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STEPS AND STRATEGIES IN PROCESS IMPROVEMENT

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SUMMARY

It has been recognized that it is profitable to apply statistical methods in quality improvement projects. The statistical methods that have been developed for that purpose in the 20th century have been made operational in the form of improvement strategies. In the literature various examples of such strategies are described. Although often presented as a uniform approach for problem solving, they are partly differing in terms of the steps and the tools they use. This paper's objective is to place the available strategies in relation to each other and to study the differences in functionality. We discuss both global differences—differences relating to the functional objectives of the strategies—and detailed differences, that is, differences that concern the steps and the tools that are exploited to arrive at the objectives. The strategies that are taken along in the collation appear to have sufficient similarities to place them in a functional framework. This framework enables one to exploit the complementary functionalities within the strategies and to use it as a generic strategy for statistically based process improvement. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS: process improvement; variation reduction; strategy; tools; SPC; Taguchi; Shainin; Six Sigma

1. INTRODUCTION

In the course of the 20th century statistical techniques were developed that make important contributions to process improvement projects in industry. These techniques were made operational in improvement programs such as Statistical Process Control (SPC) [1] and the Six Sigma program [2], which is currently popular particularly in the United States. These programs have in common that they are based on what is referred to as 'statistical thinking' [3]. Statistical thinking is based on the premises that:

- variation is all around us and present in everything we do;
- all work is a series of interconnected processes; and
- identifying, characterizing, quantifying, controlling, and reducing variation provide opportunities for improvement.

The various approaches to process improvement that are suggested in the literature range from tools and methodologies to complete stepwise approaches, or even larger (company-wide) improvement programs. In this paper we consider such approaches and we refer to them as process improvement strategies. Starting from the strategies currently available we seek to derive a framework that enables a comparison of various process improvement strategies.

The improvement strategies that we consider are strategies to find variation components and their causes, starting from a specific problem in the performance of a process. Although process improvement plays a role in both new and existing products and processes, we focus on the situation of an existing, running process during the manufacturing stage. Hence, the type of process improvement strategies under study could be defined as:

> a coherent series of steps aimed at improving the performance of a process by identifying the causes of variation and generating improvement actions.

We composed a list of improvement strategies that are well defined and generally applied in practice. The selected strategies are an implementation approach for SPC, Taguchi's methodology, the Shainin System and Six Sigma. Although differences in steps and tools can be observed, in most cases these strategies are presented as generic strategies and no indications of limited application areas are given. This paper is intended to compare the individual approaches on their functional aspects. The comparison is made

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by deriving a functional framework that enables a collation of the functional steps of the strategies and the activities and tools that constitute these steps.

The strategies that have been selected are described and reviewed in Section 2. The global functional objectives of the strategies are compared in Section 3. A detailed collation is made in Section 4, in which we derive a functional framework for the activities that the strategies consist of. The discussion and comments in Section 5 conclude the article.

2. A REVIEW OF EXISTING VARIATION REDUCTION STRATEGIES

Upon reviewing the literature for 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 process improvement strategies that comply with these requirements. Some of these 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. Below, the four strategies are briefly described. The content of each strategy, that is, the steps that it consists of and the tools that are used, is described within the functional framework in Section 4. The listed references were used as a source of information for determining the content of each strategy.

SPC (on-line)

Statistical Process Control (SPC) (cf. [1,4]) emerged in the 1920s, when it was realized that in quality control focus should not be on products, but rather on the underlying processes. The pioneering work was done by Dr Walter A. Shewhart, who invented the well known control chart [5].

Although the term SPC was used later on in senses encompassing a larger scope of quality control methodologies, we focus here on the original approach, which is referred to as *on-line* SPC (as opposed to *off-line* SPC) [1]. A stepwise approach for implementing SPC in industry is provided by Does *et al.* [6]. In the current paper we consider this implementation strategy.

SPC is concerned with underlying processes rather than with a single output characteristic. 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 that it lays on qualitative and exploratory analyses. Controlled experimentation to reduce process inherent variation (which is the subject of off-line SPC) is not really exploited. We conclude that the main area of applicability of on-line SPC is in relatively immature processes in which many instabilities and disturbances occur.

Intentionally, the implementation of SPC is company wide, which requires the incentive to come from the management. The implementation and use are typically arranged in multidisciplinary teams mainly consisting of operators and process engineers. Hence, SPC exploits techniques that are easily comprehended.

Taguchi

In the 1980s interest in variation reduction among quality engineers and statisticians in the West grew substantially. Most emblematic among the originators of this interest is the Japanese engineer Genichi Taguchi. Taguchi invented and promoted various methodologies and concepts, 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). We refer to [7] for a discussion of Taguchi’s methodologies. Although the adequacy of the methodology has been the subject of much debate among statisticians [8], the approach is popular in business practice.

As an operationalization of Taguchi’s methodologies and concepts we consider a stepwise strategy described by Ross [9]. This approach is built around Taguchi’s quantitative experimentation methodology. Variation reduction is accomplished in two ways. Based on the results from an experiment, settings for 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 [7,10,11]). If this is not sufficient, tolerance design [7] is exploited to accomplish a further reduction in variation.

The Taguchi methodology is popular in the design stage, but also applicable during manufacturing stage for improving products and processes. It is a strategy based on experimentation and hence requires a stable process. 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.

Shainin

Dorian Shainin put several techniques—both known and newly invented—in a coherent stepwise strategy for process improvement in a manufacturing environment. This strategy is called the Shainin System. Part of the strategy is promoted by Bhote [12]. Both Shainin, but especially Bhote, present the Shainin System as an alternative to SPC and Taguchi's methods. The system has been described in various papers [13,14]. Since elements of the Shainin System are legally protected as Service Marks and some methods are rarely discussed in the literature, it is difficult to obtain a complete overview.

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). This is achieved by a 'homing in' method: using statistical analysis tools, the classes of causes in which the important causes are likely to be found are selected, thus zooming in on the Red X. Once the Red X is identified, either an irreversible corrective action is taken, or the tolerances on the Red X are tightened and controlled.

The Shainin System is built around a set of tools that are plainly understood and easily applied, thereby refraining from more advanced techniques. The theory is clarified using a clear vocabulary (featuring concepts as *Red X* and *Homing in Strategy*).

Six Sigma

Six Sigma [2,15] is a philosophy for company-wide quality improvement. It is developed and promoted by Motorola and based on the insights of SPC and Design of Experiments [16]. Six Sigma is a legally protected program. Consequently, it is not possible to discuss all elements in full detail. 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.

Part of the Six Sigma program is a 'Breakthrough Strategy' (Inner MAIC-loop) for instigating improvements. 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 co-ordination of improvement projects. Since the Inner MAIC-loop complies with our definition of a process improvement strategy, it is this part of the Six Sigma program that is considered in this article.

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. It features virtually all relevant tools and techniques that have been developed in industrial statistics, from control charting to design of experiments, and from robust design to tolerance design.

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 co-ordinated by so-called Champions and Master Black Belts. Projects are conducted by Black Belts and Green Belts, who are selected from middle management. Performance is measured in a series of metrics typical for Six Sigma. The idea is to use standard metrics company wide in order that comparisons can be made.

3. A GLOBAL COMPARISON

In this section we make a global comparison of the selected strategies. The comparison is made on four dimensions. These dimensions are chosen so as to demonstrate the main differences among the strategies related to the questions: 'What is pursued by the strategy?', and 'How should the user arrive at the supposed result?' The dimensions are the following:

- the type of improvements that are pursued;
- the type of data that are used;
- the main phases in the strategy; and
- the typical user who applies the strategy.

The global comparison is summarized in Table 1.

Type of improvements

Two types of improvements are discerned.

1. Stabilization, which means that the process is brought in statistical control. The behavior of a controlled process is stable and predictable. The improvement activities comprise the elimination and prevention of disturbances and can be described as 'process fixing'.

Table 1. Global comparison of the strategies

Strategy	Type of information	Improvement types	Main phases	Typical user
SPC	• Qualitative • Observational quantitative	• Stabilization	• Planning • Analyze/improve non-experimental • Control	Multidisciplinary teams (operators and engineers)
Taguchi	• Qualitative • Experimental quantitative	• Optimization	• (Planning) • Analyze/improve non-experimental • Analyze/improve experimental	(Production) Engineers
Shainin	• Observational quantitative • Experimental quantitative	• Stabilization • Optimization	• Planning • Analyze/improve non-experimental • Analyze/improve experimental • Control	(Production) Engineers
Six Sigma	• Qualitative • Observational quantitative • Experimental quantitative	• Optimization	• Planning • Analyze/improve non-experimental • Analyze/improve experimental • Control	Middle managers and specialists

2. Optimization, which means that the parameters of the process are altered so as to improve its behavior.

SPC strives after stabilization, but offers no tools for optimizing a process. In the Shainin System no clear distinction is made between stabilization and optimization, and both types of improvements are pursued. Taguchi and Six Sigma are optimization strategies, that do not actively seek to detect and remove disturbances.

Type of data

Various types of information are exploited in the improvement strategies.

1. Qualitative information: knowledge of the process from, for instance, the operators and process engineers that work with the process, or the technicians that designed it.
2. Observational quantitative information: numerical data that are collected passively, that is, from the running process without interventions in the process.
3. Experimental quantitative information: numerical data that are collected from an experiment.

In the Shainin System the use of qualitative knowledge is rejected as being the result of 'guessing' [14]. SPC offers no tools for an active probing of the process for experimental data are not exploited. Taguchi, on the other hand, focuses on experimental data and offers no tools for exploratory studies. Six Sigma appears to be the most complete program in this respect.

Main phases

When considering the functionality of the activities in the selected strategies, it appears that the flow of the selected strategies can be grouped into three main phases.

1. Planning phase: the functionality of this phase is to identify vital quality characteristics that are the object of improvements and to prepare them for the subsequent phases.
2. Analysis and improvement phase: in this phase the process is analyzed and, as a result, opportunities for improvements are found. In the analysis and improvement activities we observe a distinction between two stages:

    (a) a stage in which qualitative and observational quantitative data are used. Typically, this non-experimental stage is aimed at stabilization improvements; and

   (b) a second stage in which experiments are conducted. This experimental stage is aimed at optimization improvements.

   The non-experimental stage is done prior to the experimental stage, mainly because it is less expensive to achieve improvements from observational studies, secondly, because a stable process is a prerequisite for experimentation, and thirdly, because variables that are taken along in the experiment should be identified and the important ones selected.

3. Control phase: the final phase involves the implementation of the improvements and the design of a control system to ensure that the improvements can be held on to.

Usually in improvement projects various analysis paths are followed simultaneously and single paths branch into multiple paths. Consequently, various activities within the analysis and improvement stage are intertwined.

Considering the strategies, we remark that Taguchi's strategy is concentrated on experimentation and hence has little attention for the planning and control phases. The experimental stage lacks in the analysis and improvement phase of SPC. When regarding the phases that are part of an improvement program, the Six Sigma program and the Shainin System appear the most complete strategies.

Typical user

The people in the organization that apply the improvement strategy are referred to as 'typical user'. The education and intellectual skills of the typical users influence the degree of mathematical sophistication of the tools that can be used in an improvement project. The hierarchical or functional position of the typical user affects the scale of the improvements that can be pursued.

We observe that on one end we have SPC that have shopfloor personnel as its intended users. As a consequence, relatively easy tools are exploited in SPC. At the other end we find Six Sigma, in which middle managers perform projects, supported by shopfloor teams. This is reflected in the tools, which are more sophisticated. Although all four strategies have a similar functionality, Taguchi's methodology and the Shainin System are ad hoc problem solving strategies, whereas SPS and Six Sigma are parts of a company-wide improvement program.

4. A DETAILED COMPARISON WITHIN A FUNCTIONAL FRAMEWORK

In order to make a more detailed comparison, we derive a functional framework. In this framework we accumulate the functionalities of the activities in the selected improvement strategies. We explain this below.

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 activities including a set of tools, whereas others are described in terms of the rationale underlying each step. Upon listing the steps of the four strategies we determined for each step the underlying objective so that the strategies could be compared and combined. While identifying corresponding objectives from different strategies, we obtained a collection of generic steps, that are the building blocks of the functional framework. Due to differences between strategies, the original order of steps within each strategy could not be maintained. For a first ordering we used the phases that we have introduced in the preceding section. For the determination of the final order of steps within the functional framework additional considerations played a part that are based on logic concerning the interdependency of steps.

In the remainder of this section we describe the steps in the functional framework in more detail. In this discussion, the logical considerations underlying the ordering of steps within each phase are clarified. In addition, for each step, a brief description of the generic goal is given, typical tools are listed and the corresponding activities in each strategy are discussed. 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 where a step of a strategy covers more than one generic step, this is indicated adding suffixes a and b. References of tools are not given explicitly when they can be found in the references given for the methodologies.

In Table 2 the steps of the functional framework and the corresponding steps of the four strategies are summarized.

Phase 1: planning

The first phase is concerned with a thorough characterization of the problem to make it suitable for a variation reduction approach. The logical order within this phase is as follows: the problem is defined

Table 2. Steps of the four selected strategies and the functional framework

	SPC	Taguchi	Shainin	Six-sigma	Functionality
Phase 1. planning	Process description (1) Cause and effect analysis (2a) Risk analysis (3a)	State the problem to be solved (1)	Define the project (1)	Select CTQ characteristic (1a)	1.1: Select and define problem
		Determine the objective of the experiment (2a)		Select CTQ characteristic (1b)	1.2: Translate problem into measurable characteristic
	Measurement analysis (6)	Determine the measurement method(s) (3)	Establish effective measuring system (2)	Validate measurement system (3)	1.3: Define and validate measurement system
				Establish product capability (4)	1.4: Assess baseline performance
		Determine the objective of the experiment (2b)		Define performance standards (2) Define performance objectives (5)	1.5: Define objectives
Phase 2: analyze/ improve non-experimental	Cause and effect analysis (2b) Risk analysis (3b)	Identify factors which are believed to influence the performance characteristic(s) (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
			List suspect variables (4)		2.4: List process variables (for Ph. 3)
Phase 3: analyze/ improve experimental		Initial screening experiment (*)	Statistically designed experiment: variables search (5a)	Screen potential causes (7)	3.1: Experimentation for screening
		Set up and conduct experiment, analyze data, interpret results (5-13)	Statistically designed experiment: full factorial (5b)	Discover variable relationships (8a)	3.2: Experimentation for model-building
		Select optimum levels (parameter design) (14)	Optimize interaction (6)	Discover variable relationships (8b)	3.3: Selection of optimal settings
		Run a confirmation experiment (15)	Better vs. Current (B vs. C) (8)		3.4: Model verification
		Tolerance design (*)	Realistic tolerances (7)	Establish operating tolerances (9)	3.5: Define tolerances for control
Phase 4: control	Control chart (7b) Out of Control Action Plan (8) Control plan (*)		Statistical process control (9) Monitor results (10)	Validate measurement system X's (10) Implement process controls (12)	4.1: Define and implement controls
	Process capability study (9)	Return to step (4) if objective is not met (16)		Determine process capability (11)	4.2: Validate effect of improvements
	Certification (10)			Audit and review (*)	4.3: Assurance/ auditing

(Step 1.1); the problem is related to a measurable characteristic (Step 1.2); how this characteristic will be measured is determined (Step 1.3); the baseline performance is measured (Step 1.4); the objectives as compared with the baseline performance are set (Step 1.5).

Step 1.1: select and define problem. The goal is to determine and prioritize the problem. Typical tools in this step include Pareto analysis and Quality Function Deployment (QFD).

- SPC. *Process description (1); Cause and effect analysis (2a); Risk analysis (3a)*. By using these tools important characteristics in the process are identified and prioritized.
- Taguchi. *State the problem to be solved (1).*
- Shainin. *Define the project (1).*
- Six Sigma. *Select CTQ (Critical To Quality) characteristics (1a).* Projects are typically selected using benchmarking and a thorough baseline analysis. Customer satisfaction and money savings are the leading principles.

Step 1.2: translate the problem into a measurable characteristic. This involves specifying the metric that is used to measure the selected problem.

- Taguchi. *To determine the objective of the experiment (2a).* This includes identifying a (measurable) performance characteristic.
- 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.

Step 1.3: define and validate the measurement system. The goal of this step is to ensure that the 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. The performance of the measurement system includes accuracy, linearity, stability and precision. Typical tools are gauge R&R study, control charts.

- SPC: *Measurement analysis (6).*
- Taguchi: *Determine the measurement method(s) (3).* It is determined how the selected characteristic will be assessed and, if necessary, the measurement system's accuracy and precision are improved.
- Shainin. *Establish an effective measuring system (2).*
- Six Sigma. *Validate the measurement system (3).*

Step 1.4: assess baseline 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).

Step 1.5: define objectives. The objectives that are to be met after the improvements are set.

- Taguchi. *Determine the objective of the experiment (2b)*: specify the performance level required when the experiment is complete.
- 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*).

Phase 2: analysis and improvement—non-experimental

The planning phase being completed, the core of the variation reduction strategy as described in the introduction of this section begins. Those causes of variation that possibly have a significant effect are identified from an infinite universe of potential causes (using qualitative tools in Step 2.1 and observational tools in Step 2.2). As mentioned before, two objectives are pursued: finding disturbances, and selecting variables that are taken along in the experiments in the next phase. This dual goal is reflected in the last two steps, in which the disturbances are removed (Step 2.3) and the process parameters 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, thereby exploiting existing knowledge. Tools that are frequently used include Ishikawa diagrams, log books, risk analysis (FMEA), brainstorming and process mapping. Shainin explicitly rejects identification of possible sources on the basis of expert insights in favor of identification based on measurements (Step 2.2) [14].

- SPC. *Cause and effect analysis (2b); risk analysis (3b).* Apart from indicating the process' most important characteristics (Step 1.1), these techniques are used to indicate and prioritize the important variation sources for each characteristic.

- Taguchi. *Identify favors that are believed to influence the performance 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).*

Step 2.2: quantitative identification of variation sources. The structure of the variation in the process reveals *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, fixed differences and variance components. An exploratory study is performed to find these symptoms, using tools such as control charts, ANOVA, multivari chart, correlation study, regression, histogram, run-chart, concentration diagram, component swapping study, analysis of means.

- SPC. *Measurements (5); control chart (7a).*
- Shainin. *Generate clues (3a).* Using tools such as multi-vari study, component swapping and paired comparisons, classes of causes that are not likely to contain the important causes are eliminated, thus homing in on the dominant variation sources.
- Six Sigma. *Identify variation sources (6b).*

Step 2.3: eliminate disturbances. Disturbances can be eliminated by means of adjustments to working procedures, by technical adjustments, by the introduction of inspections, or in a number of other ways. Some of these measures are irreversible corrective actions, others take the form of a control system.

- SPC. *Improvement actions (4).*
- Shainin. *Generate clues (3b).* Often, clues are so evident that an important variation source can be pin-pointed and no further experimentation is necessary.

Step 2.4: list process variables (for Phase 3). While the important disturbances are removed, the process parameters are listed as input for the next phase.

- Shainin. *List suspect variables (4).*

Phase 3: analysis and improvement—experimental

This phase has the list of identified process parameters put together in Step 2.4 as its input. After the vital few among these parameters are distinguished from the trivial many, the effect of these process parameters on the response is modeled. 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: the important parameters are selected (Step 3.1), for this selection of parameters a model is estimated (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 assessed (Step 3.4); and operating tolerances are established using the validated model (Step 3.5).

Step 3.1: experimentation for screening. The number of factors is reduced to conduct a simple experiment. Experimentation consists of the phases set-up experiment, conduct the experiment, and analyze the results. Typical tools are fractional factorial designs and effect plot.

- Taguchi. *Initial screening experiment (*).*
- 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 [17] for a discussion.
- Six Sigma. *Screen potential causes (7).*

Step 3.2: experimentation for model-building. 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. Typical design tools are factorial designs, central composite design, Box–Behnken design, and designs for robust design. Analysis tools are linear models [18] and analysis of variance [19].

- Taguchi. *Set up and conduct experiment, analyze data, interpret results (5–13).* In the Taguchi methodology this involves separating the factors in control and noise factors (5), determining the number of levels and values for the factors (6), identifying control factors that may interact (7), drawing the required linear graph for the control factors and interactions (8), selecting the orthogonal arrays (inner and outer) (9), assigning the factors and interactions to columns (10) and finally conducting the experiment (11). After the collection of the data is completed, the data are analyzed (12) and the results are interpreted (13).

- 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)*. Popular experimental designs are factorial designs, the central composite design and the Box–Behnken design. Concepts from response surface methodology [20] are exploited.

Step 3.3: selection of optimal settings. From the estimated model, optimal settings for the relevant parameters are selected. Optimal here means bringing the response on target *and* minimizing variation in the response. Typical tools are contour plots, calculus (to analyze the model), canonical analysis [20] and robust design (see [10,11]).

- Taguchi. *Select optimum levels (parameter design) (14)*. Typically for Taguchi experiments, the mean and dispersion are not modeled separately. Rather, the quadratic loss is modeled. In Taguchi's methodology this is operationalized using a series of metrics called *signal-to-noise ratios* (S/N-ratios). The parameters that affect the S/N-ratio are set to minimize this measure, whereupon the parameter that affect the process' location, but not the S/N ratio, are used to bring the process on target.
- Shainin. *Optimize interaction (6)*.
- Six Sigma. *Discover variable relationships (8b)*.

Step 3.4: model verification. By means of additional runs the predictive accuracy of the model for the selected parameter settings is checked.

- Taguchi. *Run a confirmation experiment (15)*. This is done to demonstrate that the chosen settings do provide the desired results.
- Shainin. *Better vs current (B vs C) (8)*. This is a non-parametric test for assessing improvement.

Step 3.5: define tolerances for control. Tolerance design [21] is used in order to find suitable tolerances around the chosen settings for the process parameters. In case the variation reduction accomplished by the elimination of disturbances (Step 2.3) and robust design (Step 3.3) is not sufficient, tolerances should be narrowed.

- 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 (7)*. These are established using a scatter plot of the response versus the dominant process parameter.
- 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.

Phase 4: control

Based on the results of the previous phases one can define and implement controls both for the output of a process and for the process parameters (Step 4.1). The effects of the improvements (Steps 2.3 and 4.1) can be validated (Step 4.2). 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 4.3). An auditing plan is developed in order that the improvements can be held on to.

Step 4.1: define and implement controls. The parameters are controlled at their selected settings. The response is monitored to detect disturbances. With the controls defined in Step 2.3 these controls form an integrated control system. Typical tools include control charts, pre-control, feedback/feedforward control, log books, mistake proofing (poka-yoke).

- 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 (9); monitor results (10)*. Shainin advocates the use of precontrol [22] instead of control charts. Positrol is provided as a technique for managing control of the process parameters.
- 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 measurement error. Also, the difference between short-term variation and long-term variation is taken into account.

Step 4.2: validate effect of improvements. Typical tools are process capability study, process capability indices, and tests such as the t-test, F-test and non-parametric tests.

- SPC. *Process capability study (9).*
- Taguchi. *Return to step (4) if objective is not met (16).*
- Six Sigma. *Determine process capability (11).* Typical Six Sigma metrics are used.

Step 4.3: 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 3 months and audited every year.
- Six Sigma. *Audit and review (*).* The project is reviewed by a Master Black Belt.

5. CONCLUSIONS AND DIRECTIONS FOR FURTHER RESEARCH

This paper compares four well-known process improvement strategies, both on a global scale and on a detailed scale. On a global scale, we observe differences in the type of data that are utilized, in the type of improvements that are pursued in the main phases of the strategy, and for the intended user.

From Table 1 we conclude that two main approaches can be discerned in the type of process improvement strategies that we consider. Our approach could be described as an experimental approach aimed at finding optimal settings for the parameters in the process. Taguchi's methods and Six Sigma are examples of this approach. On the other hand, there is a stabilization approach that seeks to identify and prevent disturbances that perturb the process. SPC represents this approach. The Shainin System is the sole strategy that has elements of both the optimization and stabilization approach, although this distinction is not made explicitly.

From this it can be concluded that the various strategies can supplement each other. It is our experience that a rigid application of either SPC or the Six Sigma program to a given project is not optimal. Processes that are dominated by instabilities and disturbances should be tackled with a problem-fixing approach such as SPC, whereas processes that seem to be in statistical control require an optimization approach, such as Six Sigma.

On a detailed scale, we place the activities of the strategies in a functional framework to study the various ways in which the selected strategies handle similar functionalities. The comparison in Table 2 confirms the complementary nature of strategies on a global level, but also shows that some strategies contain steps (i.e. functionalities) that could be useful in another strategy.

As a result, the functional framework, which is in fact a cumulation of the activities of the individual strategies, could be considered as a generic variation reduction strategy: first, because it combines the functionalities of the individual strategies; and second, because it accumulates the tools and the techniques that are employed in the selected strategies to realize the functional objectives. When using the functional framework as a generic strategy for process improvement, the planning phase of the project, in which the baseline performance is assessed, should offer a decision moment in which the direction is chosen that appears to be the most profitable. The selection of steps and tools is influenced by various situational factors. The main factor is the nature of the problem at hand (i.e. the need for stabilization versus optimization), but also other factors may influence the choice of steps and tools (cf. [23] for a further discussion). The use of the functional framework as a generic strategy for process improvement in practice is the subject of current research.

The insights presented in this paper should help practitioners from industry in understanding and selecting suitable variation reduction activities and use them in a coherent way. Further research will also pursue this goal. It will involve the formulation of a more detailed strategy within the quantitative steps of the framework. Apart from this, further research will address the field of new process development.

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Jeroen de Mast studied mathematics at the University of Leiden. Since 1998 he has been employed at the Institute for Business and Industrial Statistics of the University of Amsterdam (IBIS UvA BV) where he works on a PhD thesis on the subject of variation reduction in industrial environments. Besides these research activities he works as a statistical consultant for various Dutch companies. His experiences with SPC, Six Sigma and Shainin's methods stem from this consultation work.

Werner Schippers studied Industrial Engineering and Management Sciences at the Eindhoven University of Technology. Recently he completed a PhD thesis on the applicability of quality tools at the faculty of Technology Management at the same university. This research is directed to finding functional structures and contingency factors for quality tools. As lecturer he is also involved in courses and business projects for students in the area of process control and improvement. Besides this, he has experience in training various quality tools (such as SPC, Shainin and Taguchi) and the support of implementation projects in industry. Since 2000 he has been employed at IBIS UvA BV.

Ronald Does obtained his PhD in Mathematical Statistics at the University of Leiden, and worked at the Mathematical Center in Amsterdam from 1976 to 1981 as a Research Fellow. From 1981 to 1989, he worked at the University of Maastricht, where he became Head of the Department of Medical Informatics and Statistics. In that period his main research interests were medical statistics and psychometrics. In 1989, he joined Philips Electronics as a senior consultant in Industrial Statistics. His work involved, among other things, implementing SPC and teaching courses on Design of Experiments.

In 1991 he became Professor of Industrial Statistics at the University of Amsterdam. In 1994, he founded IBIS UvA BV, which operates as an independent consultancy firm within the University of Amsterdam. The projects at this institute involve SPC, Taguchi and Shainin methods and Six Sigma. Since last year the institute also offers a Business Improvement Program based on the Generic Variation Reduction Strategy of this paper. Already several major companies in the Netherlands implement the program.

His main research activities lie in the design of control charts for non-standard situations and the application of statistical methods in programs such as Six Sigma and the Business Improvement Program of the institute.

Edwin van den Heuvel worked as a Research Fellow at the University of Amsterdam from the period 1991 to 1996. Since 1996 he has worked for IBIS UvA BV, where he became a senior consultant in Industrial Statistics. He implements quantitative quality programs, such as Six Sigma and Statistical Process Control, at several large companies. He is one of the initiators of the Business Improvement Program of IBIS UvA BV. His research interests lie in Industrial Statistics and statistical strategies that help companies improve the quality of their products or services. He also teaches and guides students at the University of Amsterdam and supervises PhD students in their research.