedrijven simpelweg achterlopen op de bedrijven die wel succesvol zijn. De aanleiding van dit onderzoek is het vermoeden dat er niet alleen sprake is van 'achterlopen'. Op basis hiervan zijn twee onderzoeksvragen geformuleerd. Ten eerste: 'Wat zijn de belangrijkste oorzaken voor problemen bij het toepassen van bestaande kwaliteitstechnieken?'. Ten tweede: 'Hoe kunnen de problemen bij het toepassen van kwaliteitstechnieken worden opgelost?'. Het doel van het onderzoek is het antwoord op deze vragen om te zetten in een vorm die gebruikt kan worden om gebruikers te ondersteunen in het effectief gebruiken van bestaande kwaliteitstechnieken (zie Hoofdstuk 1).

Om een antwoord te krijgen op bovenstaande onderzoeksvragen is, op basis van een studie van relevante literatuur en exploratieve cases in een aantal bedrijven, een overzicht gemaakt van de oorzaken voor het niet succesvol toepassen van kwaliteitstechnieken. De aanpak en resultaten zijn beschreven in Hoofdstuk 2. (Als inleiding op het onderwerp en als basis voor een afbakening van de verzameling technieken die in dit onderzoek wordt beschouwd, is in Paragraaf 2.1 een korte historische beschrijving gegeven van kwaliteitstechnieken en hun toepassingsgebied). De studie van literatuur waarin melding wordt gemaakt van oorzaken voor problemen bij het toepassen van kwaliteitstechnieken, laat zien dat met name organisatorische factoren worden gemeld. Gebrek aan betrokkenheid van de leiding, gebrek aan training en vaardigheden, gebrek aan betrokkenheid van operators en gebrek aan inzicht in technieken en concepten worden het meest gemeld. Toch kunnen niet alle verschillen in succes verklaard worden aan de hand van deze factoren. Een groep van problemen lijkt samen te hangen met de vinden van een geschikte set van technieken voor een bepaalde situatie. De cases bevestigen de rol van organisatorische factoren, maar geven ook inzicht op de rol van kenmerken van product en proces. Verder blijken er ook diverse typen problemen te zijn (in termen van symptomen). Hierbij kunnen er meerdere samenhangende oorzaken en sub-oorzaken van zowel organisatorische als technische aard een rol spelen. Verder blijken functies van technieken gebruikt te kunnen worden bij het verklaren en beschrijven van de gesignaleerde problemen.

De resultaten van beide studies zijn verwerkt in een model voor oorzaken en symptomen. Op basis van dit model is bepaald hoe dit onderzoek zou kunnen bijdragen aan het oplossen van de gesignaleerde problemen. Omdat de bestaande literatuur zich vooral richt op organisatorische oorzaken is het tweede deel van het onderzoek vooral gericht op meer technische oorzaken die betrekking hebben op

een verkeerde afstemming van de betreffende situatie en de gebruikte set van technieken. Doel van het onderzoek is het ondersteunen van een aantal beslissingen bij het bepalen van de te volgen aanpak. Het betreft het bepalen van relevante functies, het selecteren van geschikte technieken, het bepalen van relaties tussen technieken en deels ook het bepalen van de te gebruiken methodologie voor een bepaalde techniek.

Op basis van de voorgaande analyse en het daaruit volgende model, zijn twee onderzoeksdoelen geformuleerd voor het tweede deel van het onderzoek. Ten eerste: het bepalen van de onderliggende doelen van technieken en het afleiden van een functioneel raamwerk waarin de diverse technieken kunnen worden geplaatst. Ten tweede: het bepalen van factoren die de keuze van technieken binnen dit raamwerk beïnvloeden en het op basis hiervan aangeven van richtlijnen voor het selecteren van technieken voor een bepaalde situatie (Hoofdstuk 3).

Vervolgens is voor twee hoofdgroepen van technieken, te weten procesbeheersingstechnieken en procesverbeteringstechnieken, afzonderlijk een functioneel raamwerk afgeleid en zijn factoren bepaald die van invloed zijn op de keuze van technieken binnen deze raamwerken (Hoofdstukken 4 en 5). Hiervoor is eerst een overzicht gemaakt van relevante technieken zoals die worden gebruikt in het bedrijfsleven en zoals die worden beschreven in de literatuur. Op basis van een analyse van overeenkomsten en verschillen zijn de functionele raamwerken opgesteld en zijn de belangrijkste factoren die van invloed zijn op selectie van technieken afgeleid. Voor de groep van procesbeheersingstechnieken is deze kennis ook verwerkt in sets van technieken (scenario's) voor bepaalde typen van processen (Appendix 4). De resultaten van bovenstaand onderzoek zijn per hoofdgroep gepubliceerd in een apart artikel, dat als basis heeft gediend voor het betreffende hoofdstuk.

In Hoofdstuk 4 blijkt dat er naast de SPC-discipline (Statistische Procesbeheersing) nog drie andere disciplines relevant zijn als het gaat om het beheersen van (de kwaliteit) van productieprocessen. Het betreft Total Productive Maintenance, Automatic Process Control en Poka Yoke. De beheersingstechnieken uit de vier disciplines moeten worden gezien als een coherente set van technieken waaruit gekozen kan worden bij het inrichten van de beheersing van een proces. Het nut van het maken van een functioneel raamwerk is daarom niet alleen het structureren van technieken binnen een discipline, maar vooral ook het integreren van deze disciplines.

Op basis van een eerste globale analyse van de verschillen en overeenkomsten van de vier disciplines is gekozen voor een functioneel raamwerk met twee dimensies. De eerste betreft de 'plaats' in het proces waar gemeten wordt (de input van een beheersingstechniek). Hierbij wordt onder andere een onderscheid gemaakt tussen metingen aan de diverse (groepen) procesfactoren en on-line en off-line metingen aan de output van een proces. De tweede dimensie betreft het type interventie dat gepleegd wordt op basis van deze metingen en hun verwerking. Hierbij wordt onderscheid gemaakt tussen interventies in de diverse procesfactoren,

beheersingstechnieken met een niet vooraf gespecificeerde interventie in het proces, en beheersingstechnieken die met name gericht zijn op het zekerstellen van de kwaliteit van de output van een proces. De twee dimensies zijn gecombineerd in het Integrale Procesbeheersing Model (Integrated Process Control model). Het model illustreert het verband tussen de technieken van diverse disciplines. Verder worden ook de verschillende toepassingswijzen (functies) van een bepaalde beheersingstechniek duidelijk.

In Hoofdstuk 4 wordt ook ingegaan op richtlijnen voor keuzen van functies en technieken binnen het raamwerk. Er kunnen een aantal contingentiefactoren worden aangegeven. Deze hebben onder andere betrekking op de dominantie van een bepaalde procesfactor, het type verstoring dat deze procesfactor met zich meebrengt en factoren die gerelateerd zijn aan de mogelijkheid en noodzaak van zowel metingen als interventies aan proces of output. Om een meer praktijkgerichte inhoud te geven aan de doelstelling van beslissings-ondersteuning is een aanzet gegeven voor het maken van scenario's of ontwerp-profielen voor procesbeheersingstechnieken. Aan de hand van het type procesfactor dat dominant is, en het bijbehorende verstoringpatroon wordt een aantal suggesties gedaan voor technieken en hun functie.

In Hoofdstuk 5 wordt ingegaan op technieken die worden gebruikt voor het verbeteren van de (kwaliteit) van productieprocessen. Uit een inventarisatie van de relevante literatuur blijkt dat dergelijke technieken vaak in de vorm van een stappenplan (een stapsgewijs uitgevoerde set van technieken) worden gebruikt. Naast een stappenplan voor het invoeren van SPC wordt ook veel gebruik gemaakt van de Taguchi aanpak, het Shainin systeem en de Zes-Sigma aanpak. Dergelijke stappenplannen hebben karakteristieken van de af te leiden functionele structuur. Toch blijken er verschillen te zijn tussen de stappen die zijn opgenomen in de diverse stappenplannen en de inhoud van iedere stap. Er zijn zowel overlappende als complementaire delen. Daarom zijn de bestaande stappenplannen als uitgangspunt genomen voor het opstellen van een (generiek) functioneel raamwerk voor procesverbeterstechnieken.

Op basis van een eerste vergelijking van de vier beschouwde stappenplannen, is een globale opzet gemaakt voor het functionele raamwerk. De uiteindelijke structuur van het raamwerk is afgeleid door de achterliggende functies van de stappen in ieder stappenplan te bepalen, overeenkomstige stappen onder één noemer te brengen (te weten de stappen van het functioneel raamwerk) en vervolgens op basis van logische overwegingen tot een definitieve indeling en volgorde van deze stappen te komen. Dit heeft geleid tot het Integrale Procesverbetering Model (Integrated Process Improvement model). Het model laat de verschillende functies en samenhang van technieken zien. Ook worden de belangrijkste verschillen tussen de vier beschouwde stappenplannen duidelijk. Met name de verschillen in aandacht voor stabiliseren (in Fase 2) en optimaliseren (in Fase 3) van processen, en de duale rol van kwalitatieve en observationele kwantitatieve technieken in de tweede fase van het model worden duidelijk.

Het opgestelde functionele raamwerk kan worden gezien als een generiek model. Een dergelijk model heeft als voordeel dat een zelfde kader wordt gebruikt voor diverse verbeterprojecten. Er is echter wel sprake van situationele factoren die de keuze van stappen (en technieken) binnen het raamwerk beïnvloeden. De belangrijkste factoren hebben betrekking op de aard van het aan te pakken probleem, de hoeveelheid aanwezige proceskennis, en deels daarmee samenhangend de mogelijkheid en noodzakelijkheid voor het gebruik van bepaalde typen van technieken.

Als afsluiting zijn de resultaten van het onderzoek bediscussieerd in het licht van de oorspronkelijke onderzoeksvragen en onderzoeksdoelstelling (Hoofdstuk 6). Alhoewel de keuze van het aandachtsgebied voor het tweede deel van het onderzoek lijkt te duiden op het onderzoeken van een minder belangrijk deel van de oorzaken van problemen, dragen de resultaten van dit onderzoek juist bij aan concrete mogelijkheden voor het aanpakken van organisatorische problemen. De resultaten zouden met name kunnen worden verwerkt in trainingsmiddelen om zodoende de geconstateerde problemen met betrekking tot training en kennis van technieken te verminderen.

Het proefschrift wordt afgesloten met aanbevelingen voor verder onderzoek in relatie tot het onderzochte onderwerp.

Curriculum Vitae

Werner Schippers was born on June 4, 1969, in Bergeijk, the Netherlands. In 1987 he received his VWO diploma from the Rythovius College in Eersel after which he started his study in Industrial Engineering and Management Science at the Eindhoven University of Technology. He finished his graduation project in 1992. After a period of free-lance work for implementing his graduation project at DAF Trucks Eindhoven, he started his Ph.D. work at the same University as a member of the section of Fabrication Technology at the Department of Industrial Engineering and Management Science. During this research project, the department was reorganized resulting in the fact that the Ph.D. work is now positioned within the section Quality of Products and Processes of the Department of Technology Management. The research project, which was initiated in November 1994, concerned the structure and applicability of quality tools. This thesis concludes this study.

Apart from this thesis, the Ph.D. work resulted in a number of papers that have been presented at international conferences and published in the International Journal of Quality Science (merged with the International Journal of Quality and Reliability Management), the International Journal of Production Economics, Quality and Reliability Engineering International and the International Journal of Environmental Conscious Design and Production. The research was performed in cooperation with various industrial companies and the Institute for Business and Industrial Statistics of the University of Amsterdam.

In 1997, Werner Schippers was appointed as a part-time lecturer at the Department of Technology Management. As a lecturer he was involved in courses and assignments in the area of the control and improvement of production processes. From September 2000, Werner Schippers will start working for the Institute for Business and Industrial Statistics of the University of Amsterdam. Here he will be involved in research and consultancy in the field of quality control and improvement programs.

Besides his work in the above field, since 1994, he runs a business in the design and manufacturing of steel furniture and sculptures for various designers and other customers. The cover pictures one of these products*.

* 'Dozenkast', stainless steel
by Piet-Hein Eek, Geldrop, the Netherlands.