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Quality Quandaries: Design for Six Sigma: Method and Application

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INTRODUCTION

In the past 20 years, Six Sigma has developed into a standard method to organize quality and efficiency improvement in industry and service, with many corporations and firms claiming important financial benefits (Breyfogle 2003; Snee and Hoerl 2004). There are many activities in organizations relating to quality and efficiency, and they should not all be organized in the same way. Juran (1989) proposed a generally accepted distinction of activities related to quality into planning, control, and improvement.

- *Quality planning* consists of the determination of what customers want and the development of the products and processes that are required to comply with these needs. This work is typically organized in specialized staff departments such as marketing and product and process development.
- *Quality control* consists of the on-line and real-time monitoring of production or service delivery, the detection of irregularities, and the reaction to these irregularities. A typical control system encompasses elements such as a control plan (or quality control handbook), control points and loops (statistical process control [SPC] control loops, feedback, and feed-forward controllers), and inspections. Quality control is reactive in nature and deals particularly with what Juran (1989) called *sporadic problems*. Its organization should be integrated with the regular (production, back office, service delivery, or other) process, and nowadays its execution is typically the responsibility of the people who execute the process (Does et al. 1999).
- *Quality improvement*, finally, is the organized and systematically pursued improvement to increase quality and efficiency to unprecedented levels (Juran [1989] called this *breakthroughs*). Unlike quality control, quality improvement is not an on-line affair but should be executed in the form of projects (the project-by-project nature of quality improvement). Such improvement projects typically tackle what Juran (1989) called *chronic problems*, eliminating them once and for all: recurring stagnations or constant levels of waste, poor service, or scrap.

The distinction between control and improvement, sometimes described as *on-line* vs. *off-line quality management*, is important. Quality control's main intent is to defend the status quo by reacting to problems (firefighting). If, in the course of this operation, an opportunity is encountered to improve the process, then it is of course seized, but the reactive and opportunistic

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approach of control is completely different from improvement, which searches for improvement opportunities systematically. Examples of approaches for quality improvement are Taguchi's off-line quality control, process optimization using design of experiments, business process reengineering (BPR), and Six Sigma's DMAIC (abbreviating the main phases Define, Measure, Analyze, Improve and Control) methodology (cf. De Mast et al., 2006). Regular Six Sigma projects are mainly conducted in the operational part of organizations (e.g., manufacturing, back office, care) or in basic support functions such as accounting and sales, where the routine tasks are carried out. Stagnations and structural problems are tackled; improvements often are found in the form of a control system or modifications in the standard way of working. Occasionally, a redesign of part of the process is needed.

A major part of the problems in processes can be prevented, however, by taking possible problems during manufacturing and operations into account during product and process development. In order to apply the basic principles of Six Sigma in product and process development, an adaptation of the methodology has been developed. This adapted methodology is called Design for Six Sigma (DfSS). DfSS is the methodology for quality planning (cf. Creveling et al. 2003; Lunau 2009).

DFSS ON A STRATEGIC LEVEL: BUSINESS STRATEGY

According to a famous quote of Heraclitus: "Panta rhei, kai old menei" ("Everything flows and nothing remains"); that is, businesses develop, mature, age, and die. In order to sustain, companies must outlive their individual businesses. Typical life cycle models for businesses and products include the stages embryonic, growth, maturity, aging. The place of innovation in a business strategy can be characterized in three horizons of growth:

1. Core businesses horizon (defend the organization's core businesses and extend them by piecemeal incremental innovation).
2. Emerging businesses horizon (develop and deploy new products that are to become tomorrow's core businesses).
3. Future options horizon (explore opportunities for the future).

Resources should be divided sensibly over all three horizons. Too much emphasis on the first horizon means increasing today's profits at the expense of future profits.

In a competitive market, being as good as a competitor means that you do not make a profit (principle of perfect competition). A good strategy sets a company apart from its competitors, thus enabling the company to make a profit. A company must decide on what dimensions—quality, service, better understanding of customers' needs, with price being first—it plans to be different from its competitors (strategy is about choosing). Companies that do not develop a strategy (companies that do not make choices) to focus their improvement efforts may improve their performance, but this improvement will not be converted into higher profits.

Until the 1980s, underperformance was generally accepted. Since the 1980s the "discipline of the market" was introduced: companies must perform—now and in the future—or perish. Also, there is a changing focus of innovations: over a product's life cycle the focus of innovation shifts from product innovation to process innovation.

A balanced business strategy can be as follows:

- Use DMAIC to defend and extend today's profit generators (horizon 1).
- Use DfSS to develop inventions and opportunities into new products that provide added value to customers and thus develop tomorrow's revenue drivers (horizon 2).
- Pursue options for the future (horizon 3), which is a matter of more fundamental technological and market research.

What sets DfSS apart from "regular" process and product design?

- Less emphasis on ideal performance, more emphasis on manufacturability, reliability, maintainability. Standard principles are the following:
  - Robust design (design products and processes in such a way that they function well in nonideal circumstances);
  - Reduce complexity of products and processes (thus reducing the probability of mistakes);
  - Inventory as early as the design phase which mistakes and problems are likely to occur; and Design preventive mechanisms.

- Altogether the emphasis is on robustness and mistake-proneness and less on ideal performance.
- The driving principle is not technology but added value for stakeholders. Good product and process design is not exclusively technology driven but is also driven by what stakeholders consider to be value. In DfSS this is embodied by a disciplined translation process that starts from the stakeholder. His or her functional requirements are translated to technical requirements and these are translated into product specifications and process settings and finally a control plan. Critical parameter management is applied to keep track of the relationships of parameters on different levels.
- Early warnings: testing and feedback in early phases ensure that the designers focus on weaknesses in the design, instead of being carried away by a drive to continue improving features that are already strong points. Early warnings include feasibility study, design review by experts, prototype testing, reliability and lifetime testing, capability studies, and capability flow-up.

DfSS ON A TACTICAL LEVEL: PHASES, STEPS, AND TOOLS

Regular Six Sigma projects follow the DMAIC method. The logic of a DfSS project is that the design is the translation of functional requirements into technical solutions and translation of these into reliable products and processes to produce them reliably. Also, DfSS uses roadmaps as means to structure projects and facilitate project tracking.

For DfSS projects there is a modified methodology: DIDOV. The phases are as follows:

1. Define: projects should not be started thoughtlessly. Organizations must think through carefully where they invest their efforts and money. To enable a purposeful project, the project's objectives should be concrete and specific. To avoid wasting time on trifling matters, there should be a thorough analysis of which process or product has to be designed. To minimize political squabbling, there should be clear agreements on deliverables, investments (time!), and procedures. To get the project going, there should be a project team and a project review board (including a champion).
2. Identify: development of a set of functional and nonfunctional requirements for the product or process to be developed, based on perceived market opportunities, customer wishes, and the company's strategy.
3. Design: development of concept designs; selection of the most promising ones; identification of design parameters but also nuisance variables and disturbances; assessment of risks in the selected high-level design by experts.
4. Optimize: elaboration of the concept into a detailed design; establishment of specifications (nominal values and tolerances) for design parameters.
5. Verify: Product or process validation and readiness plan; design of a quality control system.

Other variants of DfSS methodology exist; for example, DMADV (Define, Measure, Analyze, Design and Verify/Validate). DfSS employs many techniques that are familiar in the regular Six Sigma program. The main additions are critical parameter management, theory of inventive problem solving (TRIZ), reliability engineering, and a number of principles and techniques from methodical design (morphological grid, Pugh matrix). In Figure 1 the roadmap to carry out DfSS projects is given.

Each of the IDOV phases consists of three steps, which use the following tools (cf. Lunau 2009):

Define	
Identify	1. Determine customer requirements 2. Establish functions and subfunctions 3. Define functional requirements
Design	4. Develop solutions for each function 5. Develop and score concept designs 6. Elaborate the high-level design
Optimize	7. Identify parameters 8. Specify the nominal design 9. Design for X
Verify	10. Verification trials 11. Design process controls 12. Transfer to operations

FIGURE 1 Roadmap for DfSS projects.

I. Identify
1. Determine customer and business requirements. Tools: customer-needs mapping, voice of the business and voice of the customer analyses.
2. Establish functions and subfunctions: establish main functions that the product or process should deliver and break them down into subfunctions.
3. Define functional and nonfunctional requirements: based on identified customer and business needs, define a set of functional requirements (i.e., specifications for the functions) and nonfunctional requirements (all other specifications). Tools: quality function deployment (QFD).

II. Design
4. Develop solutions for each function: establish a set of candidate technical solutions for each of the functions that the product or process should deliver. Tools: creativity tools such as brainstorming, synectics, and TRIZ.
5. Develop and score concept designs: combine candidate solutions per function into integrated conceptual solutions and select the most promising concept. Tools: morphological grid, Pugh matrix.
6. Elaborate the high-level design: Break down the system into subsystems and components and assign functions to components. Tools: design review.

III. Optimize
7. Identify parameters: identify design parameters, nuisance variables, and failure modes and their effects. Tools: design failure mode effects analysis (DFMEA), design of experiments, transfer functions.
8. Specify the nominal design: specify target values for the design parameters. Tools: design of experiments, parameter optimization, robust design.
9. Design for *X*: optimize the design from various perspectives, including design for reliability, design for robustness, design for manufacturability, tolerance design, and design for maintainability. Tools: reliability engineering, robust design, tolerance design.

IV. Verify
10. Verification trials: design and execute the product or process validation plan. Tools: functional tests, MEOST, use verification, process/product capability analysis.
11. Design process controls. Tools: SPC, feedback and feed-forward control, control plan, FRACAS, process failure modes and effects analysis (PFMEA).
12. Transfer to operations: project discharge.

APPLICATION: CLOSED-LOOP FLUX CONTROL
Background

Printed circuit assemblies can be found in all kinds of electrical and electronic products, including cars, mobiles, airplanes, computers, and tools. Printed circuit boards (PCBs), populated with electronic components such as integrated circuits, chip components, capacitors, etc., comprise circuit assemblies. The components are attached to the assemblies with solder; these solder connections or joints are both electrical and physical. A conventional way of creating these solder joints is through the use of what is known as a *wave soldering process*. In such a process the printed circuit board is moved across a flowing wave of hot liquid, or molten, solder. The molten solder contacts the surfaces to be joined—components to the circuit board itself—and forms solder joints and a functional assembly.

Before these boards can be soldered, the surface has to be cleaned and prepared with a chemical called *flux*. Once the flux is applied, the board is heated to evaporate the solvent of the flux and to bring energy into the board. Then the board is ready to be soldered. The amount of flux that is applied is critical to the soldering process. The function of the flux is to clean the surface of the assembly so that molten solder will wet to the metal surfaces and prevent soldering defects. Think of solder as a metal glue that binds and bonds the parts together while creating electrical pathways for the circuit.

The number of electronic assemblies in cars, airplanes, or computers is increasing rapidly. Air bags, navigation systems, and motor controls are examples. In the automotive industry, traceability is important

due to potential claims when parts fail in the field. For this reason, electronics manufacturers should be able to trace how much flux is applied to any assembly. Flux residues can result in electromigration and thus cause failures. Bar code systems, flux flow meters, and management information software makes traceability of the applied flux amount possible.

In this real-life example we discuss the design of a closed-loop flux control. Due to space limitations we do not provide a full discussion of all the steps of this Design for Six Sigma project.

Problem Definition

Design and implement a new methodology of measuring and controlling the amount of flux in the machine. A consistent amount of flux will reduce the number of solder defects. The business case for the company was assessed at more than 100,000 Euros yearly and the return of investment for the customer at less than 2 years.

Identify

The assemblies are transported automatically and mechanically via a chain conveyor over a flux application device. Air and flux are mixed in a manner similar to spray painting technology, and the flux is spray-applied to the bottom side of the board using an atomized spray nozzle. On the basis of interviews with three major clients and a survey, the functional and nonfunctional requirements in Table 1 were established.

During spraying, there will be a loss of flux, resulting in higher flux consumption. The nozzle is mounted on a moving mechanism. Depending on the speed of the mechanism and the atomizing air pressure, the loss will be between 10 and 40%. That flux will be exhausted in order to avoid contamination of the machine. Although the flux suppliers will recommend a certain amount of flux on the board (target), the best setting must be defined for each board design. In order to have a stable process, it is important that the amount of flux that is sprayed to the board is equal for all boards. Consistency is more important than achieving a defined amount (target). Not enough flux on the board will result in solder defects. Conversely, too much flux is cosmetically undesirable and also increases electromigration risk.

Flux consumption is measured per PCB with a flow meter, and flux overspray is measured by weighing the PCB. Repeatability and uniformity of deposition are measured across and within PCBs with a fluxometer.

Design

For flux depositing (function 1) various alternative flux types were considered, but alcohol and volatile organic compound (VOC)-free water-based fluxes are the most popular in the industry. For the control function (function 2), three types of flux flow meters

TABLE 1 Functional and Nonfunctional Requirements

Function 1: deposit flux
Functional requirement 1.1: repeatability of flux deposition (vital)
Functional requirement 1.2: uniformity of deposition (vital)
Functional requirement 1.3: deposition volume synchronized with conveyor speed (desirable)
Functional requirement 1.4: ability to perform selective location fluxing (desirable)
Functional requirement 1.5: consistency of quality across a range of board thicknesses (vital)
Function 2: control
Functional requirement 2.1: control by means of SPC (desirable)
Functional requirement 2.2: closed-loop control of deposition (desirable)
Functional requirement 2.3: effective guidelines for machine parameter settings (desirable)
Functional requirement 2.4: provide pro-deposition graphs for fluxer at all ranges of the machine spec (minor)
Function 3: setup and maintenance
Functional requirement 3.1: speed of nozzles change (vital)
Functional requirement 3.2: length of maintenance interval (desirable)
Nonfunctional requirements
Nonfunctional requirement 1: complete documentation (desirable)
Nonfunctional requirement 2: low flux consumption (desirable)
Nonfunctional requirement 3: availability of information (desirable)

	Coriolis flow meter	Thermo dynamic flow meter	Micro liquid flow sensor	Nozzle fluxer (today)
Flux amount	5	4	4	3
Flux deviation	3	3	3	3
Flux overspray	4	3	3	3
Service calls	5	5	2	3
Sold units	2	5	4	3
Total score	19	20	16	15

FIGURE 2   Pugh matrix of the different flux meters.

TABLE 3   Overview of the Number of Defects with Respect to the Amount of Flux

Flux amount [mg/cm^2]	Defects 0603	Defects SOT
0.0	80	88
0.7	21	70
1.7	2	28
4.1	2	20
4.9	2	10
5.8	0	8
6.6	4	10

The Pugh matrix of this study is presented in Figure 2. Based on this matrix the Coriolis and thermodynamic flow meters are real competitors; the final decision was postponed to the Optimize phase.

were considered: an expensive flux meter (Coriolis principle) and two cheaper alternatives (a thermodynamic flow meter and a micro liquid flow sensor). They were compared to the current solution, a nozzle fluxer having only a flow detection sensor. The Pugh matrix helps to identify the concept that best fulfills functional requirements (cf. Pugh 1991).

Optimize

With board dimensions in the range of 100–400 mm (width), conveyor speeds in the range of 80–180 cm/min, and pressures of the flux tank in the range of 0–450 mBar, a Box-Behnken experiment was set up to establish the relation of the flux deposition with these three factors. The results are given in Table 2.

TABLE 2   Results of the Box-Behnken Experiment

Response Surface Regression: mg/cm^2 versus Board width. Conveyor speed. Pressure tank
The analysis was done using coded units.
Estimated Regression Coefficients for mg/cm^2

Term	Coef	SE Coef	T	P
Constant	4.6996	0.1357	34.639	0.000
Board width	−1.9362	0.1532	−12.639	0.000
Conveyor speed	−1.6313	0.1532	−10.648	0.000
Pressure tank	2.7417	0.1455	18.844	0.000
Pressure tank ∗ Pressure tank	−1.3496	0.1989	−6.784	0.000
Board width ∗ Pressure tank	−0.8775	0.2520	−3.482	0.002
Conveyor speed ∗ Pressure tank	−0.7825	0.2520	−3.105	0.006

$S = 0.5040$ R-Sq $= 97.4\%$ R-Sq(adj) $= 96.6\%$

Analysis of Variance for mg/cm^2

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	6	183.944	183.944	30.6573	120.68	0.000
Linear	3	166.723	167.021	55.6738	219.16	0.000
Square	1	11.692	11.692	11.6916	46.02	0.000
Interaction	2	5.529	5.529	2.7646	10.88	0.001
Residual Error	19	4.827	4.827	0.2540		
Lack-of-Fit	11	3.924	3.924	0.3567	3.16	0.057
Pure Error	8	0.903	0.903	0.1129		
Total	25	188.770				

FIGURE 3 Technical specifications of both flow meters.
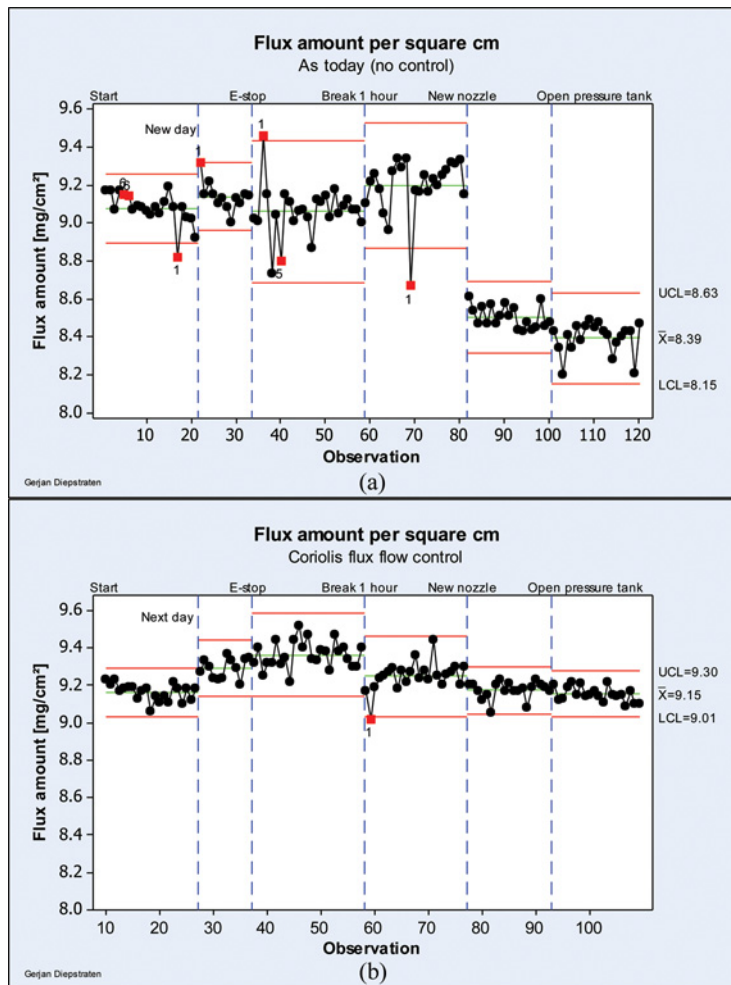

FIGURE 4 Differences between (a) no control and (b) control via the Coriolis flow meter.

Based on these results it is easy to determine the optimal pressure of the tank if the input parameters are the flux deposition, conveyor speed, and board width, thus facilitating feed-forward control; for example, with the flux deposition equal to $4.7\,\text{mg/cm}^2$, conveyor speed equal to $130\,\text{cm/min}$, and board width equal to $250\,\text{mm}$, the pressure should be 270 mBar. Note that the other dimension of the board (length) were not significant.

Another experiment was carried out to figure out the amount of flux deposition needed to get a good wetting of the solder, a limited number of flux residues, and a low number of solder defects. Flux depositions ranging from 0 to $10.7\,\text{mg/cm}^2$ were used in the experiments. For $5.8\,\text{mg/cm}^2$ there is excellent wetting and above $7\,\text{mg/cm}^2$ there is too much flux residue. In Table 3 an overview of the number of defects on the 0603 components and the SOT components is given. The best results are with a flux amount of $5.8\,\text{mg/cm}^2$.

The variation of the measurements of flux flow made by the Coriolis flow meter was much less than by the thermodynamic flow meter. The main reason is because the Coriolis flow meter is able to take 10 samples per second and the thermodynamic flow meter can only take 1 sample per second.

Verify

It was decided to offer two machine options: option 1: The thermodynamic flow meter recording the flux deposition values; option 2: The Coriolis flow meter not only recording but also regulating (closed-loop control) the flux deposition. In Figure 3 the technical specifications are given.

Because of flux residues, the upper limit for this assembly and flux will be approximately $7\,\text{mg/cm}^2$. The target is approximately $6\,\text{mg/cm}^2$ because at this amount of flux the defect level is the lowest and the residues are acceptable. The lower limit will be around $5\,\text{mg/cm}^2$. Less flux will result in minor soldering yields. In Figures 4a and 4b the difference is shown between no control and control by the Coriolis flow meter.

Without control the amount of flux is sensitive to E-stops, production breaks, and replacements of the nozzles. With the control mechanism the overall performance has been improved. The project was finished by introducing SPC closed loops to monitor the amount of flux and a control plan.

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