Design for Six Sigma: *caveat emptor*

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Abstract

Purpose – The purpose of this paper is to describe the historical approach to concurrent engineering (CE) which has resulted in product line management (PLM) and then evaluates the theoretical models that have been proposed for design for Six Sigma (DFSS) in order to determine which model is able to provide the most consistent approach with historical development of PLM.

Design/methodology/approach – The approach begins with an overview of the approach taken by the Union of Japanese Scientists and Engineers (JUSE) in the development of a coherent quality methodology for structured analysis and problem solving – the Deming Wheel of plan-do-check-act (PDCA) which has become the standard model in Japanese total quality management to define a logical decomposition in process management. In Japan, PDCA is the single logical model which has been broadly accepted as the construct for understanding how to develop both strategic and operational quality methods. The second step in the approach is to examine a similar American development of the model for statistical problem solving that is applied in the Six Sigma method for statistical problem solving: define-measure-analyze-improve-control (DMAIC). Next, the paper examines the historical sequence in the way the product development process has developed over the past forty years, with emphasis on its military origins (especially CE) and which resulted in the generic model for PLM. The final part of this paper examines the models that have been proposed to implement DFSS over the past ten years and evaluate their logical congruence with the engineering community's design process.

Findings – Problems in alignment with the engineering design process were identified with all of the DFSS models and with the non-structured or "heuristic" approach to developing a coherent body of knowledge related to DFSS.

Originality/value – This paper provides a challenge to the quality community as well as to the academic community. The paper points out the need for rigorous examination of logical models that are proposed for guiding the thinking of practitioners in the use of quality methods for both the engineering of products and business systems. An expose of lack of rationality in the way an approach to DFSS has been investigated calls for more responsibility in the management of the development of this body of knowledge.

Keywords - Six sigma, Total quality management, Research and development, Production management

Paper type General review

Introduction

The need for agreed-upon logical models for the coordination of human work is a phenomenon of the twentieth century. It was first recognized as a result of scientific management, which has led to the Japanese plan-do-check-act (PDCA) model and more recently to the development of a model for improvement methodologies in the American

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Six Sigma movement and creation of the define-measure-analyze-improve-control (DMAIC) model. Efforts over the past ten years have been pursuing a similar development for what was generically referred to as design for Six Sigma (DFSS) since the late 1990s.

Systems thinking and concept of mental models has evolved out of the body of work that was founded on the pragmatic philosophy of William James (1842-1910) and expanded upon with the logical approach to thinking of John Dewey (1859-1952). Systems thinking commenced in the mid-1940s and expanded greatly during the late 1960s with the work of Ludwig von Bertalanffy (1901-1972) (von Bertalanffy, 1968), Kenneth E. Boulding (1910-1993), C. West Churchman (1913-2004), Russell L. Ackoff (1919-2009) (Ackoff and Emery, 1972), and Jay W. Forrester and his school of systems dynamics (Forrester, 1961, 1968). Most recently systems thinking evolved into a popular approach under the guidance of Senge (1990). The purpose of this paper is not to investigate this chain of development, but to make use of its approach to examine the models for quality thinking. However, we should note that the development of PDCA preceded development of the general systems method and is therefore an important source of information for learning about both the systems approach and the methodology that it promotes.

From the observations of modeling history, it is clear that when the model for a concept is first developed that there is an initial divergence caused by the different structures proposed until the scientific method prevails and there is a convergence upon an accepted model, borne out of rigorous examination of the alternatives. To establish this history in the quality movement, we shall first examine the evolution of the Japanese PDCA model as an instructive example of this phenomenon and then use this perspective to understand what lessons that should be learned in the early evolutionary stages of DFSS.

Lessons learned from Japanese development of PDCA model

The Japanese PDCA methodology progressively evolved from the scientific method originated by Sir Francis Bacon (1561-1626) in his masterpiece *Novum Organum* (Bacon, 1620) in which he identified three steps of investigation: hypothesis, experiment, and evaluation. Adam Smith (1723-1790) in *An Inquiry into the Nature and Causes of the Wealth of Nations* (Smith, 1776, 2000) added to the dialog by separating work according to a division of labor. A further distinction between "planning" (management's specialization) and "doing" (the job of workers) was made by Frederick W. Taylor (1856-1915) in his *The Principles of Scientific Management* (Taylor, 1911, 1990) whereby managers apply scientific management principles to planning the work and the workers perform the tasks. The Japanese had summarized Taylor's method using a model that they described as "plan, do, see" to evaluate the outcome of the execution of the scientific plans (Kano, 2005). This development occurred before the model of Walter A. Shewhart (1891-1967) was introduced during the early lectures of W. Edwards Deming (1900-1993) (Kano, 2005). Kaoru Ishikawa (1915-1989) had previously credited Taylor's work with influencing the Japanese development of the PDCA methodology (Ishikawa, 1985).

Shewhart (1939) reinterpreted Taylor's model for mass production as a three step process: specification (making a hypothesis); production (carrying out an experiment); and inspection (testing the hypothesis) and thereby linked it to the work of

Francis Bacon. This was the logical basis for the models proposed by Dr Deming. In a paper relating the origins of PDCA, Noriaki Kano (b. 1940) of the Tokyo Science University traced the development of Japanese PDCA from its 1951 conceptual origin in Deming's lecture (Kano, 2005). The following description draws heavily upon the findings of Kano and his investigation of the original source material in the Japanese Scientists and Engineers (JUSE) archives.

The starting point of this history is the initial lecture by Deming to JUSE in 1951. In the lecture notes prepared by Kenichi Koyanagi (1903-1965) of Deming's 1951 lecture, he describes an eight-step model proposed for viewing production as a system: quality consciousness; quality responsibility and infrastructure requirements of design and production; study of various elements such as raw materials, machines workers and their attributes; development and design; manufacturing; testing; redesign; and sales. Ishikawa simplified this model to include just four steps: design, production, sales, and survey. In 1952, according to the lecture notes of Shigeru Mizuno (1910-1989), a member of the original JUSE Research Committee on Quality Control (1948), Deming changed his model and used the following steps to define his systems model as a Shewhart Cycle (his observations were repeated when he took notes on Deming's 1954 lectures):

(1) design the product (with appropriate tests);
(2) make it; test it on the production line and in the laboratory;
(3) put it on the market;
(4) test it in service through market research; find out what the user thinks of it and why the non-user has not bought it; and
(5) redesign the product in light of consumer reactions to price and quality and continue around and around the cycle.

Up until this point in time, there is no Japanese record of a "PDCA" model in Deming's lectures. Joseph M. Juran (1904-2008) also lectured Japan on quality management in 1954 and one student of his lecture believes that he may have helped to stimulate the thinking on the PDCA model (Kolesar, 2008) In any case, Kano observed that following the 1959 lecture by Deming, Mizuno recommended that the PDCA model was a more meaningful way to describe Shewhart's Model and afterwards this PDCA model was named "the Deming model" in honor of Deming's introduction of the core of this logical concept.

At this point in time PDCA became the Japanese standard model for improvement and problem solving. The model was promoted by Ishikawa and used by the JUSE Research Committees that developed the theory of quality management and investigated the best way to apply this theory in the quality practices of organizations (for an example of how this approach was achieved relative to planning processes, see Akao, 1991).

While the PDCA cycle is called the Deming Cycle, it is noteworthy that Deming did not make a specific claim to originate this cycle in his major works (Deming, 1986, 1993). In his book, *Out of the Crisis*, Deming expounded upon a model that presented a six-step process:

(1) What could be the most important contributions of the team? What changes might be desirable? What data are available? Are new observations needed? If yes, plan a change or test. Decide how to use the observations.

(2) Carry out the change or test decided upon, preferably on a small scale.
(3) Observe the effects of the change or test.
(4) Study the results. What did we learn? What can we predict?
(5) Repeat Step (1) with knowledge accumulated.
(6) Repeat Step (2) and onward (Deming, 1986).

Those familiar with the literature on quality management will recognize that Deming was expounding upon the "spiral" approach to the iterative application of PDCA or "turning the PDCA wheel" as the continuous improvement process operates over time to deliver ever enhanced performance results (creation of this "spiral" concept is most appropriately credited to Juran (1974).

Later in his book *On the New Economics* (Deming, 1993) he redefined PDCA by calling it plan-do-study-act which he claimed was a better description of the method:

- plan a change or test aimed at improvement;
- do – carry out the change or test (preferably on a small scale);
- study the results (What did we learn? What went wrong?); and
- act – adopt or abandon the change or test and continuously improve by completing the cycle again.

Of course, by this time the PDCA cycle was widely referred to as the Deming Cycle and his suggestion of an alternative wording to the model can be cynically viewed as a way to more formally attach his name to the origins of the model.

However, while Japan uses PDCA as a general approach to describing how processes operate, the Japanese have also amplified the application of the PDCA method specifically for problem solving in conjunction with a set of basic quality tools and statistical methods (paralleling the development of DMAIC in the United States during the 1980s). This is an important historical precedent that is noteworthy for considering the development of the Six Sigma decision models for both problem solving (DMAIC) and process and product development (DFSS).

Improvements extend PDCA to problem-solving project

Invention credit for this development should be given to Juran (1973) who suggested using a problem-solving quality control (QC) story in his initial lectures to Japanese managers (Kolesar, 2008). This was the approach was standardized for QC circles and broadly disseminated as the quality circle movement grew after its establishment in 1962 by Ishikawa. Later, Tatsuo Ikezawa (b. 1928) revised Juran's model and transformed it into *QC Story for Management* (Ikezawa, 1970) and Hitoshi Kume edited a textbook, *Statistical Methods for Quality Improvement*, for the Association for Overseas Technical Scholarship an organization that taught the methods of Japanese total quality control (TQC) and problem solving to business leaders and scholars coming to Japan from around the world (Kume, 1985). It was this methodology that was transferred to Florida Power & Light (FPL) as part of its application for the JUSE Deming Application Prize (1985-1987) (Kano, 2005). Katsuya Hosotani (b. 1938) referred to this approach as the as the QC seven-step formula (Hosotani, 1989). Further developments of this idea within a JUSE team lead by Kano extended the QC story from problem solving to project improvement management in the book *Task Achieving QC Story for QC Circles* (Kano, 1993). In 1997, Kano proposed application of this method for the purpose of achieving breakthrough and creativity in his book *Task Achieving QC Story for Management* (Kano *et al.*, 1997).

There is a most valuable lesson to learn in this modern history of Japanese quality development. Across a 50-year period the Japanese have been able to maintain consistency in development of their logic. Today, the Japanese standard approach to total quality management (TQM) still uses PDCA. By maintaining a single logical model, the thinking behind the model has evolved to become more and more explicit and clear and the fundamental logic of the PDCA model has not changed. The initial contributions of Shigeru Mizuno and Kaoru Ishikawa were preserved across a generation of Japanese quality thinkers who used a foundation generated from the ideas of Taylor, Shewhart, and Deming. In the end, they honored Deming by attaching his name to the cycle as it was his wheel model that gave them the idea that there could be such a generalized improvement model. After having described the intellectual history of PDCA, it is instructive to compare and contrast the logical development of the Six Sigma logical model that has largely replaced the use of PDCA as an American development for a logical model used for Six Sigma problem solving: DMAIC.

Examining the origins of DMAIC

Faced with this substantial history for the logical progress in advancement of PDCA, creation of a unique Six Sigma DMAIC model seems strange. Indeed, Kano's point regarding a shift away from PDCA is a criticism about the Six Sigma method that should not be taken lightly. Indeed this causes problems on two levels: it shows a potential lack of respect for the tradition of PDCA and it also demonstrates ignorance of the legacy of Japanese quality development. Indeed, the generation of a new model without bridging from the previous history appears to illustrate a "not invented here" syndrome or the practice of "quality du jour" – switching to a new quality method, slogan or "catch phrase" for the sake of its "newness." Such change is not adding value, but in reality these decisions destroy intellectual value by grabbing something new and rejecting historical lessons without applying critical examination to alignment the new understanding with past lessons learned and thereby form an improved system for quality management. It seems that a major opportunity was missed. So, how did DMAIC process evolve?

In the 1984, Bill Smith (1929-1993) joined Motorola after a long career with the General Systems Corporation where he worked for Armand V. Feigenbaum, inventor of the concept of TQC which employs the PDCA model and was a stimulus for Ishikawa's (1985) TQC approach. Thus, the PDCA model should have been inherent as a core element in the development of an approach to Six Sigma. This was not to be the case. In 1987, Smith became vice president of quality for the communications sector which launched a critical element in the Motorola quality program – the Bandit project (Watson, 1994). At the start we should note that the DMAIC process has not always been the process used in Six Sigma. The initial Six Sigma process that was defined in the Motorola University Design for Manufacturing training program launched in March 1988 was defined by Smith as "six steps of Six Sigma" (Motorola Corporation, 1990):

(1) Identify the product created or the service provided.

(2) Identify the customer(s) for the product or service, and determine what is important to them (requirements in measurable terms).

(3) Identify your needs in order to provide the product or service.
(4) Define the process for doing your work.
(5) Mistake proof the process and eliminate defects and waste.
(6) Ensure continuous improvement by measuring, analyzing and controlling the improved process.

Clearly, this definition contains elements of what would become known as DMAIC, but its approach is actually close to the original process that Deming defined which generated PDCA in Japan. This "six-step" process also integrates elements of lean production from Toyota and was also based on the influence of the thinking of Juran who was one of the quality gurus that Motorola consulted (Juran, 1968).

It should be noted that during the second half of the 1980s decade, Motorola was fighting a desperate commercial battle to revive its pocket pager business and the communications sector where Smith lead quality initiative for the Bandit Project. This initiative benchmarked and "stole" the best ideas from across the world to incorporate them into a totally new business model that was capable of resurrecting market share and turning around Motorola's losses to Japanese competitors. In the light of this intent, it becomes a little clearer why a "fresh" approach to problem solving was desired – especially one that broke-away and ignored Japanese-dominated quality developments. To stimulate thinking about what to do differently, the Motorola Communication Sector's quality department requested that its Japanese subsidiary provide it with the details of the JUSE QC Story publications so they could understand the improvements that were underway to the PDCA method. Kano reports that information was provided by Kazuko Nishizaki in 1989 who reported that Motorola incorporated this information into its initiative to deploy the Six Sigma improvement methodology (Kano, 2005). Thus, it is clear that Motorola was aware of the latest developments in Japanese thinking at the time that it developed the first generation of the DMAIC model. However, strong energy associated with the need to resurrect American business following its startling loss to Japan of computer memory chip business in the early 1980s caused a fervor that is best labeled as "Buy American." Thus, the solution to quality improvement had to have a uniquely "American" flavor that could be seen as "better" than the Japanese developments.

In the period from its founding in 1990 to 1993, the Six Sigma Research Institute of Motorola University, under the direction of its founder Mikel Harry re-examined a variety of corporate measures and models. The original "six steps of Six Sigma" model was considered as were ideas on machine and process control studies from Perez-Wilson (1989) and Harry's doctoral research on the application of sequential logic filters for problem solving which were paired to specific methods and tools. To distinguish their approach from the American use of PDCA and to focus teams on the statistical aspects, the Six Sigma Research Institute initially named their problem-solving process measure-analyze-improve-control (MAIC), based on the work of Harry, and supplemented these steps with the logical elements from Perez-Wilson.

The MAIC problem-solving model is based on these roots from as well as a number of external sources. This approach defined a sequence of methods to reduce the number of variables contained in a scientific experiment by processing data using series of four logical filters: recognition, classification, analysis (these steps are roughly analogous to the DMA steps of DMAIC), and control (Harry, 1985). Research conducted by the

Motorola Corporate Quality Group into the ideas of the major quality gurus (Deming, Juran, Crosby, and Feigenbaum) lead to incorporation of the "best ideas" from these "leading thinkers."

In the end, the MAIC method added to the work of Harry and Perez-Wilson: Joseph M. Juran's quality journey along with Dorian Shainin's advanced diagnostic tools; Genichi Taguchi's loss function; basic graphical analysis tools (Rumbler-Brache process diagrams); basic QC tools found in the Japanese QC Story and PDCA model; team-based problem solving as found in the Japanese Quality Circles: cycle time reduction and mistake proofing from the Toyota Production System; and more advanced tools such as statistical process control and designed experiments (Harry, 1993, 1997). A formulation of the sequence of analyses contained in MAIC created a more rigorous analysis process than had been applied in the American TQM up to this point in time; however, it was not greatly different from the description of how to apply PDCA with statistical methods in QC story methodology as promoted by JUSE (Kume, 1985) which had formed the basis of the approach to quality improvement taken by FPL at this same time period and was disclosed through collaboration among leading American companies in their support of the FPL bid to gain the Deming Application Prize.

Evidence in literature suggests that up to the time Six Sigma was implemented at AlliedSignal in 1993 that MAIC was the process used for analysis (Harry, 1993). However, MAIC did not stay stationary for a long time. During the 1997, deployment of Six Sigma in General Electric (GE) management recognized that the problem-solving process did not do an adequate job to establish a business reason to improve. So, GE encouraged adding a "define" step to precede the MAIC steps. Thus, by 1997 the consultant-recommended approach to Six Sigma evolved to DMAIC (Harry, 1997). (When the author was working with Nokia mobile phones on its Six Sigma program in 1998, MAIC was the initial model used, but Six Sigma Academy soon transitioned to the new model and added the "define" step as a prelude to MAIC.) The purpose of "define" was to establish the boundaries of the problem, define the performance indicator, establish the potential entitlement gain available to improve the current state, and to initiate a charter from management to commission a DMAIC improvement project (Harry, 2000b). However, within three years, Harry had introduced three other steps to further expand DMAIC. "Recognize" was defined as a precursor to DMAIC – to align with strategic change and problem-solving activity for the project selection and coordinate projects across functional areas and focus improvement on the full business system. Harry also recommended "standardize" and "integrate" follow the DMAIC process to assure that project recommendations were put into practice, standardized in the work experience, and leveraged to all applicable applications of the learning. These steps consolidate improvements into standard work and integrate lessons learned and new knowledge into all potential applications within a business system and paralleled the extension of the Japanese PDCA model to link with an standardize-do-check-act (SDCA) model as promoted by Kano in the methodology he named *Task Achieving QC Story* (Kano, 2005; Harry, 2000b; Harry and Schroeder, 2000).

The final evolution of the DMAIC model was initiated by George (2001) to formally recognize integration of the lean production tools and methods in the DMAIC logic whereby he proposed changing the name of the Six Sigma initiative to Lean Six Sigma (LSS). However, this extension was in reality a moot point, because even the earliest methods of Six Sigma proposed by Motorola had included work process simplification, cycle time reduction, mistake proofing, and all the other tools that were part of the Toyota Production System (Motorola Corporation, 1990; Harry, 1993). So the shift in label from "Six Sigma" to "LSS" was a marketing invention and another example of the "not invented here" syndrome which did not add any substantial improvement to the way that DMAIC analysis had been taught or conducted before that time. However, the power of market-based advertising; the desire for "new" ideas; and a "backlash" against "Cowboy quality" all combined to make this new LSS label broadly adopted (Maguire, 1999).

Understanding the new DMAIC tradition

Thus, for most American companies, DMAIC became a popular solution to problem solving and it was perceived as an advance over the standard American style PDCA methodology found in companies applying the early versions of TQM. Why did American management welcome DMAIC over PDCA, or at least over PDCA as practiced American style? We can postulate a number of reasons:

- Most-importantly, American companies did not want to look like they were using the methods of Japanese competitors to turn back the threat. We must remember that during this time there was a strong patriotic backlash on both sides of the Pacific (Morita and Ishihara, 1991). Many improvements made by Japanese companies were indeed incorporated without attribution (although in fairness, it should be noted that there has not been much in the way of attribution for many of the sources of process tools that were incorporated into DMAIC).
- Many American applications of TQM and PDCA focused on the extensive use of structured opinion analysis tools (e.g. brainstorming, affinity diagrams, multi-voting) rather than data analysis tools. Thus, often the result of a TQM project was just agreement on the common team wisdom rather than creation of profound knowledge of process performance based on statistical analysis of the problem.
- There was a lack of connectivity among the various statistical tools that were included in the basic TQM toolkit. Indeed, many quality presentations in the mid to late 1980s would picture a "TQM Umbrella" covering a group of statistical tools and methods as a means to illustrate what was included. But, this graphic picture failed to communicate what should be the logical order or sequence of application for these tools. This lack of structure made it seem that all tools were equally valuable and could be applicable whenever desired by a team. This led many teams to select their "favorite tool" for analysis and permitted them to ignore tools or methods that they did not understand or found more difficult to apply.
- There was an unclear pathway for analysis from step to step – while Japanese PDCA was closely linked to the set of "seven basic QC tools" but PDCA improvements reflected in the QC story processes developed under the auspices of JUSE were not widely exposed to Americans and the momentum to correct the same problem took over as many companies collaborated in the work of the Six Sigma Research Institute so DMAIC took on a life of its own that was independent from the Japanese refinements of PDCA.
- Previous implementations of statistical process control (e.g. based on the author's personal experience in the early to mid-1980s at Hewlett-Packard) did not link

"scientific measurement" principles to the use of support process control methods – or define what would be a good follow-up process to investigate concerns about special cause variation (this was addressed early in the development of MAIC and was seen as a major breakthrough in thinking (Perez-Wilson, 1989; Harry, 1993).

- There is also an American arrogance that dictates "Made in America" is a better label for just about everything! Thus, industry had a prejudice toward accepting "news" about this method and shifting to what it perceived as a different "quality product" even though perhaps the largest difference was in the labeling.

What is the next phase of DMAIC evolution?

The biggest problem in DMAIC was its weak front end that aligns with strategy and identifies which projects should be defined. Harry recommended adding a recognize step to link DMAIC projects to strategic change management. In addition, DMAIC fell apart in its concluding steps as control does not aptly describe how to close a project and effect a change. Perhaps this is an issue with DMAIC that could have been healed by using the updated PDCA logic. In Japan, PDCA is linked to SDCA standardization cycle. The combination of these two cycles accounts for the activity to change and standardize (in other words to manage effectively) an organization so that change projects are integrated into daily management. While PDCA provides a front-end analysis for problem solving, once the system passes a "check" for stability, then it transitions into the SDCA cycle. Instead of taking the Japanese approach, Harry proposed adding the Standardize and Integration steps to DMAIC (Harry, 2000a). Despite all its problems, DMAIC was actually much better understood and developed than was the approach to DFSS – this is the final focus of this paper. When the DMAIC approach can provide no further improvement and more capability is required then DFSS is invoked. So, how did the DFSS logical models originate?

The evolution of design quality to concurrent engineering

Throughout much of the first half of the twentieth century, the process of design applied the craftsman model to identify "new ideas" and through iterative testing prepare them for the market. The initial structured model for design was typically called test-analyze-fix (TAF), a 1970s model for the iterative steps of the engineering process. The engineering management process evolved by the US Department of Defense (DOD) in the 1980s in an effort to improve management of the acquisition process for weapon systems which had significant cost over runs (Watson, 1985). It is instructive to note that the development of the military's approach to concurrent engineering (CE) overlapped in timing with the development of DFSS. In Juran's (1992) seminal work on design quality, there is no mention of CE, product line management (PLM) or DFSS.

Robert G. Cooper summarized the current state of the art in product development in his 1980s era "stage-gate" model for the design and implementation of new product development: ideation (Gate 1 initial screen); Stage 1 preliminary screen (Gate 2 secondary screen); Stage 2 detailed investigation (build the business case) (Gate 3 decision on business case); Stage 3 development (Gate 4 post-development review); Stage 4 testing and validation (Gate 5 pre-commercialization business analysis); Stage 5 full production and market launch (post-implementation review) (Cooper, 1985).

One of the major works on product development of the early 1990s was the study by Steven C. Wheelwright and Kim B. Clark of Harvard Graduate School of Business.

The initial state of the new product development process logic is described as a development strategy that relies on cross-functional integration of a design-build-test cycle though a sequence of development prototype testing: initial concept testing, design verification testing, design maturity testing, production verification testing, and volume production (Wheelwright and Clark, 1992). At this time a cross-industry study by consulting firm Pitaglio, Todd, Raburn, and McGrath identified structured product development as a best practice (naming the steps: concept evolution, planning and specification, development, evaluation, and product release) and also they recommended cross-project management for effective resource scheduling across a portfolio of projects that are managed at functional interfaces (McGrath *et al.*, 1992).

Cooper had dictated the state of the art in design engineering until the military decided to move forward under the leadership of the Defense Advanced Research Projects Agency in the early 1990s and it introduced the term "CE" in its Defense Initiative on Concurrent Engineering. It is noteworthy that at about the same time the DOD adopted TQM as a methodology – causing these two streams of thinking to merge (Rosenblatt and Watson, 1991; Cousins, 1991a, b; AitShalia *et al.*, 1995; Prasad, 1996, 1997).

Karl T. Ulrich and Steven Eppinger proposed a generic six phase product development process: planning, concept development, system-level design, detail design, testing and refinement, and production ramp-up which served to simplify the CE process and transition it toward PLM (Ulrich and Eppinger, 1995, 2000). C. Merle Crawford and C. Anthony Di Benedetto promoted a "new products process" that included strategic planning, concept generation, pre-technical evaluation, technical development, commercialization, and launch as a logical structure for PLM (Crawford and Di Benedetto, 1997, 2008) which signaled the final stage in transformation of the CE process into PLM.

In 2001, Brian Semkiw, CEO of Rand Worldwide, proposed using three-phased PLM process consisting of the phases of product planning, product development, and product management to summarize the second generation in development of PLM (following the TAF first generation). Gregory H. Watson suggested that the integration of DFSS methodology into PLM would create a third generation of PLM (Watson, 2005).

Evolution of the concept of DFSS

DFSS began its life as an ill-defined method in search of a logical framework. To answer the question what is DFSS, consider some of the various definitions from literature:

(1) "While Six Sigma helps fix what is broken [. . .] Design for Six Sigma helps to design things that don't break in the first place, things that do more and cost less" (Chowdhury, 2002a, b).

(2) "The ultimate goal of DFSS is to:
- Do the right things.
- Do things right all the time" (Yang and El-Haik, 2003).

(3) "The term 'Six Sigma' in the context of DFSS can be defined as the level at which design vulnerabilities are *not effective* or minimal. Generally two major design vulnerabilities may affect the quality of a design:
- Conceptual vulnerabilities that are established because of the violation of design axioms and principles.

- Operational vulnerabilities due to the lack of robustness in the use environment. Elimination or reduction of operational vulnerabilities is the objective of [. . .] Six Sigma" (Yang and El-Haik, 2003).

(4) "DFSS adds another dimension to product development, called critical parameter management (CPM). CPM is the disciplined and focused attention to the design's functions, parameters, and responses that are critical to fulfilling the customer's needs [. . .] DFSS is about preventing problems and doing the right things at the right time during product development. From a management perspective, it is about designing the right cycle-time for product development of new products. It helps in the process of inventing, developing, optimizing, and transferring new technology into product design programs. It also enables the subsequent conceptual development, design, optimization, and verification of new products prior to their launch into their respective markets" (Creveling *et al.*, 2003).

(5) A broader definition was offered in Watson (2005): "DFSS has three major components: product line management, design and new product development project management, and the Six Sigma toolkit (define-measure-analyze-design-verify (DMADV)) that is applied in the product creation process. The definition of DFSS that we will use is: *Design for Six Sigma is a process to define, design and deliver innovative products that provide competitively attractive value to customers in a manner that achieves the critical-to-quality characteristics for all the significant functions*."

Alternative approaches to the process of DFSS

To understand logical structures of alternative DFSS models, a literature search was performed to identify the proposals that have been made. A summary of this search is reported below.

Initially, Harry (1997) made no mention of a unique logical model for DFSS. As Harry's ideas crystallized by 2000, he referenced DFSS, but incorporates it as part of the "improve" phase of DMAIC. "The closer a company comes to achieving Six Sigma, the more demanding the improvements become. At 4.8 sigma companies hit a 'wall' that require redesigning of processes, known as 'Design for Six Sigma'". They later stated that "the improve phase encompasses the process known as DFSS, as well. Using DFSS, the processes that create the products or services are designed from the beginning or reconfigured in such a way that they produce six sigma" (Harry and Schroeder, 2000).

Harry also cites GE Medical Systems (GEMS) as the initiator of DFSS as reported in the 1997 GE Annual Report where GE described that after 1998 every new product will be the result of DFSS application (Harry and Schroeder, 2000). However, until this time, DFSS was contained in the DMAIC framework and was invoked following the DMA (from DMAIC) whenever new capability was required and then the team would shift to the final steps of design and verify to complete the sequence DMADV. At least one handbook written in this period as an attempt to develop a structured body of knowledge for Six Sigma did not mention either DMAIC or DFSS, while in its 2003 edition the DMADV model is recognized (Pyzdek, 2001, 2003).

In 2001, the American Society for Quality (ASQ) introduced a new journal dedicated to the Six Sigma movement. The first two articles it published on this subject did not refer to a specific model, but used the general DFSS framework to describe the approach

(Berryman, 2002; Humber and Launsby, 2002). ASQ also publishes handbooks for black belts and green belts to study Six Sigma. It is interesting to note that while the *Black Belt Handbook* defines DFSS as the DMADV model (Kubiak and Benbow, 2009), the *Green Belt Handbook* offers both the DMADV and identify-design-optimize-verify (IDOV) models (Munro *et al.*, 2003).

It must be noted that until this time most DFSS work was being developed by consultants who needed to differentiate their methodology from others as they sought an advantage in promoting their own consulting practices. This conclusion becomes clear when one considers the degree of logical chaos that prevailed in the period 2000-2005 in promotions of DFSS:

- Tennant (2002) (an independent management consultant) recognized that DFSS has a DMADV model (based on his past experience in GE) but proposes a different model, define-customer-concept-design-implement (DCCDI) based on self-analyzed linguistic clarity that is not very strongly convincing and not related to practice by any rigorous analysis. Perhaps, it was the litigious nature of the Six Sigma community during this period of time that lead to this development as some firms legally challenged the rights of other firms to use the same models and terms in promoting related practices of management consulting in the Six Sigma methods (despite the fact that the trademark for Six Sigma was held by Motorola who had generously put it into the public domain for use by all organizations).
- Chowdhury (2002a, b) of American Supplier Institute declares there is no consistency among practitioners about the terms that define the process. As a result, the acronyms range from DMADV to define-measure-explore-develop-implement (DMEDI) to identify-define-develop-optimize-verify (IDDOV). He states that it "really does not matter what you call it. The DFSS methodology is still a straightforward five-step process, just as is Six Sigma's DMAIC." (p. xvi). He then uses the process IDDOV to refer to DFSS. Chowdhury cites the GEMS history from 1998 to 2001, but does not identify their methodology as DMADV (p. 12). He does not describe the origins of IDDOV.
- Creveling *et al.* (2003) ignored DMADV completely. Creveling promotes two other methods: invent-innovate-develop-optimize-verify for new designs and sub-systems and concept design, design development, optimization and verify certification which are derived from the consulting of Steve Zinkgraf of Sigma Breakthrough Technologies, Inc. Creveling further acknowledges that CDOV is "largely based on Walter Shewhart's famous contributions".
- Yang and El-Haik (2003) also ignore the DMADV model completely and do not address it – proposing an alternative that they named identify-characterize-optimize-verify (ICOV) (identify requirements-characterize the design-optimize the design-verify the design). There is no reference given to the origin of the ICOV model, so it is considered a unique logical model that is outside the frame of this historical development.
- Brue and Launsby (2003) (Six Sigma Consultants, Inc.) propose a unique logical model for DFSS – the plan-identify-design-optimize-verify process; however, they do reference other models but state that since there is no standard that all models are equal: DMADV, define-measure-analyze-design-optimize-verify

(DMADOV), DCCDI, DMEDI, define-measure-analyze-design-improve-control (DMADIC), and RCI (however, the origins of these models are not described by them).

- Refreshingly, Breyfogle (2003) (principal of the Smarter Solutions consultancy) cites the DMADV model and does not reference any other methodology.
- When Evans and Lindsay (2005) initially refer to DFSS they reference DMADV and then cite the CDOV approach proposed by Creveling *et al.* (2003) and then they postulate the logical equivalence of the models by stating that the DMA phases of DMADV are equivalent to the concept development phase in CDOV and that design and optimization are equal to the design phase while verification is equal in both models. Based on these choices they elect to describe the CDOV model in their book.
- In a book focused on management methods related to DFSS, Watson (2005) (consultant with Business Excellence Solutions, Ltd) described the DFSS process as relative to PLM methods and suggested a different logical meaning for the steps of the DMADV model. He proposed wholly distinct actions in the DMA phases of the DMADV model compared with DMA phases of the DMAIC model (Watson, 2003). However, this approach creates confusion as now two logical models have different actions related to the same named steps. Indeed, clarity would have been better achieved by renaming the steps in the DMADV model.
- When ASQ hired consultant Scripps (Scripps & Associates) to develop a DFSS webinar (delivered April 14, 2005), he identified several competing models (based on a citation from www.isigma.com): the first DFSS model identified was the DMADV model which is attributed to use at GE Plastics in 1996; the second model is identified as IDOV with no source attached; the third model identified was ICOV which Scripps credits to the consulting company SigmaPro. The fourth model is the revision of the GE DMADV to add a step and become DMADOV. The next model cited is Tennant's model DCCDI. The sixth model cited was created by Price Waterhouse: DMEDI. Because he identified no prevailing model, Scripps took the unorthodox approach to create a totally new model which he proposed to serve as the industry standard: identify-design-evaluate-affirm-scale-up (Scripps, 2005).
- Jiang *et al.* (2007), wrote in *Quality Progress* Magazine (published by the ASQ) on the approach for integrating design for excellence with DFSS and in their article they only referenced DMADV as a DFSS process.
- When Park and Anthony (2008) describe DFSS, they identify competing models that exist DMAD(O)V (cited as a GE upgrade to DMADV), IDOV (no origin citied) and define-initiate-design-execute-sustain was proposed by the Qualtec Consulting Company, and then propose the use of another modification of DMADV: DMA plus the extra steps of redesign-implement-control for transactional Six Sigma.

Assessment of the current state of DFSS model logic

This development of models for DFSS logic is reminiscent of the comment by Box *et al.* (2005): "all models are wrong, but some models are useful." The DFSS model requires stiff academic discipline to set it aright. Consider the following unresolved questions that have been raised as a result of this review of the ten-year history in the development of DFSS logic:

- Should the entry into DFSS be linked to the DMAIC model or should the logical models for DMAIC and DFSS be independent?
- Should there be one model for DFSS (e.g. DMADV or its equivalent or three (a program management model, project management model and a logical toolkit for organizing the use of design tools (e.g. a model like DMADV)?
- Does "Identify" recognize all of the front-end issues that must be considered in a design or should three steps describe the front end (the logical equivalent of Watson's DMA)?
- Does the design phase include optimization or are these two distinct steps?

Clearly from the profusion of models offered, there is no general agreement on these questions. However, what we can see that two issues should be challenged from an engineering perspective:

(1) Should the quality community dictate to the engineering community the process to use for design? Note that the initial steps used in DMAIC do not relate to the preliminary processes in the CE or PLM models. An assessment of a current process or product may lead to the conclusion that there is not enough process capability to achieve its performance targets and conclude that DFSS is required. But, this is not equivalent to following the first three logical steps of DMAIC in all applications of DFSS.

(2) Engineers would find it strange to divide design into two phases. Note that in the DMADV process that the output of DMA is the high-level conceptual design, which is ready for detailed design. Thus, the "design" that occurs in the Design phase should refer to detailed engineering design which is an iterative process that concludes the concepts of both design and optimization. A design should not be considered to be complete unless it has been optimized. These are not separate tasks, but closely related tasks which require an iterative sequence of work to achieve optimization.

Some models collapse the DMA activities of DMADV into a single step (focusing on either identification or conceptualization of the design outcome). However, the PLM approach has three distinct steps that typically involve different focus groups within an organization: define spotlights on creating the high level conceptual design based on product line dynamics, technology available and business needs. Measure focuses on the market, customer and competitive research required to sharpen the technical design into a marketable product. Analyze creates a business case (using risk-benefit analysis) based on a high-level design and a financial assessment of the opportunity (Watson, 2005). Since each of these phases involves different groups, it is a good practice to separate these individual model steps. Continuing to examine the last two steps of the DMADV model we see again that different parts of the organization are involved – design is an engineering task that will involve the iterative technical design, development testing, and redesign to the point of optimization for the intended purpose. Verification is an external focus on testing the design in its intended market and "polishing the design" in preparation for market launch. This last phase should involve both dedicated user tests (so-called α and β-tests) as well as studying market price tolerance to validate the commercial expectations.

Perhaps the largest question of all from this proliferation of models is the confusion that it causes to potential users. There are three unique applications of DFSS: product (although it could be argued that hardware and software are unique applications), service, and business process improvement. Does each of these applications need a unique model or could they all follow the same logical model? It would be more elegant to apply a single logical model that represents all applications of the DFSS toolkit, much like DMAIC can be applied for both engineering and business applications. DMAIC is used for both product and service improvements with the key distinctions at the level below the logical model based on the types of data and processes that are being analyzed.

One additional expectation for a new DFSS model would be that its acceptance should not generate an undue influence for any consulting venture. Since most of the models proposed come from consulting firms it is not proper to choose one of the current models over the others and thereby endorse a single approach. So, how to proceed? Let's turn to the earlier lessons from the development of PDCA in Japan to see what this history suggests. It would be conceptually tidy if the approach to Six Sigma were bundled as tightly as the logic used by the Japanese quality movement to simultaneously separate and link PDCA and SDCA. Would this be a possibility, and if so, then who should be asked to make this contribution?

Concluding comments

Let us begin with an observation from this intellectual history of DFSS that the authors believe is still most appropriate:

> The strength of DFSS is not in its stand-alone performance, but it comes from integration of methods and concepts that have been independently developed into a system of thinking and working that result in product designs that serve customers better while generating attractive profit. DFSS is not strategic planning but it builds upon the "recognize" component in strategic planning where business improvement needs are unveiled. DFSS is not program management, but it provides a philosophy and methodology for more effectively coordinating multiple project programs. DFSS is not project management, but it supports project managers with an analytical process that facilitates a "right-the-first-time" approach to product creation. Finally, DFSS is much more than the DMADV process, but DMADV is one way to summarize how DFSS fits into an overall business system. While DFSS is somewhat amorphous in this format, it becomes defined within the context of an organization's specific business system. Thus, there is no one-size-fits-all definition of DFSS, rather DFSS concepts and methods must be adapted and customized to support a particular business purpose, cultural style and design technology in order for it to have real substance. DFSS supports management of design programs in the product creation process (Watson, 2005).

Certainly, this observation is open to challenge. However, the point is clear that distinctions in the way that DFSS is applied will vary by organizational business model and the application of a specific logical model needs to comprehend the distinctions in product design requirements for various types of businesses. This will be challenging. However, perhaps there is a way to move forward, if the global quality community can learn a lesson from way that the JUSE Research Committees developed the Japanese approach to TQM and use a similar approach to developing the standard logical models for Six Sigma.

In May, ASQ (2009) announced the formulation of a quality body of knowledge (QBOK) which would organize the intellectual property of quality that has been generated over the past 60 years and provide stewardship to assure that quality information contained in the QBOK is important, accessible, dependable, accurate and authentic (ASQ, 2009). One of the objectives of the QBOK is to evaluate gaps in the recognized quality knowledge base and to work with teams of experts to close such gaps. It should be clear from the observations in this paper that the western quality movement is facing an intellectual challenge regarding the logical approach to DFSS. Observing the vacillation in understanding the proposed logical models for DFSS, we conclude that tasking the QBOK team to develop a standard approach to this methodology is a good application of this team's energy. In establishing this task, ASQ should engage the engineering community to help improve the quality and acceptability of the final design.

Until such an approach matures and reaches consensus, then the best advice that can be given to companies that are interested in implementing DFSS is: *caveat emptor*.

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