An Analysis of the Six Sigma DMAIC Method from the Perspective of Problem Solving

Jeroen de Mast, Joran Lokkerbol
University of Amsterdam, Institute for Business and Industrial Statistics
Amsterdam, The Netherlands

Please cite this article as:
De Mast, J., and Lokkerbol, J. (2012). "An analysis of the Six Sigma DMAIC method from the perspective of problem solving". *International Journal of Production Economics* **139**(2) 604–614.

1. Introduction

Six Sigma is defined by Linderman et al. (2003) as "(…) an organized and systematic method for strategic process improvement and new product and service development that relies on statistical methods and the scientific method to make dramatic reductions in customer defined defect rates."
Academic research, such as Zu et al. (2008) and Schroeder et al. (2008), has tried to determine which elements in Six Sigma make it effective. Besides its role structure and focus on metrics, Six Sigma's structured improvement procedure is seen as a novel and effective contribution to quality management. This improvement procedure is generally known under the acronym DMAIC, standing for Define, Measure, Analyze, Improve and Control.

DMAIC is similar in function as its predecessors in manufacturing problem solving, such as Plan-Do-Check-Act and the Seven Step method of Juran and Gryna (Balakrishnan et al., 1995). In the theory of organizational routines, DMAIC is a metaroutine: a routine for changing established routines or for designing new routines (Schroeder et al., 2008). Originally described as a method for variation reduction, DMAIC is applied in practice as a generic problem solving and improvement approach (McAdam & Lafferty, 2004). It is instrumental in the implementation of Six Sigma as a process improvement methodology (Chakravorty, 2009).

Six Sigma and its DMAIC method emerged and developed in practice. It built on insights from the quality engineering field, incorporating ideas from statistical quality control, total quality management and Taguchi's off-line quality control. Their wide adoption in practice warrants a critical scientific analysis. One aspect of a scientific evaluation of Six Sigma is to critically compare its principles with insights from established scientific theories.

This work aims to study the Six Sigma DMAIC method from the perspective of scientific theories in the field of problem solving as published in the operations research and management science (OR/MS) and industrial engineering (IE) literatures. Six Sigma is often described as a problem solving methodology, and for that reason, theoretical insights from the problem solving literature should provide insights on DMAIC. The purpose of the analysis is to identify limitations of the method. These identified limitations may be an inducement for attempts at improving the method. But some limitations may be inherent to DMAIC, as it is not plausible that a strong method can be applicable without restrictions in all circumstances. In those cases, the practical value of identified limitations is that they provide a basis for advising users when the DMAIC method is suited.
Since an authoritative or uniform account of the DMAIC method does not exist, we have worked with a large number of sources, varying in degrees of quality, clarity and coverage. In the next section, we describe the sources we have used to obtain a carefully balanced understanding and rendering of the DMAIC procedure. We also outline our approach for studying DMAIC from the perspective of a number of themes in the problem solving literature. The subsequent sections treat these themes, and each formulates a number of conclusions. In the final Discussion and Conclusions section we seek to integrate the individual conclusions into a comprehensive characterization of DMAIC as a problem solving method.

2. Source material and methods

2.1 Six Sigma's DMAIC method

The Six Sigma phenomenon does not refer to a single, clearly delineated method. Rather, it refers to a related collection of practices in organizations, such as Six Sigma courses taught to professionals, textbooks written by consultants, and improvement projects and initiatives undertaken under the flag of Six Sigma. In studying DMAIC, there are essentially two options: to study the method as it is prescribed in courses, textbooks and other instructional media (prescriptive accounts), or to study it as it is factually applied by practitioners in improvement projects (descriptive accounts). Here, we limit ourselves to the first option, leaving descriptive studies of DMAIC applications for further study. Thus, our source material for understanding the DMAIC method consists of prescriptive accounts of the method, such as course manuals, textbooks, and papers.

De Koning & De Mast (2006) make a rational reconstruction of Six Sigma's methodology. Conceiving the Six Sigma method as a system of prescriptions, they discern four classes of elements of the method:

- A model of the function and purpose for which the method applies.
- A stage model (DMAIC) providing a stepwise procedure.

- o A collection of techniques.
- o Concepts and classifications, such as Critical-to-Quality (CTQ) characteristics and the distinction between the *vital few* and the *trivial many* causes.

Define: Problem selection and benefit analysis **D1.** Identify and map relevant processes. **D2.** Identify stakeholders. **D3.** Determine and prioritize customer needs and requirements. **D4.** Make a business case for the project.
Measure: Translation of the problem into a measurable form, and measurement of the current situation; refined definition of objectives **M1**. Select one or more CTQs. **M2.** Determine operational definitions for CTQs and requirements. **M3.** Validate measurement systems of the CTQs. **M4**. Assess the current process capability. **M5.** Define objectives.
Analyze: Identification of influence factors and causes that determine the CTQs' behavior **A1.** Identify potential influence factors. **A2.** Select the vital few influence factors.
Improve: Design and implementation of adjustments to the process to improve the performance of the CTQs **I1.** Quantify relationships between Xs and CTQs. **I2.** Design actions to modify the process or settings of influence factors in such a way that the CTQs are optimized. **I3.** Conduct pilot test of improvement actions.
Control: Empirical verification of the project's results and adjustment of the process management and control system in order that improvements are sustainable **C1.** Determine the new process capability. **C2.** Implement control plans.

Table 1: Rational reconstruction of the DMAIC procedure, after De Koning & De Mast (2006).

Based on an extensive analysis of descriptions of these elements in the practitioners' literature, De Koning & De Mast (2006) conclude that these various accounts have enough commonalities to consider them variations of a single method, thus claiming convergent validity for the method. From a large number of sources, the functions of the DMAIC stages and their steps and prescribed actions are reconstructed as in Table 1. De Koning & De Mast also link techniques and tools to these DMAIC stages. From their analysis of the contents of the method, they arrive at the following characterization of Six Sigma's method:

- o The method prescribes that problems are parameterized and quantified.
- o Improvement actions are derived from discovered relationships among variables.
- o In particular, Six Sigma's method and techniques are largely driven by causal modeling, in which a process's Critical-to-Quality (CTQ) characteristics are regarded as the effects of causal influence factors (the Xs).
- o Techniques such as design and analysis of experiments, process capability study, and gauge R&R study[1] are iconic for Six Sigma.

[1] This is a statistical technique for evaluating the repeatability and reproducibility of measurement systems.

Table 1 gives the function of each stage of the DMAIC procedure, and the individual steps typically prescribed for delivering these functions. For its strong empirical basis, we take the rational reconstruction of De Koning & De Mast (2006) as our primary reference and operational definition of Six Sigma's DMAIC method. We have complemented this reconstruction by studying a large number of additional sources, which we describe below.

ASQ's Body of Knowledge. The American Society for Quality is one of the largest Six Sigma certification bodies in the world. We studied its *Six Sigma Black Belt Body of Knowledge* (ASQ, 2007a) and *Six Sigma Black Belt Certification Requirements* (ASQ, 2007b).

Textbooks and course-books. The practitioners' literature on Six Sigma is substantial; at the time of writing, Amazon lists 1052 books with the phrase "Six Sigma" in the title. We selected the top 100 ranked by Amazon's *Bestsellers Ranking* from this list, thus seeking to focus on titles having substantial impact among practitioners. From these 100 titles, we excluded those books that do not provide substantial coverage of techniques, method, or project selection criteria, and we excluded books that are not primarily about DMAIC (but focus on other areas such as Lean principles or Design for Six Sigma). We studied the remaining books as manifestations of the method. Our account will refer to a selection of the titles in this sample.

Six Sigma course material. DMAIC is taught to large numbers of professionals. Hoerl (2001) and Chakravorty (2009) give general overviews of Six Sigma courses at various levels. Our third source of additional material consists of training manuals that the authors were able to study in detail, such as the one by Open Source Six Sigma (2011).

Practitioners' publications. Practitioners' journals such as *Quality Engineering* (Taylor and Francis, London), *Quality Progress* (American Society for Quality, Milwaukee) and *International Journal of Six Sigma and Competitive Advantage* (Inderscience, Geneva) offer a source of advice and testimonials about Six Sigma, although often based on personal experience and opinion. Where relevant, we have referred to publications in these journals.

These sources, in addition to our primary definition of DMAIC based on De Koning & De Mast (2006), provide a multiform conception of Six Sigma's method. We have taken care to avoid drawing conclusions from a single or a limited number of manifestations of the method.

2.2 Themes in the problem solving literature

Problem solving has been studied extensively in the OR/MS/IE literature. Following the definition given by Ackoff & Vergara (1981), we understand a problem as a choice situation in which a person attaches negative value to the current state of affairs, and is in doubt which course of action to take. Problems come in a wide variety of types. Jonassen (2000), for example, proposes a typology discerning eleven types, ranging from logical puzzles via troubleshooting to social dilemmas. The problem solving literature offers various stepwise models for the problem solving process, such as:

- Osborn-Parnes (Evans, 1997): 1. Mess finding; 2. Fact finding; 3. Problem finding; 4. Idea finding; 5. Solution finding; 6. Acceptance finding.
- March and Simon (MacDuffie, 1997): 1. Problem identification; 2. Diagnosis; 3. Solution generation; 4. Implementation.
- MacDuffie (1997): 1. Problem definition; 2. Problem analysis; 3. Generation and selection of solutions; 4. Testing and evaluation of solutions; 5. Routinization — Development of new routines.

From the problem solving literature, we selected a number of themes as bases for our studies of DMAIC. These themes, which provide the structure for the rest of the paper, are the following.

1. Problem solving methods can be generic, or specific for a certain task-domain (Newell, 1969).
2. Problems vary on a continuum ranging from well-structured to ill-structured (Smith, 1988).
3. Problem solving entails a variety of generic problem solving tasks (Smith, 1988).
4. Diagnostic problem solving concerns the discovery of the causes of problematic behavior (De Mast, 2011).
5. Remedial problem solving concerns the development of solutions (Smith & Browne, 1993).

Each of these themes is elaborated in one of the following five sections. For each theme, we review scientific insights as documented in the literature (*theoretical development*). Next, we critically confront accounts of DMAIC with these theoretical insights (*application to DMAIC*), which results in a number of conclusions that identify limitations and points for improvement in Six Sigma. The final section seeks to integrate the individual conclusions into an overall characterization of DMAIC as a problem solving method.

3. Generality versus domain specificity

3.1 Theoretical development

The first theme that we discuss is the generality of problem solving methods, and its ramifications for their applicability. The problem solving literature asserts that problem solving methods that are specific for a restricted task-domain tend to be more powerful than generic problem solving methods. For this reason, the former are sometimes called *strong methods*, and the latter *weak methods*. The phenomenon is referred to as the *power/generality trade-off* (Newell, 1969): the more task-specific a method, the more useful support it can provide for problems within its range, but the smaller the range of problems for which it is applicable. The phenomenon is named the usability/reusability trade-off in knowledge engineering (Fensel & Motta, 2001): specificity makes a method more usable in a specific situation, but less reusable in other situations. Knowledge engineering tries to overcome the trade-off by providing, in addition to a generic method, task-specific adaptors, which differentiate and specialize the generic method for a specific task (Fensel & Motta, 2001).

3.2 Application to DMAIC

Six Sigma's DMAIC method is a rather general method. Its original task-domain was variation reduction, especially in manufacturing processes. This original task-domain can be traced in the terminology of early breakdowns of DMAIC into detailed steps, such as the influential and widely used 12 step model adopted by *General Electric* (see p. 129 in Harry & Schroeder, 2006). Causes are referred to as *Variation Sources*, and controlling variation by setting tolerances to variation sources is an inherent element of the DMAIC method (step 9. in the 12 step model).

Later, the method was used for more general tasks, such as quality improvement, efficiency improvement, cost reduction, and other pursuits in operations management, and beyond manufacturing in services, healthcare, and other types of operations. This development is apparent in books such as Snee & Hoerl (2005), titled *Six Sigma beyond the Factory Floor*, and trends observed in the thorough literature review of Brady & Allen (2006). Snee & Hoerl (2005) describe differences between the manufacturing task environment and non-manufacturing environments, such as a lack of tangible output and products, a lack of a process view of work, the scarcer availability of useful measurements, and a greater human element. The last difference refers to the fact that in non-manufacturing processes such as services and healthcare, customers and patients are involved in the process itself, and one has to deal with employees rather than machines. Snee & Hoerl (2005) identify a number of adaptations necessary for non-manufacturing task-domains (ibid., pp. 33–36, 49, 232–238, and Ch. 7), such as:

- Modifications in terminology and exemplars.
- More attention and emphasis for setting up adequate measurement systems.
- More emphasis on process mapping.
- Differences in the relative usefulness of Six Sigma techniques; for example, the higher prevalence of non-normal or discrete distributions in non-manufacturing environments requires different statistical analysis methods.

The Six Sigma practitioner community started to publish books proposing domain-specific adaptations of DMAIC from about 2002. This has resulted in books with titles such as *Lean Six Sigma for Supply Chain Management* (Martin, 2006), *Improving Healthcare Quality and Cost with Six Sigma* (Trusko et al., 2010), *Six Sigma for Financial Services* (Hayler & Nichols, 2006), and *Six Sigma in the Pharmaceutical Industry* (Nunnally & McConnell, 2007).

Task-domain specific adaptations encountered in these books include:

- Terminology and examples that have been adjusted for the particular task-domain.
- The introduction of additional techniques, or the de-emphasis of standard Six Sigma techniques. For example, to make the method more powerful for applications in supply chain management, Martin (2006) includes techniques from operations research in the Analyze phase, and the book *Six Sigma for Financial Services* (Hayler & Nichols, 2006) proposes to use Six Sigma in combination with Lean and Business Process Management (BPM). On the other hand, the gauge R&R study and the design and analysis of experiments - techniques emblematic for Six Sigma in manufacturing - are given much less emphasis in a book on Six Sigma for healthcare such as Trusko et al. (2010). Hoerl (2001) mentions response surface methodology as less suited for applications in finance domains, but mixture experiments, techniques from reliability engineering and multi-dimensional tolerancing are noted as potential augmentations for applications in engineering.
- Task-domain specific checklists and templates; for example, Martin (2006) offers a list of 12 generic CTQs especially for projects in supply chain management, while Trusko et al. (2010, pp. 22–23) offer a list of seven generic defect and error types specific for the healthcare domain.
- A model of Six Sigma's purpose and business rationale adapted to a particular task-domain, as in Trusko et al. (2010), who explain the rationale for Six Sigma in healthcare organizations.

We take this as evidence that Six Sigma practitioners experience the power/generality trade-off, and try to overcome it by augmenting the Six Sigma methodology with domain-specific adaptations. In studying publications relating to different application domains, it is apparent that the strain between the ambitions of being generic on the one hand, and of providing powerful, specific and operational methodological support on the other, is manifest in many aspects of the DMAIC method. This is a recurrent theme in the subsequent sections of this paper.

The observations above motivate our first conclusion.

Conclusion 1. The DMAIC method is, as all problem solving methods, subject to the power/generality trade-off, which has first resulted in an evolution towards more generality (beyond manufacturing and variation reduction), and later into a large number of domain-specific adaptations.

4. DMAIC and well- and ill-structured problems

4.1 Theoretical development

To be able to characterize the sort of problems for which DMAIC is suited, the second theme that we study is that of problem structure, ranging from well-structured to ill-structured. Although the problem solving literature does not unanimously provide a crystallized definition, a well-structured problem is generally described as one for which the problem solver, although he or she does not know the solution, at least knows how to approach it. Routine problems fall in this category, for which the objectives and constraints are clear, and for which the problem solver can apply a known algorithm; examples include math problems and logical puzzles. For ill-structured problems such a schema for attempting to find a solution is not available or the problem solver does not recognize it, and there is a lack of clarity about how the problem should be approached. For ill-structured problems, the problem solving process typically involves a search for the objectives, for a useful representation of the problem, or for an effective approach (see Smith, 1988; Evans, 1992; and Jonassen, 2000).

Since Six Sigma is a method for solving problems in the empirical world, we exclude from our discussion such highly structured abstract problems as logical problems, algorithmic problems and story problems in Jonassen's (2000) typology, or conceptual problems in Bartee (1973).

To delineate further the type of problems for which DMAIC may be effective, we use a framework proposed by Pidd & Woolley (1980) and Woolley & Pidd (1981), who discern four types of problem solving (see Table 2). The first type of problem solving they call the *checklist stream*, and it concerns highly structured problems that can be solved by following a known algorithm. This conception of problem solving assumes an unambiguous and undisputed problem definition, such as a failure or a deviation from a standard, and a uniquely correct solution. The problem solving process is represented as following a tightly specified step-by-step procedure leading the problem solver to a uniquely correct problem analysis and solution. Kepner and Tregoe's problem solving method, and Shainin's statistical engineering algorithm (Steiner et al., 2008) are prototypes of this view on problem solving.

In Pidd and Woolley's (1980) second notion of problem solving, the *definition stream*, a problematic situation is coerced into the template of a (mathematical) modeling approach or decision procedure such as causal modeling or linear programming. Problem formulation, according to this view, consists of the selection of a set of variables, and problem solving proceeds by mathematical modeling and optimizing the relations between these variables.

Table 2: Four notions of problem solving, adapted from Pidd & Woolley (1980).

1. Checklist problem solving   The goal is unambiguous, as is the problem analysis process, which follows a stepwise procedure.
2. Definition problem solving   The problem is coerced into the template of a mathematical modeling problem, in which a solution is derived from modeling and optimizing relationships between variables.
3. Science research problem solving   Problem solving as a scientific activity, with emphasis on empirical fact finding to discover the real problem.
4. People problems   The problem is highly subjective and depends on personal values and perceptions; negotiation and reconciliation are important elements of problem solving.

The third viewpoint is the *science research stream*, which sees problem solving as a scientific activity. The nature of the problem and the goal are not considered given in an unambiguous way, and a suitable approach is not given by a checklist procedure, nor are they prompted by a template of a mathematical modeling problem. Instead, research is required to understand problems in their context, to prevent premature conceptions of a problem, and to decide on a suitable approach (cf. Evans, 1997). To this end, the problem solving process starts by a fact finding stage, in which quantitative data and other observations are collected and analyzed to discover the real problem and its nature.

The last viewpoint is the *people stream*, which addresses problematic situations characterized by intangible, interpersonal and subjective aspects. Jonassen (2000) mentions these examples: Should abortions be banned?; How to resolve the Kosovo crisis?; Should wealth be redistributed through tax policies? For this type of problems, the least structured ones, there is no objective problem, only conflicting standpoints, subjective perceptions, and incongruent values held by individuals and groups, and an understanding of the problem must be arrived at by a process of negotiation. Such social dilemmas are “messy” (Ackoff & Vergara, 1981); they involve a complex and large number of strongly interdependent issues in a pluralistic context (Ho & Sculli, 1997). The OR/MS/IE literature has produced a number of studies of how such ‘messes’ can be structured, and how a multitude of personal viewpoints can be reconciled (e.g. Rosenhead, 1996; Mingers and Rosenhead, 2004; Shaw et al. 2004; and Eden, 2004).

4.2 Application to DMAIC

We examined our sources to learn which of the four notions of problem solving apply to Six Sigma. The evidence suggests that DMAIC is applicable in a variety of ways. Sometimes DMAIC facilitates a type of problem solving that resembles Checklist Problem Solving as defined in Table 2. In other applications, DMAIC functions as a template for Definition Problem Solving, or as a model for Science Research problem solving.

For well-structured routine problems Six Sigma often works according to the Checklist notion. For specific domains, such as healthcare and financial service operations, the practitioners' literature acknowledges that many Six Sigma projects are generic, that is, many projects concern standard problems for which a known analysis and solution approach exists. The literature offers templates for such routine projects, sometimes called *generic projects*, in which especially the Define and Measure phases have been worked out to a high level of detail. Such collections of templates for generic projects are offered, for example, in De Koning et al. (2008) and Niemeijer et al. (2011). Thus, problem definition boils down to selecting a matching template, and problem analysis follows the steps prescribed by the template.

Within companies, especially larger ones, it is also common to share best practices in project databases (for example, the *Six Sigma Database* in Gitlow & Levine, 2004). The project reports stored in such databases function as solution schemas for routine and generic problems. Niemeijer et al. (2010) may serve as an example of the way in which the Six Sigma field reduces routine problems to checklist problem solving. The authors report on a DMAIC project that substantially reduced the length of stay of patients in a hospital's trauma nursing department. The approach then was used as a solution model for similar initiatives at other departments in the hospital. These derivative projects are well characterized as checklist problem solving, with a clear and unambiguous goal, and copying the analysis steps from the solution model.

The application of Six Sigma to less routine problems often matches the description of Definition Problem Solving. This type of Six Sigma projects coerces problem solving into the framework of statistical modeling of cause and effect relations. Problem definition boils down to defining the right CTQs, and problem analysis amounts to discovering the causal influence factors (the *X*s), driven by techniques for statistical modeling of cause-and-effect relations such as design and analysis of experiments and response surface methodology. Improvement actions and remedies are derived from established causal relations between these CTQs and *X*s, and follow standard patterns based on statistical model building, such as response surface optimization, robust design, and tolerance design (De Koning & De Mast, 2006).

In the literature, Six Sigma is often associated with the Science Research notion of problem solving (for example, Wruck & Jensen, 1994; and De Mast, 2007). For relatively ill-structured problems, in which the CTQs and nature of the problem are not clear, a fact finding stage aims to establish the real or most urgent problem on the basis of data. This fact finding takes place in the Measure stage in DMAIC. It can be quite elaborate, and typically involves techniques such as baseline process capability analysis, value stream mapping, and the Pareto chart. It results in a definitive problem definition, in terms of CTQs and objectives, given at the end of the Measure phase (generic step M5 in Table 1). Sometimes, Six Sigma projects stop after the fact finding stage, for instance, because the current situation is not as problematic as it had been perceived, or because the nature of the problem is different from what had been anticipated, and, given this new notion, it is not considered opportune to deal with it immediately or in the manner originally anticipated.

There are many case studies in the literature that match the application of DMAIC as Definition or Science Research Problem Solving. Desai (2006), for example, reports on a project in a small engineering company. The original problem description was that ineffective production planning and control resulted in failure to meet delivery commitments. This problem definition was not accepted by the team for lack of specificity and for being tied to an unproved cause. An extensive data analysis, studying records and correspondence of the previous five years, resulted in a refined problem definition, stating that the average rate of late deliveries was 38%, with an average delay of 48 days. The aim was for a reduction of 50% in the late delivery rate. Further data analysis, process analysis and brainstorming yielded a list of potential causes of the problem, such as *No evaluation of past commitments*, and *No scientific basis for commitments*. These causes were the basis for corrective actions. The team summarized their scientific attitude in their *Lessons Learned*: “Never try to devise corrective actions based on perceived causes.” Empirical fact finding to discover the real problem typifies this project, which has the character of Science Research Problem Solving.

Our studies suggest that Six Sigma’s DMAIC procedure leaves little room for the last notion of problem solving in Table 2 - People Problems. Rather than dealing with the ambiguous and subjective nature of these sorts of problems, DMAIC instead forces project leaders to capture problems in terms of facts and measurable variables. Overviews of Six Sigma’s toolbox (e.g., George et al., 2004; ASQ, 2007a; De Koning & De Mast, 2006) do not include techniques for exploring differences of opinion, subjective perceptions, and different values and interests of people, nor does Six Sigma offer techniques for negotiation and reconciliation. Typically, projects are selected based on their expected contribution to improving efficiency, cost or customer value (e.g., Pande et al., 2000, pp. 139–141) – a practice that recognizes the company as the sole relevant party, and denies other viewpoints based on people’s personal values and interests. Typical of most accounts, Snee & Hoerl (2003, pp. 78 ff.) advise to select projects with clear and quantitative measures of success, and to avoid fuzzy objectives, which amounts to the claim that DMAIC is not suited for problematic situations described above as a *mess*, in which many subjective problems are intertwined.

The observations above motivate our second conclusion.

Conclusion 2. We conclude that Six Sigma's DMAIC method is applicable for a wide range of well- to semi-structured problems:

Conclusion 2a. DMAIC, and especially domain-specific detailed elaborations of DMAIC ("generic projects"), serve as templates for routine problems, thus turning them into well-structured checklist problems.

Conclusion 2b. DMAIC and its underlying rationale of statistical and causal modeling serve as a general, and thus more flexible but weaker guide for less routine projects. The fact finding techniques in the Measure stage help in structuring more complex systems of problems and discovering the real problem and a suitable approach on the basis of data.

Conclusion 2c. DMAIC appears unsuited for ill-structured messes in which human dynamics, subjective perceptions, and personal values are important aspects. Problem structuring methods aimed at exploring and reconciling multiple subjective viewpoints, such as described in Mingers & Rosenhead (2004), are likely to be better suited to these types of problems.

5. Six Sigma and problem solving tasks

5.1 Theoretical development

In the previous sections, we have explored the limitations of DMAIC in terms of generality versus domain specificity, and in terms of well- versus ill-structured problems. In this section we explore the applicability of DMAIC to problems in terms of the problem solving tasks that these problems entail.

Problem solving involves a great diversity of tasks. It is generally recognized in the literature that the activities that problems entail are strongly determined by the nature and specifics of the problem being addressed. It is considered unlikely that humans have a generic "problem solving" faculty (Smith, 1988), and early efforts to design a generic problem solving procedure, such as Newell and Simon's General Problem Solver, have been abandoned.

Based on the premise that problems are diverse in the tasks that they entail, Smith (1988) proposed that many management problems could be decomposed into nine generic sub-problem types – see Table 3 (numbered I through IX in the right column). Decomposing a problem into generic sub-problems facilitates the translation of a problematic situation into problem solving tasks. While some problems may involve all nine sub-problems, most problems entail only a subset. For example, implementation problems, where one needs to put a solution into effect, only involve sub-problems V *(Design)* and IX *(Persuasion)*. But knowledge problems, where one needs to acquire certain understanding or information, only involve sub-problem III *(Research)*, or a combination of III *(Research)* and IV *(Diagnosis)*. Design problems involve the generic sub-problems of I *(Goal-setting)* and V *(Design)*, perhaps followed by IX (*Persuasion),* while V (*Design)* can in turn be decomposed into VI *(Alternative generation)*, VII *(Prediction of effectiveness)*, and VIII *(Evaluation of alternatives)*.

Table 3: Collation of the DMAIC phases (1. through 5.; left column) and Smith's (1988) generic sub-problems (I. through IX.).

1. Define Problem selection and benefit analysis.	I. *Goal-setting* (determining what one wants and appropriate levels of relevant objectives)
2. Measure Translation of the problem into a measurable form (CTQ), and assessment of the current situation.	II. *Description* (determining through observation and thought what happens to be the case) III. *Research* (the acquisition of knowledge through directed investigation) I. *Goal-setting* (based on the results of description and research, reformulate one's goals)
3. Analyze Identification of influence factors and causes that determine the CTQ's behavior.	IV. *Diagnosis* (providing causal explanations of why things are what they are)
4. Improve Design and implementation of adjustments to the process to improve the performance of the CTQs.	V. *Design* (determining how to achieve a desired state or end). This involves three subtasks: VI. *Alternative generation* VII. *Prediction of effectiveness* VIII. *Evaluation of alternatives* IX. *Persuasion* (gaining the consent of others)
5. Control Adjustments of the process management and control system in order that improvements are sustainable.	V. *Design*, possibly followed by IX. *Persuasion*, to develop and implement a control system.

5.2 Application to DMAIC

We use Smith's taxonomy to establish the sort of problems for which DMAIC is a suitable model by comparing the functionality of the DMAIC stages (as defined in Table 1) with the nine generic sub-problems.

As shown in Table 3, DMAIC incorporates all nine sub-problem types, and thus, applies to relatively extensive problems that entail all of Smith's sub-problems. This is confirmed by assertions in the practitioners' literature, which claim that problems of a more limited scope are unsuited as Six Sigma projects. In particular, implementation problems, named *solution-known* or *just-do-it* projects in the Six Sigma literature, are not considered proper Six Sigma projects (e.g., Snee & Hoerl, 2003, pp. 76–77; or Pande et al., 2000, p. 143). Also knowledge problems are not considered proper DMAIC projects; they are not, for example, accepted as Six Sigma projects in the ASQ's certification program (ASQ, 2007b) because they lack improvement actions and thus real financial benefits. For design problems, a related methodology is offered named Design-for-Six-Sigma. The practitioners' literature mentions a number of models for this method, such as DMADV (Design-Measure-Analyze-Design-Verify; see Snee & Hoerl, 2003). We did not include Design-for-Six- Sigma methods in our study because the commonalities evident among various accounts are relatively unconvincing.

We observe that Six Sigma does not offer much flexibility in dealing with the large diversity of real-life problems and the tasks that they imply, and DMAIC is claimed to be unsuited especially for problems of a limited task content. Kepner & Tregoe's rational processes (Kepner & Tregoe, 1997) are an example of a somewhat more flexible system. It offers three methods intended for specific problem types (problem analysis, decision analysis, and potential problem/opportunity analysis), and a fourth method (situation appraisal) that offers support in assessing the nature of a problem and in identifying which of the other three methods is suited.

This analysis motivates our third conclusion about the DMAIC method.

Conclusion 3. The DMAIC model describes rather extensive problem solving processes, in which a problem is first understood in terms of symptoms (the Measure stage), and then, after diagnosis, in terms of causes (Analyze). The design of remedies is less than half of the procedure. DMAIC is not a suitable model for less extensive problem solving processes, such as *solution-known* projects and design problems.

6. Six Sigma and diagnosis

6.1 Theoretical development

In the previous sections we have found that DMAIC coerces problem solving in the approach of statistical modeling of cause-and-effect relations, possibly preceded by a fact finding stage to establish the problem to be solved. DMAIC represents relatively extensive problem solving processes, including both diagnosis and the design of a remedy. In this and the next section, we study these two aspects in more depth.

The topic of diagnosis, the discovery of the causes of problematic behavior, has been well studied in artificial intelligence, medical diagnosis and troubleshooting of devices. Studies in the OR/MS/IE literature include Wagner (1993), Balakrishnan et al. (1995), MacDuffie (1997), and Smith (1998a). In this section we aim to understand how DMAIC prescribes that project leaders go about diagnosing the problem they study, and identify potential limitations of the method.

De Mast (2011) present a detailed study of the diagnostic process itself, which we use here as a basis for our discussion of the DMAIC method (see Table 4); see also Benjamins (1995) and Rasmussen (1981). The process involves a repeated alternation of hypothesis generation, the identification of candidate causal explanations, and hypothesis testing. Hypothesis generation is driven by observations and findings on the one hand, and reasoning from domain knowledge on the other. Domain knowledge driving diagnosis typically includes models of the physical structure of the system under study, such as a breakdown into its components and parts, and functional models, which represent how the system or process works. Identifying candidate causes by reasoning from the system's physical and functional structure is called deep reasoning or model-based diagnosis in the literature (Davis & Hamscher, 1988). Domain knowledge driving the identification of candidate causes also includes general scientific knowledge of physics, electronics, or other scientific disciplines relevant to the system under study. A last type of domain knowledge that we mention is fault knowledge, that is, experiential knowledge about known problems and their known causes. Fault knowledge could be in a compiled form, such as fault dictionaries and taxonomies, or in a raw form, as recollections of earlier problems in people's memories, or as descriptions of problematic episodes on the internet. Identifying candidate causes by recognizing the symptoms as indicative of a known problem is called shallow reasoning.

Hypothesis testing is aimed at rejecting or accepting candidate explanations as the true cause. It is driven by observations, which may be quantitative measurements and test results, or less structured sources of information such as anecdotes and findings.

The efficiency of the diagnostic process depends on the search strategy, which sequences diagnostic tasks such as hypothesis generation, hypothesis testing, and the creation or exploration of domain knowledge. De Mast (2011) shows that many well-known search strategies for diagnosis, such as the half-split strategy (Rasmussen, 1981), the topographic search (Rasmussen, 1981), Shainin's strategy of elimination and zooming in, and Kepner and Tregoe's problem analysis, are manifestations of a class of strategies named branch-and-prune. Branch-and-prune strategies seek to balance between excessive divergence of the search space and excessive convergence by treating the search space as a hierarchical tree structure, in which high-level and general causal directions are branched into more detailed causal explanations. The problem solver works top-down, aiming to prune high-level branches in their entirety, before elaborating only a limited number of branches into more detail.

Table 4: Elements of the diagnostic process, after De Mast (2011).

Hypothesis generation Identification of candidate causes, by shallow reasoning (the problem is recognized as a known problem) or deep reasoning (causes are identified by reasoning from the system's physical and functional structure and general scientific knowledge).
Domain knowledge Structural models: a decomposition of the system or process into physical components. Functional models: a model of the system's or process's functioning. General scientific knowledge relevant for understanding the system under study. Fault knowledge: information about known problems, as captured in fault dictionaries, taxonomies, and recollections of earlier problematic episodes.
Hypothesis testing Rejection or confirmation of candidates as the true cause.
Observations Measurements, test results, and less structured sources of information.
Search strategy Tactics employed in selecting and sequencing activities done for hypothesis generation and testing, and other activities done in the search for the problem's causes.

6.2 Application to DMAIC

Based on the framework for diagnosis discussed above, we review DMAIC's methodological guidance for diagnosis. The Six Sigma toolbox (De Koning & De Mast, 2006) includes generally known techniques for hypothesis generation, such as the cause and effect diagram, brainstorming, data mining, five why's, and exploratory data analysis. For the testing of hypothesized causes, Six Sigma offers strong and advanced techniques, such as statistical hypothesis testing and design and analysis of experiments.

Strategic advice for efficient diagnosis is virtually absent in Six Sigma. Most accounts, such as Pyzdek (2003) and Breyfogle (2003), offer no search strategies for efficient diagnosis. They merely offer an incoherent and poorly structured collection of techniques for hypothesis generation and testing. A rudimentary strategy is offered in Pande et al. (2000, pp. 256–275), whose *Root Cause Analysis Circle* comprises the steps (a) Analyze data / process; (b) Develop causal hypothesis (one or more); (c) Analyze data / process; and (d) Refine or reject hypothesis. One or more cycles finally result in (e) Confirm & select 'vital few' causes.

In some course manuals a so-called *funneling strategy* is proposed, as in Open Source Six Sigma (2011) and George et al. (2004, pp. 12–13). It suggests to start with brainstorming about potential causes, facilitated by a fishbone diagram, thus identifying a substantial number of candidate causes. Next, using analytical tools such as regression, the project leader narrows down the list of candidate causes until the 'vital few' remain. A related strategy is the one in Gitlow & Levine (2004, pp. 146 ff.), where potential causes are identified from the process flowchart, which are then organized in a cause-and-effect diagram and matrix. Other sources for hypothesized causes are mentioned, such as process knowledge and a literature review. Using statistical experimentation or scoring methods such as the failure mode and effects analysis (FMEA), the high-risk causes are singled out. Note that such funneling strategies do not offer such control against excessive divergence or premature convergence of the search tree as do branch-and-prune strategies.

The importance of advanced domain knowledge for diagnosis is not fully recognized in accounts of DMAIC. Basic techniques are proposed for exploring and laying down the physical and functional structure of the system under study, such as the flowchart, SIPOC or the value stream map (George et al., 2004). But there is virtually no systematic methodological support for identifying candidate causes from these simple domain models, beyond group discussion techniques such as the cause-and-effect diagram and five why's (George et al., 2004). Neither is there substantial support for exploiting general scientific knowledge for the identification of candidate causes; we found only cursory encouragements to discover cause-and-effect relations from expert literature or scientific repositories.

Also DMAIC's employment of fault knowledge (knowledge of known problems and their known causes) is rudimentary. Some accounts of the method suggest to the problem solver to search for lessons learned from similar problems or from the expert literature (e.g., Gitlow & Levine, 2004, p. 178). In most accounts, only quite general problem taxonomies are featured, such as 5M (Manpower, Machines, Materials, Methods and Measurements; Gitlow & Levine, 2004). More recent accounts of Six Sigma, named Lean Six Sigma (to be discussed in the next section), offer a taxonomy of 7 or 8 typical inefficiencies in processes named *standard forms of waste*. But these taxonomies are so general as to merely provide broad directions; more detailed taxonomies, as for example in Smith (1998a), could not be found in our source material. Interestingly, some accounts of DMAIC prescribe that in the Control phase, the problem solver should document fault knowledge for facilitating efficient diagnosis of future problems. This technique is the OCAP (out-of-control action plan; e.g., McCarty et al., 2004), in which known problem types with known solution strategies are laid down. The majority of accounts of DMAIC (for example, Breyfogle, 2003) do not motivate project leaders to search for fault knowledge in the expert or scientific literature at all.

We observe that fault knowledge and scientific knowledge are in general not fully recognized in accounts of DMAIC as useful sources for identifying causes of problems. By analogy, Six Sigma seems to advocate trying to diagnose patients with a medical condition solely by brainstorming and exploratory data analysis techniques, but without benefiting from insights from a scientific field such as physiology, and knowledge about known disorders as embodied in disease taxonomies. Hopp & Spearman (2008, pp. 189–190) describe DMAIC as treating problematic systems as a black box, where causes are discovered by analysis and experimentation, but there is no provision for building or benefiting from an edifice of theory about the behavior of systems. Hopp & Spearman (2008, p. 179) mention, as an example, a plant that has high inventory levels, poor customer service, and low productivity; DMAIC would prescribe to discover the causes of these problems by means of cause and effect diagrams, brainstorming, exploratory data analysis, and five why's. However, many such problems are known and well-understood issues, and the probable causes can be readily found in standard textbooks on operations management.

In our evidence, we found the following notable exception, where Six Sigma does promote experiential domain knowledge at more than an elementary level as a source for diagnosis. Specifically, some organizations offer project databases, where project leaders can consult relevant projects for inspiration (e.g. Gitlow & Levine, 2004, p. 224), and also the Six Sigma literature has started to offer collections of projects, which project leaders can consult for inspiration (cf. the references to collections of generic projects mentioned earlier, and the many books and papers containing Six Sigma case studies, such as Bisgaard, 2009).

We speculate that the relatively minor role of advanced domain knowledge in Six Sigma is partly a consequence of the power/generality trade-off: advanced domain knowledge will, by its nature, be relevant to only a specialized domain, and thus, the extra power obtained by incorporating advanced domain knowledge comes at the expense of a loss in generality of the method. This speculation is in line with our findings discussed in an earlier section that specialized elaborations of DMAIC, such as Martin (2006) for applications in supply chain management, do incorporate more advanced domain knowledge.

The analysis above motivates conclusions 4 and 5 about Six Sigma's prescriptions for diagnosis.

Conclusion 4. Six Sigma offers strong methods for the testing of conjectured causes, but only limited methodological support for the identification of candidate causes. In particular, DMAIC does not offer much strategic guidance for ensuring efficiency of the diagnostic search.

Conclusion 5. Six Sigma promotes diagnosis on the basis of brainstorming and exploratory data analysis rather than driven by scientific insights and fault knowledge.

7. Six Sigma and remedial problem solving

7.1 Theoretical development

The last theme we discuss is that of remedial problem solving. The design of a remedy, that is, of a solution to a problem, can vary from routine design, via innovative design, to creative design (Gero, 1990). Smith & Browne (1993) enumerate three sources for the generation of potential remedies - analysis, experience and creativity. Analysis refers to the improvement of a system by finding optimal settings and configurations by mathematical optimization techniques. Such approaches, also referred to as *parametric design* (Sapossnek, 1989), start from a conceptual decomposition of a system into a number of controllable variables or into primitive objects (for instance, parts of a machine, or elementary tasks in a process). Optimization techniques are used to find a satisfactory combination of settings for the controllable variables, or a satisfactory combination of primitive objects. The limitations of parametric design are often emphasized, namely, that its role is restricted to fine-tuning the remaining degrees of freedom in an existing product or process or after the most difficult and creative parts of the design of remedies have been completed (cf. Smith & Browne, 1993).

The second source for the generation of remedies is experiential knowledge. Domain experts have a store of proven, ready-made solution schemas for known problems in their memories based on their experience and that of colleagues, and they may consult libraries of best practices and standard solutions available for many fields. These earlier solution experiences may function as a model for inspiring a remedy in the case under study.

The third source identified by Smith & Browne (1993) is creativity. Creative problem solving has been the subject of a substantial body of OR/MS literature; for example, Ackoff & Vergara (1981) and MacCrimmon & Wagner (1994). Literature offers a vast collection of techniques for stimulating creativity, as in Summers & White (1976) and Smith (1998b). These techniques exploit principles such as analogy, metaphor, and the identification of relational parallels between the problem and a remote domain of experience.

7.2 Application to DMAIC

The development of remedial actions against problems is done in DMAIC's Improve phase. Six Sigma textbooks emphasize that the Improve phase should be inspired by the diagnosis done in the Analyze phase, and that remedies should be designed in response to identified causes (eg.: "Always start with a confirmed root cause", George et al., 2004, p. 254). In early accounts of DMAIC, remedies follow standard solution patterns such as:

- Response surface optimization: the establishment of optimal settings for controllable variables.
- Robust design: the establishment of settings for controllable variables that make a process or product maximally insensitive to nuisances.
- Tolerance design: the establishment of suitable bounds for the variation in input variables.

These solution patterns follow the approach of parametric design described above, and are based on mathematical analysis, typically regression analysis followed by numerical optimization to establish optimal parameter settings, or Monte Carlo simulation to establish suitable tolerance limits. Note that these solution patterns are restricted to fine-tuning the parameters of an existing process or product design, and exclude more essential redesign of a process or product.

Some, especially more traditional accounts of Six Sigma, do not offer much beyond these parametric solution patterns. The chapter on the *Improvement Phase* in Breyfogle (2003), for example, merely discusses techniques based on experimental modeling of causal relations. Some accounts motivate the project leader to actively search for experiential sources. For instance, George et al. (2003) suggest the following sources of solution ideas: best practices, other projects that have faced similar or related challenges, and benchmarks. In more recent years, Six Sigma courses and textbooks have augmented the DMAIC method by solution patterns based on experiential sources. Most prominent is the assimilation of a collection of standard patterns for process design and control known as Lean, Lean Thinking or Lean Manufacturing, which originate from Toyota's operations management practices (Jayaram et al., 2010). In the latest decade, the name *Lean Six Sigma* has caught on to refer to this integration of DMAIC and Lean (George, 2002). For standard problems in processes, Lean Six Sigma offers standard and simple cures such as 5S, visual controls, and kanban.

Although most accounts acknowledge in one place or another that remedies can have non-creative sources such as common sense, best practices and expert input (Pande et al., 2000, p. 281], many accounts go quite some way in stimulating readers to be creative and think out-of-the-box (e.g., Pande et al. 2000, p. 277). For the development of nonstandard, creative solutions, the Six Sigma toolbox offers some generic techniques such as brainstorming and the affinity diagram (George et al., 2004). The level at which these techniques are expounded in Six Sigma courses and textbooks is typically quite elementary. For example, Breyfogle (2003, pp. 967–970) is one of the more elaborate discussions in our source material, but it offers no methodological guidance beyond a number of general recommendations (“Suspend judgment”, “Develop a positive attitude”, etc) and explanations of the brainstorming and affinity diagram techniques.

Table 5: Approaches for the development of remedies promoted by Six Sigma (right column), and linked to the source that they exploit.

Mathematical analysis (parametric design)	Response surface optimization. Robust design. Tolerance design.
Experience (ready-made solution schemas)	Ideas inspired by similar projects, best practices and benchmarking. Best practices from Lean, such as kanban, 5S, and visual management. Standard approaches for process control, such as the control plan, statistical process control, and pre-control.
Creativity	Improvements inspired by brainstorming and the affinity diagram technique.

In line with standard theory in quality management, Six Sigma recognizes that for some problems once-and-for-all solutions are not available, and thus, that a remedy can also consist of continued monitoring and control. In the Control phase of the DMAIC model, techniques such as the control plan, statistical process control and pre-control are suggested, which are standard solution patterns, and thus have an experiential source. Most accounts of DMAIC are quite prescriptive in how process control should be organized, and creative solutions are not encouraged.

The above analysis, summarized in Table 5, motivates conclusions 6 and 7 about Six Sigma’s prescriptions for remedial problem solving.
Conclusion 6. Six Sigma recognizes that remedies can be ‘one-time’ interventions (designed in the Improve stage), but may also consist of continued control activities (designed in the Control stage).

Conclusion 7. Sources for the development of remedies vary from mathematical and statistical analysis, via experiential sources such as best practices, to creativity. The methodological support provided for creative problem solving is elementary.

8. Discussion and conclusions

We start this concluding section by pointing out the most important limitation of this research. In this study, we conceive of DMAIC as a problem solving method, and analyze it from that perspective. We claim that this perspective gives useful insights and results in useful conclusions about the method, but we emphasize that this perspective is by no means exclusive, and other perspectives (for instance, the goal-theoretic perspective chosen in Linderman et al., 2003) may result in equally interesting conclusions.

The seven major conclusions of our studies have been presented in the preceding sections. Here we seek to integrate this set of conclusions into a comprehensive view on DMAIC as a problem solving method.

Our study has brought to light some characteristics of problem tasks for which DMAIC may be a suitable method. DMAIC is applicable to empirical problems ranging from well-structured to semi-structured, but not to ill-structured problems or pluralistic messes of subjective problems (*people problem solving*, in the framework used in the paper). DMAIC is suitable for rather extensive problem solving tasks, requiring all of the components of problem definition, diagnosis, and the design of remedies. It is less suited for problem tasks of a smaller scope.

Six Sigma is a *generic* method. The advantage of such methods is that they are versatile. The disadvantage is that task-domain specific methods can be more powerful because they can be more specific and operational in the guidance they can provide. Task-domain specific methods can also benefit from advanced task-specific domain knowledge, which we found to be absent in generic accounts of Six Sigma. Domain specific elaborations of DMAIC partly overcome these weaknesses inherent to general methods. The limitations of generic versions of DMAIC are not generally recognized in the practitioners' literature. An exception is Goh (2010), who mentions as the first out of a number of 'Six Sigma tragedies': "The belief that Six Sigma (as typical Black Belts know it) is universally applicable", and thus, that mastery of DMAIC obviates domain-specific expertise.

Six Sigma has its origin in quality engineering, which has traditionally had a strong emphasis on statistical methods. For example, ASQ (2007a) suggests that around 45% of the questions in the ASQ's Black Belt exam are about statistical concepts and techniques, as are, for example, 55% of the pages in a book on Six Sigma techniques such as Pyzdek (2003). Even in books on *Lean* Six Sigma, statistical techniques are dominant. For example, 45% of the pages in George et al. (2004) are devoted to statistics. The strong basis in statistical methodology provides strength to the method, which offers powerful techniques for fact finding and empirical testing of ideas before they are accepted. It is also responsible for some of the limitations of the method, in that methods originating in fields other than statistics are under-represented. For example, SPC (statistical process control) techniques are emphasized for process control, but PID (proportional-integral-derivative) controllers (Box et al., 2009), which originate in the field of control engineering, are virtually absent in the method's toolbox. Statistical techniques for empirical model building, such as the theory of the design and analysis of experiments, are emphasized, while other methods for model building, such as the finite element method (Reddy, 2005) or techniques from operations research, that may be more appropriate in many situations, are not offered as alternatives.

The strong and somewhat one-sided origins in statistics may also be responsible for the unsatisfactory methodological support that DMAIC offers for efficient problem diagnosis. We propose that in this respect, it should be considered inferior to competing problem solving methodologies in industrial engineering, such as Shainin's (Steiner et al., 2008) and Kepner and Tregoe's (Kepner & Tregoe, 1997) problem solving approaches.

One of the acclaimed strengths of Six Sigma is its structured method (Zu et al., 2008; Schroeder et al., 2008). Reasoning from the perspective of problem solving, we note that the DMAIC model functions as a problem structuring device. It breaks down a problem solving task into a sequence of generic subtasks, represented and defined by the Define-Measure-Analyze-Improve-Control stages. More detailed accounts break down these subtasks into more specific deliverables (see the generic steps in Table 1). Deliverables and subtasks, finally, are associated to problem solving techniques, such as gauge R&R studies, process capability analysis and design and analysis of experiments (see De Koning & De Mast, 2006). In this fashion, the DMAIC procedure helps a user to find a strategy for analyzing and solving a problem, and thus structure the problem at hand.

We believe that adopters of Six Sigma methodology and the DMAIC problem solving approach should be aware of their characteristics and potential limitations. This paper has highlighted the characteristics of the DMAIC approach and its limitations, specifically from a problem solving perspective. In addition, the paper has pinpointed directions where the approach may be improved.

References

Ackoff, R.L., Vergara, E., 1981. Creativity in problem solving and planning: a review. European Journal of Operational Research 7, 1–13.

ASQ. 2007a. Six Sigma Black Belt Body of Knowledge. American Society for Quality, Milwaukee.

ASQ. 2007b. Six Sigma Black Belt Certification Requirements. American Society for Quality, Milwaukee.

Balakrishnan, A., Kalakota R., Si Ow, P., Whinston, A.B. 1995. Document-centered information systems to support reactive problem-solving in manufacturing. International Journal of Production Economics 38, 31–58.

Bartee, E.M. 1973. A holistic view of problem solving. Management Science 20(4), 439–448.

Benjamins, R. 1995. Problem-solving methods for diagnosis and their role in knowledge acquisition. International Journal of Expert Systems 8(2), 93–120.

Bisgaard, S. 2009. Solutions to the Healthcare Quality Crisis: Cases and Examples of Lean Six Sigma in Healthcare. ASQ Quality Press, Milwaukee.

Box, G.E.P., Luceño, A., del Carmen Paniagua-Quinones, M. 2009. Statistical Control by Monitoring and Adjustment, second ed. Wiley, New York.

Brady, J.E., Allen, T.T. 2006. Six Sigma literature: A review and agenda for future research. Quality and Reliability Engineering International 22, 335–367.

Breyfogle, F.W. 2003. Implementing Six Sigma: Smarter Solutions Using Statistical Methods, second ed. Wiley, New York.

Chakravorty, S.S. 2009. Six Sigma programs: An implementation model. International Journal of Production Economics 119, 1–16.

Davis, R., Hamscher, W.C. 1988. Model-based reasoning: Troubleshooting. In: Shrobe, H.E. (Ed.), Exploring Artificial Intelligence. Morgan Kaufmann, San Francisco, pp. 297–346.

De Koning, H., De Mast, J. 2006. A rational reconstruction of Six Sigma’s Breakthrough Cookbook. International Journal of Quality and Reliability Management 23(7), 766–787.

De Koning, H., De Mast, J., Does, R.J.M.M., Vermaat, M.B., Simons, S. 2008. Generic Lean Six Sigma project definitions in financial services. Quality Management Journal 15(4), 32–45.

De Mast, J. 2007. Integrating the many facets of Six Sigma. Quality Engineering 19(4), 353–361.

De Mast, J. 2011. The tactical use of constraints and structure in diagnostic problem solving. Omega 39(6), 702–709.

Desai, D.A. 2006. Improving customer delivery commitments the Six Sigma way: Case study of an Indian small scale industry. International Journal of Six Sigma and Competitive Advantage 2(1), 23–47.

Eden, C. 2004. Analyzing cognitive maps to help structure issues or problems. European Journal of Operational research 159, 673–686.

Evans, J.R. 1992. Creativity in OR/MS: Improving problem solving through creative thinking. Interfaces 22(2), 87–91.

Evans, J.R. 1997. Creativity in OR/MS: The creative problem-solving process, Part 1. Interfaces 27(5), 78–83.

Fensel, D., Motta, E. 2001. Structured development of problem solving methods. IEEE Transactions on Knowledge and Data Engineering 13(6), 913–932.

George, M.L. 2002. Lean Six Sigma: Combining Six Sigma Quality with Lean Speed. McGraw-Hill, New York.

George, M.L., Rowlands, D.T., Price, M., Maxey, J. 2004 The Lean Six Sigma Pocket Toolbook: A Quick Reference Guide to 100 Tools for Improving Quality and Speed. McGraw-Hill, New York.

Gero, J.S. 1990. Design prototypes: A knowledge representation schema for design. AI Magazine 11, 26–36.

Gitlow, H.S., Levine, D.M. 2004. Six Sigma for Green Belts and Champions: Foundations, DMAIC, Tools, Cases, and Certification. FT Press, New Jersey.

Goh, T.N. 2010. Six triumphs and six tragedies of Six Sigma. Quality Engineering 22(4), 299–305.

Harry, M., Schroeder, R. 2006. Six Sigma: The Breakthrough Management Strategy Revolutionizing the World's Top Corporations. Crown Business, New York.

Hayler, R., Nichols, M. 2006. Six Sigma for Financial Services: How Leading Companies Are Driving Results Using Lean, Six Sigma and Process Management. McGraw-Hill, New York.

Ho, J.K.K., Sculli, D. 1997. The scientific approach to problem solving and decision support systems. International Journal of Production Economics 48, 249–257.

Hoerl, R.W. 2001. Six Sigma Black Belts: What Do They Need to Know? Journal of Quality Technology 33(4), 391–406.

Hopp, W.J., Spearman, M.K. 2008. Factory Physics, third ed. McGraw-Hill, New York.

Jayaram, J., Das, A., Nicolae, M. 2010. Looking beyond the obvious: Unraveling the Toyota Production System. International Journal of Production Economics 128, 280–291.

Jonassen, D.H. 2000. Toward a design theory of problem solving. Educational Technology Research and Development 48, 63–85.

Kepner, C.H., Tregoe, B.B. 1997. The New Rational Manager. Kepner-Tregoe, Princeton.

Linderman, K., Schroeder, R.G., Zaheer, S., Choo, A.S. 2003. Six Sigma: a goal-theoretic perspective. Journal of Operations Management 21, 193–203.

MacCrimmon, K.R., Wagner, C. 1994. Stimulating ideas through creativity software. Management Science 40, 1514–1532.

MacDuffie, J.P. 1997. The road to 'Root Cause': Shop-floor problem-solving at three auto assembly plants. Management Science 43(4), 479–502.

Martin, J.W. 2006. Lean Six Sigma for Supply Chain Management. McGraw-Hill, New York.

McAdam, R., Lafferty, B. 2004. A multilevel case study critique of Six Sigma: Statistical control or strategic change? International Journal of Operations and Production Management 24(5), 530–549.

McCarty, T., Daniels, L., Bremer, M., Gupta, P. 2004. The Six Sigma Black Belt Handbook. McGraw-Hill, New York.

Mingers, J., Rosenhead, J. 2004. Problem structuring methods in action. European Journal of Operational Research 152, 530–554.

Newell, A. 1969. Heuristic programming: Ill-structured problems. In: Aronofsky, J. (Ed.), Progress in Operations Research, Vol. 3. Wiley, New York.

Niemeijer, G.C., Does, R.J.M.M., De Mast, J., Trip, A., Van den Heuvel, J. 2011. Generic project definitions for improvement of healthcare delivery: A case-based approach. Quality Management in Health Care 20(2), 152–164.

Niemeijer, G.C., Trip, A., Ahaus, K.T.B., Does, R.J.M.M., Wendt, K.W. 2010. Quality in trauma care: Improving the discharge procedure of patients by means of Lean Six Sigma. Journal of Trauma 69(3), 614–619.

Nunnally, B.K., McConnell, J.S. 2007. Six Sigma in the Pharmaceutical Industry: Understanding, Reducing, and Controlling Variation in Pharmaceuticals and Biologics. CRC Press, Boca Raton, FL.

Open Source Six Sigma. 2011. Certified LSS Black Belt eBook. Open Source Six Sigma, Scottsdale, AZ.

Pande, P.S., Neuman, R.P., Cavanagh, R.R. 2000. The Six Sigma Way: How GE, Motorola, and Other Top Companies are Honing Their Performance. McGraw-Hill, New York.

Pidd, M., Woolley, R.N. 1980. Four views on problem structuring. Interfaces 10(1), 51–54.

Pyzdek, T. 2003. The Six Sigma Handbook: The Complete Guide for Greenbelts, Blackbelts, and Managers at All Levels, Revised and Expanded Edition. McGraw-Hill, New York.

Rasmussen, J. 1981. Models of mental strategies in process plant diagnosis. In: Rasmussen, J., Rouse, W.B. (Eds.), Human Detection and Diagnosis of System Failures. Plenum Press, New York, pp. 241–258.

Reddy, J. 2005. An Introduction to the Finite Element Method, third ed. McGraw-Hill, New York.

Rosenhead, J. 1996. What's the problem? An introduction to problem structuring methods. Interfaces 26(6), 117–131.

Sapossnek, M. 1989. Research on constraint-based design systems. In: Gero, J.S. (Ed.), Artificial Intelligence in Design. Springer-Verlag, New York.

Schroeder, R.H., Linderman, K., Liedtke, C., Choo, A.S. 2008. Six Sigma: Definition and underlying theory. Journal of Operations Management 26, 536–554.

Shaw, D., Westcombe, M., Hodgkin, J., Montibeller, G. 2004. Problem structuring methods for large group interventions. Journal of the Operational Research Society 55, 453–463.

Smith, G.F. 1988. Towards a heuristic theory of problem structuring. Management Science 34, 1489–1506.

Smith, G.F. 1998a. Determining the cause of quality problems: Lessons from diagnostic disciplines. Quality Management Journal 5, 24–41.

Smith, G.F. 1998b. Idea-generation techniques: A formulary of active ingredients. Journal of Creative Behavior 32(2), 107–133.

Smith, G.F., Browne, G.J. 1993. Conceptual foundations of design problem solving. IEEE Transactions on Systems, Man, and Cybernetics 23(5), 1209–1219.

Snee, R., Hoerl, R. 2003. Leading Six Sigma: A Step by Step Guide Based on Experience with GE and Other Six Sigma Companies. FT Press, New Jersey.

Snee, R.D., Hoerl R.W. 2005. Six Sigma Beyond the Factory Floor. Pearson Prentice Hall, New Jersey.

Steiner, S.H., MacKay, R.J., Ramberg, J.S. 2008. An overview of the Shainin System for quality improvement. Quality Engineering 20, 6–19.

Summers, I., White, D.E. 1976. Creativity techniques: Toward improvement of the decision process. Academy of Management Review 1(2), 99–107.

Trusko, B.E., Pexton, C., Harrington, J., Gupta, P.K. 2010. Improving Healthcare Quality and Cost with Six Sigma. FT Press, New Jersey.

Wagner, C. 1993. Problem solving and diagnosis. Omega 21, 645–656.

Woolley, R.N., Pidd, M. 1981. Problem structuring — A literature review. Journal of the Operational Research Society 32(3), 197–206.

Wruck, K.H., Jensen, M.C. 1994. Science, specific knowledge and total quality management. Journal of Accounting and Economics 18, 247–287.

Zu, X., Fredendall, L.W., Douglas, T.J. 2008. The evolving theory of quality management: The role of Six Sigma. Journal of Operations Management 26, 630–650.