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A hierarchical decision procedure for productivity innovation in large-scale petrochemical processes

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Abstract

Maintaining the best quality is essential for the survival of a company in a globally competitive world. Six Sigma activity has been widely accepted as one of the most efficient and powerful problem-solving methods for quality issues. The define-measure-analyze-improve-control (DMAIC) approach based on data has been very powerful for identifying, defining, solving a problem, and controlling the solution. However, for many process engineers, the DMAIC approach is so general an approach that they have difficulty defining and solving problems. To solve this limitation, we need to introduce the knowledge of chemical industries to the DMAIC. This paper presents a hierarchical decision procedure for quality improvement that can enhance the power of the Six Sigma approach dramatically by capturing the domain-specific knowledge for the design, operation, and control of petrochemical processes and integrating them into a hierarchy of decisions. The proposed hierarchical decision procedure offers a well-organized knowledge structure so that a user with little experience in the chemical industry can solve a quality problem. The procedure progresses through a hierarchy of decision levels reflecting the structural information of large-scale petrochemical processes. At every level, the systematic procedures offer heuristics and/or techniques to generate candidates, evaluate generated candidates, and choose the most promising candidates. The procedure allows us to save significant amounts of time and cost, since a user can find the cause of the quality problem and its solution in an efficient and systematic manner. Each level effectively evaluates the candidates and validates the results. We believe that the procedure can be applied to many other large-scale petrochemical processes.

Keywords: Hierarchical decision procedure; Vital few causes; Process improvement; Large-scale; Petrochemical process

1. Introduction

Productivity innovation is essential for a company to compete and survive in a highly competitive global market. To improve productivity, chemical industries have employed various management methods, such as Six Sigma, total quality management (TQM), total quality control (TQC), and quality control (QC) to guarantee product quality consistently regardless of various variations and disturbances. In particular, Six Sigma has consistently produced amazing results and economic values (Tong, Tsung, & Yen, 2004; Kim, Han, & Han, 2004; Kim, Lee, Han, & Han, 2004; Lee, Min, Han, Chang, & Choi, 2004; Wiklund & Wiklund, 2002; Hahn & Doganaksoy, 2000; Ashton, 1998). Six Sigma suggests various supporting tools such as fishbone diagrams, process mapping, Pareto charts, multivariate charts, and histograms. Although this problem-solving method, called define-measure-analyze-improve-control (DMAIC), is very powerful, it does not offer an efficient way to integrate domain knowledge into the powerful problem-solving methods (Mast, 2003; Han & Lee, 2002). As a result, until an engineer becomes highly experienced, he or she is not good at solving problems.

This paper proposes an efficient and systematic procedure for productivity innovation that combines DMAIC with a hierarchical decision procedure. The hierarchical decision procedure, based on the same concept proposed by James Douglas, is a well organized problem-solving method that consists of various powerful methods and knowledge (Douglas, 1985). Therefore,

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a significant amount of analysis time and cost is saved by reducing unnecessarily numerous trial-and-error iterations based on 'educated guesses'. It is important to find out the *Vital Few Causes* (VFCs) for degraded product quality and to remove their impacts on the quality variable effectively. Much research has been performed to identify VFCs and/or to improve processes. In the area of informatics research, Garcia-Muñoz, Kourtri, MacGregor, Mateos, and Murphy (2003) uncovered possible reasons for major quality problems occurring in an industrial batch process. Yacoub and MacGregor (2004) proposed a control of product quality in the subspace defined by the latent variable models built from historical data. Chu, Qin, and Han (2004) developed a new method for fault detection and operation-mode identification based on variable selection. However, these works have been limited to a single unit process or piece of equipment. When previous approaches are applied to industrial petrochemical processes, the following difficulties arise: (a) the problem has a wide variety of possible causes such as equipment trouble, manual control, operational variation, and seasonal effect spread all over tens of unit processes; (b) the causality among possible causes is also complex due to recycle loops, control systems, time delay, and so on; (c) many operations still depend on operation experience and the limited data available are not sufficient to explain the various phenomena; and (4) only a few experts in such problem-solving techniques as process knowledge, experience, and statistical techniques are available.

This article presents a hierarchical decision procedure to apply the Six Sigma approach to a continuous, single-product petrochemical process successfully. The proposed procedure draws its motivation from the hierarchical decision procedure for conceptual design of petrochemical processes (Douglas, 1985). The proposed hierarchy reflecting structural process knowledge greatly reduces the time and cost of improvement by choosing only promising solution paths from the tremendous search space. Unlike the best-first search (Rich, 1983; Nilsson, 1980), this method enables us to find a set of promising candidates than the beat one at each decision level because several candidates can affect product quality simultaneously. At every decision level, we provide a systematic decision procedure consisting of generation, assessment, and selection steps based on heuristics and/or statistical techniques. Major heuristics are the specified check lists based on 5M1E (Materials, Manufacture, Man, Machine, Measurements, and Environment) to identify possible sources of variation and opportunities for improvement. As important statistical techniques, there are (a) *House of Quality* (HOQ) to quantify and compress many subjective data collected from questionnaires; (b) Taguchi's loss function to build models of quality, environment, and safety cost; and (c) mixed integer linear programming (MILP) to find the optimal set of improvement opportunities while satisfying constraints on cost, time, and human resource. The systematic procedure helps nonprofessionals to identify the VFCs accurately and easily and excellent opportunities in practice. The hierarchical decision procedure has been applied successfully to a purified terephthalic acid (PTA) process. The quality has been improved with lower cost and minimum risk within a short time. The quality was greatly enhanced and significant economic profit obtained.

2. The proposed hierarchical decision procedure for improving product quality

The application of the proposed procedure is limited to impurity quality problems in continuous, single-product petrochemical processes. The following assumptions are made: (a) the single target quality variable is already defined, and (b) there are no measurement errors such as sensor failure or calibration errors. The proposed procedure concentrates on: (a) rapid identification of VFCs for the quality problem and (b) proposing a few effective ways to correct the quality problem, rather than proposing the best ways. The procedure is decomposed into a hierarchy of decisions that consist of following steps:

1. Vital few causes are identified by applying pre-defined rules.
2. Each VFC is evaluated and ranked.
3. Opportunities are generated for each VFC.
4. Each opportunity is evaluated and ranked.
5. The economically effective opportunity is chosen and implemented.

Various heuristics based on industrial practices, statistical techniques, assessment criteria, and selection techniques are identified and incorporated into the procedure as knowledge modules.

Phase I. Hierarchical Identification of VFCs

(1) Identify major unit processes related to the quality problems from the target process.
   - (a) Generate unit-process candidates, in which byproduct concentration is out of normal operation range.
   - (b) Evaluate each unit process candidate generated using hypothesis test for correlation coefficient between byproduct concentrations and product quality.
   - (c) Select major unit processes related to the quality problem.

(2) Identify potential causes from the identified major unit processes.
   - (a) Generate cause candidates using the 5M1E check list.
   - (b) Evaluate influences of each cause candidate on product quality based on interviews, questionnaires and the house-of quality diagram.
   - (c) Select causes related to the quality problem.

(3) Identify vital cause candidates (VFCs) from the identified causes.
   - (a) Generate a propagation path from each cause to product quality. The path include symptom variables. Key process variables are chosen using statistical variable selection method out of symptom variables.
   - (b) Merge all propagation paths into a single network where main cause-and-effect relationships from causes to the quality are drawn.
   - (c) Select root causes in the network as VFCs based on a root-cause analysis.

(4) Validate the identified VFCs.
   - (a) Collect historical data for KPVs existing on the propagation path of each identified VFC.