"THE IMPACT OF KNOWLEDGE ON QUALITY"

by

Amit S. MUKHERJEE*
and
Luk N. VAN WASSENHOVE**

93/30/TM

* Visiting Assistant Professor of Technology Management, at INSEAD, Boulevard de Constance, 77305 Fontainebleau, France.

** Professor of Operations Management and Operations Research, at INSEAD, Boulevard de Constance, 77305 Fontainebleau, France.

Printed at INSEAD, Fontainebleau, France

The Impact of Knowledge on Quality

Amit Shankar Mukherjee, INSEAD
Luk N. Van Wassenhove, INSEAD

To appear in: *Field Studies in Quality Management*, edited by Phillip Lederer, Uday Karmarkar and Ramchandran Jaikumar, HBS Press, Boston.

Michael A. Lapré provided invaluable assistance in collecting and analyzing the data. We thank the management and employees of N.V. Bekaert, S.A. for their unstinting cooperation. We gratefully acknowledge the financial support provided by the Research & Development Department of INSEAD and (for a part of the field research) by the Division of Research, Harvard Business School. Lydia Price, Hau Lee, Carlos Cordon and Bernard Desgagne made helpful comments. Comments are welcome.

Abstract

By focusing on culture and tools, the literature creates a chicken-and-egg question for empirical researchers studying quality improvement efforts, since the long term use of quality tools is essential for creating a quality culture and a quality culture is needed for effective use of quality tools. We deal with this problem by studying the nature of knowledge used to improve quality. We use Principal Component Analysis to analyze the output of 37 tightly structured projects undertaken by one European firm during the 1980s. We identify four latent characteristics of the output: Experience Knowledge, Formal Knowledge, Domain Knowledge and Complexity. We show that these dimensions also describe the output of 15 less structured projects. Regression analysis of the impact of these dimensions on two project level performance indicators shows that the importance of Formal Knowledge increases as projects become less structured. We argue that this line of research will ultimately help us make normative recommendations to managers about the implementation strategies they should follow.

1. Introduction

In recent years, several researchers and thinkers about management have suggested that knowledge and information are increasingly becoming the basis of corporate competition (Sahal, 1981; Jaikumar, 1988; Hayes & Jaikumar, 1988; Adler, 1989; Drucker, 1989, 1990; Badaracco, Jr., 1991; Scott-Morton, 1991). While this idea is slowly gaining ground in the literature on technology and operations management (particularly in the area of advanced manufacturing technologies), it has not been associated with the other acknowledged basis for corporate competition: quality.

That these two concepts *can* be linked is not difficult to establish. The essential element of the link is the long-accepted idea that products embody information (Allen, 1977; Clark & Fujimoto, 1991). Hence, efforts to improve product quality must, implicitly or explicitly, seek to improve the firm's stock of information. What is much more difficult to establish is the idea that the two concepts *should* be linked. The supportive argument consists of establishing that the traditional foci of the quality literature (on the topics of a culture of quality and the tools of quality) impede the development of understanding of the real drivers of progress on quality in a given organizational environment. Assertions that the use of tools like Quality Function Deployment (Hauser & Clausing, 1988) or the Taguchi Method (Kackar, 1985) actually resulted in measurable improvements are - given all the uncontrolled intervening variables - nothing more than statements of faith. In these circumstances, the study of the knowledge which actually enabled progress and the structural and infrastructural elements of the organization which contributed to the production of that knowledge is likely to help us establish more direct cause-and-effect statements. We believe that such insight would help firms jointly optimize the management of knowledge and the management of quality. We discuss these issues in §2.

In §3, we show that the appropriate empirical research project needs to adopt a longitudinal perspective, control for or eliminate potentially confounding factors (like variations in product and resource markets) and acquire detailed information about technological and managerial systems. We argue that such considerations led us to conduct our study in one firm, N.V. Bekaert, S.A. We then describe Bekaert in some detail, present the universe of quality improvement projects from which we selected our sample and describe the coding of our data on these projects. This paper reports on work in progress and we readily acknowledge that we have a long way to go. In particular, we are, at present, merely at the stage of determining the nature of the knowledge which affected project-level measures of quality at Bekaert. In the months to come, we not only have to perform our analysis at the product and factory levels, but also have to tie our "dimensions of knowledge" back to their determinants in the firm.

§4 is the first of the two analytical parts of our paper. Therein, we discuss the use of Principal Component Analysis (PCA) to analyze the output of 37 tightly structured quality projects executed by workers and their foremen. We identify four latent characteristics of the output, which we call Experience Knowledge, Formal Knowledge, Domain Knowledge and Complexity. We then establish statistically that these characteristics may also be used to describe the output of 15 broader, less structured projects undertaken by groups led by technicians, engineers and managers.

In §5, we use ordinary least square regression to relate the characteristics of the project outputs to two related but distinct project-level performance indicators, goal achievement and the ability to make consistent changes in performance. We show that as projects become less structured, the relative importance of Formal Knowledge (vis-a-vis the more learning-by-doing oriented Experience Knowledge) rises. We argue that this change is due to the difficulty of relying on experiential knowledge to establish cause-and-effect relations as the factory environment becomes more complex.

In §6, we discuss our plans to increase both the amount of data we will collect and the scope of analysis we will perform. Finally, in §7, we discuss the value of this stream of research. We argue that from an "Expected Value of Perfect Information" perspective, it will help us make normative recommendations to managers about the breadth of quality improvement activities they should undertake and the implementation strategy they should follow. While we are a long way from this goal, we feel that the possibility that we will reach it well justifies the research agenda we have set for ourselves.

Before we proceed to the substantive sections of this paper, we wish to note that terms like 'knowledge,' 'information,' 'data' and 'organizational learning' have very different meanings in different academic disciplines. What is worse, like the terms 'ambiguity' and 'complexity,' even within defined disciplines, the meanings are often inconsistent. We do not wish to get involved in an ultimately fruitless debate about the true meanings of these terms and so, we wish to make our perspective on them clear. By *data*, we mean the qualitative and quantitative details firms collect about their productive units. *Information* is refined data to which some value is attached. *Knowledge* is the stock of information and *organizational learning* is the process of acquiring data and creating information and knowledge which have the potential for helping the firm achieve some performance goals. We readily acknowledge that these definitions are not perfect, but they will suffice for our purposes. Finally, we state for the record that at several places in this paper we have used the terms knowledge and information interchangeably. We have done so when the use of the terms in the literature we cite is problematical and when a choice between the two will not have any substantive impact on the issues we are discussing.

2. Why Study the Management of Knowledge for Total Quality Control?

Over the last fifteen years, a huge number of papers and books have been written on quality improvement. Yet, as David Garvin (1987) pointed out, managers often do not know what it means, how it should be measured and how different functional areas contribute to it. In our opinion, a good part of the problem is the nature of the issues which dominate the literature.

Most normative, implementation-oriented works have characterized the institutionalizing of a "quality culture" as the single most important element of a firm's quality improvement efforts (Crosby, 1979; Deming, 1982; Schonberger, 1982; Hall, 1983; Ishikawa & Lu, 1985; Imai, 1986; Walton, 1986; March & Garvin, 1986; Juran & Gryna, 1980). For example, Ishikawa characterized Total Quality Control (TQC) as a "... thought revolution in management" (Ishikawa & Lu, 1985, pp. 103). and Schonberger (1982) argued that concepts like "Perfection," "Habit of improvement" and "Easy to see quality" (pp. 51) were far more important sources of the apparent Japanese advantage in product quality than the implementation of Statistical Process Control (SPC) *per se*. Such descriptions have given the TQC concept in particular an arguably justified aura of a philosophy. After all, the reported experiences of firms which have succeeded in acquiring reputations for quality show that incorporating it in every facet of their operations required nothing short of an indoctrination program (Bhote, 1989; Gabriel & Beer, 1992; Johnson, *et. al.*, 1992).

A second important characteristic of the literature is its preoccupation with tools and policies which can potentially help firms improve both design and conformance quality by orders of magnitude. Some of these include: Quality Function Deployment (Hauser & Clausing, 1988); Taguchi Methods (Kackar, 1985); Design for Manufacturability (Bolwijn, *et. al.*, 1986; Walleigh, 1989; Whitney, 1988); Seven Statistical Tools of SPC (Wadsworth, *et. al.*, 1986); Quality Control Circles (Ishikawa & Lu, 1985); daily feedback of defect rates (Hall,1983; Imai, 1986); treating the next (internal) process as a customer and adoption of the customer's viewpoint (Ishikawa & Lu, 1985) and multi-functional steering committees (Juran & Gryna, 1980; Deming, 1982; Hall, 1983; Ishikawa & Lu, 1985).

We feel that the twin foci of the literature - on culture and on quality enhancement tools and policies - create a chicken-and-egg question. On the one hand, it is often difficult to create a culture which emphasizes quality without a long-term use of quality enhancement tools and policies. On the other hand, quite paradoxically, it is difficult to effectively use these tools and policies when a culture which prizes quality does not exist. Motivation is not sufficient. It can ebb away quickly if not reinforced by tools which create considerable improvement by concentrating resources on the right problem. Conversely, tools which are not firmly embedded in empowering and motivational efforts (training) for the workers and in good organizational support (resources, encouragements, rewards) will be quite impotent.

Under the circumstances, empirical researchers in quality are faced with a difficult problem. If they want to understand what makes for an effective TQC program, where do they look? Can they ever say that a specific tool or policy really made or marred a quality improvement effort? For example, can they establish the effectiveness of the Taguchi method on the basis of anything other than the anecdotal evidence about Ina Tile Company (Kackar, 1985; Byrne & Taguchi, 1986)? The answer seems to be an unqualified "No."

We believe that one way of dealing with this problem is to focus on the management of knowledge and information used to improve quality. Since this is not an option discussed - to the best of our knowledge - in the literature, we discuss it in some detail. We first describe the role that knowledge/information play in quality improvement and then discuss how their study can improve our understanding of quality improvement efforts.

Our choice is based on an idea which has long been recognized in the literature: a product is an embodiment of information (Allen, 1977; Clark & Fujimoto, 1991). This implies that the better is the knowledge/information used to create a product, the better it will be. All attempts to improve the quality of a product are ultimately reducible to the idea of improving its producer's knowledge base. Therefore, a firm which systematically seeks to improve product quality must, in some sense, attempt to improve the precision and accuracy of the cause-and-effect statements in its knowledge base.

The empirical researcher interested in studying the efficacy of the range of tools and policies available for improving quality (or their domain of applicability) could follow a two stage procedure. He or she could first attempt to identify characteristics of the knowledge necessary to achieve some measure of quality improvement (see Figure 1). Next, he or she could attempt to link these characteristics with specific organizational structural and infrastructural elements needed to produce such knowledge. By creating a comprehensive typology of knowledge characteristics across plants and industries, he or she could possibly create systematic - rather than anecdotal - evidence of what works and under what conditions.

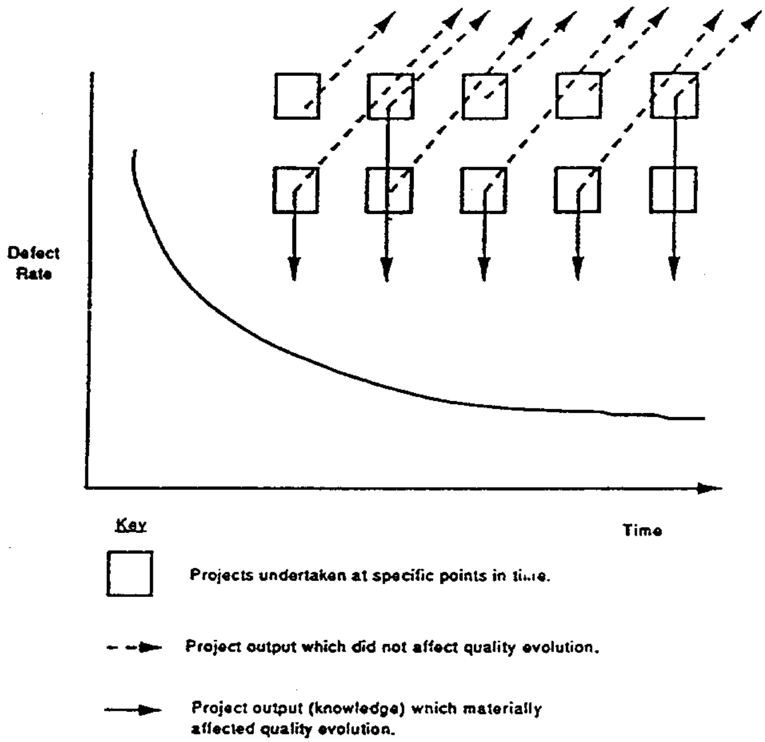

Figure 1: Evolution of Knowledge and Quality

This paper represents a first step in this direction. We do not yet possess all the data we need to address all of the nuances of the research agenda we have proposed. As such - and as is discussed in greater detail in the next section - we will look at a relatively small set of the projects which were executed, for most part, over a five year period. We will assess the impact of the knowledge produced by these projects on two *project level* measures of performance. Later in the paper, we will describe how we will expand this work.

3. Research Design and Data Base

3.1 Overview of the Project: A field research project which seeks to tackle the issues discussed above must:

- *Adopt a Longitudinal Perspective*: In order to understand how knowledge/information affects performance, it must track the creation and use of knowledge over time. This feature, which is implicit in Figure 1, is essential because the creation of knowledge is not instantaneous and its application may involve significant time lags.

- *Control for/Eliminate Potentially Confounding Factors*: Any study of the micro-management of knowledge could potentially be affected by factors such as variations in product and resource markets, production technology, general management policies, corporate culture and geographical location.

- *Delve into the Details of Product and Manufacturing Technologies*: One would be hard pressed to assert with any confidence that some bit of knowledge had a specific impact if one did not understand the underlying technologies.

- *Have Access to Detailed Data about the Systems Used to Improve Quality*. Naturally, such a depth of access poses a major problem of assuring the confidentiality of the host firms' proprietary information. In turn, this fact highlights the veracity of Eccles' (1985) assertion, "in field research, formal criteria of research design may be of far less significance than enthusiastic cooperation of the companies involved" (pp. 301).

We felt that the most effective manner in which we could simultaneously satisfy all four of these requirements was to limit our study to a single firm. We chose N.V. Bekaert, S.A., with which both of us had prior research and/or teaching relationships[1]. Our project received the enthusiastic backing of CEO Karel Vinck, who wanted to quickly build on the momentum created by Bekaert's winning of two major quality awards. Relevant details about this Company and its production process are presented later in this section.

In the interest of producing output within a reasonable time frame, we made two significant decisions about the scope of our research efforts. First, we decided to undertake a retrospective analysis of Bekaert's quality improvement efforts over the last decade. Naturally, this posed some difficult data collection problems, particularly with respect to the quality and comprehensiveness of data from the earlier years. Second, we decided to limit the study to only one of Bekaert's many plants[2]. In consultation with the Company's management, we picked the *Aalter* plant in Belgium, for Bekaert had initiated many of its innovative quality improvement efforts there.

3.2 The Host Company: The Bekaert group of companies operates 48 plants in 15 countries and employs over 12,500 workers. In 1991, total revenues were about $1.8 billion. Though it is currently involved in some other industrial sectors, since 1885, wire drawing has been the mainstay of Bekaert's business. It is the world's largest independent producer of steel wire.

---

[1] One of us has been involved in educating several of the Company's managers and engineers, while the other has conducted field research (for his doctoral thesis) in its plants.

[2] In this paper we will report on some data from other plants (see §3.6).

The Aalter plant belongs to the Steel Cord Main Business Unit, whose principal output is steel wire ("tire cord") used in the production of steel belted radial tires. Bekaert accounts for approximately one-third of the world's production of tire cord. While this large a market share gives it the power to shape the industry, it also leaves it vulnerable to the major technological or economic shifts. During the 1980s, for example, its customers in the tire manufacturing industry experienced traumatic change and turmoil. These travails naturally had a powerful impact on Bekaert. What had once been a relationship-oriented business quickly became a transaction-oriented business as tire makers made simultaneous demands of high quality, short lead times, low cost and product line flexibility.

Bekaert began to respond to these challenges early; it initiated a pilot quality improvement program at the Aalter plant in 1981. Through its joint venture with the Bridgestone Company of Japan, it had relatively ready access to knowledge about Japanese quality control techniques. Nevertheless, ten years passed before it could claim to have deployed the TQM philosophy in most (but not all) of its Steel Cord plants. Its diligent efforts seem to have borne fruit, for in 1990, its Aalter plant earned the European Quality Award for Leadership in Total Quality Management, which was the precursor to Europe's equivalent of Deming Prize of Japan and the Baldrige Award of the USA. In 1992, its Burgos plant won the runner-up award for the first European Foundation for Quality Management Award.

3.3 The Production Process[3]: The raw material for tire cord, called 'rod,' was steel wire about 5.5 mm in diameter. Steel mills supplied Bekaert with several huge coils of rod which they had created during one heating of a furnace. These coils, said to belong to one 'heat', generally had fairly uniform, but not identical, properties. No manufacturer could assure homogeneity.

Plant personnel first *pickled* the rod. They dipped it in acid and borax baths and dried it in ovens. The acid cleaned the rod and the borax facilitated lubrication at the next production stage.

Plant personnel then loaded the rod on to *dry drawing* machines, called BA machines. The rod passed through a soap box which contained dry, powdered soap. The borax coating enabled the rod to 'pick up' the soap, which smoothed the passage of the rod through the die. The effectiveness of this process of 'drawing' (Figure 2), which lay at the heart of tire cord production, depended on two critical factors: the shape of die and the quality of lubrication. They determined the shape of the wires produced, critical physical properties like breaking load and some types of wire fractures. Hence, Bekaert routinely monitored 'drawability,' i.e., the number of dies consumed to produce a metric ton of wire. Changes in the die - either its wearing out or its disintegration - determined the "consumption" of the die; naturally, the quality of lubrication had an impact on consumption.

After dry drawing, large (1000 kg) spools of wire were *patented* on IPH lines. By subjecting the spool to a chemical and heat treatment, this process changed the chemical structure of the wire and improved its ductility. A second stage of *dry drawing* on CA machines followed, which left the wire with a 1.7 mm diameter.

---

[3] This section is entirely based on Mukherjee (1992).

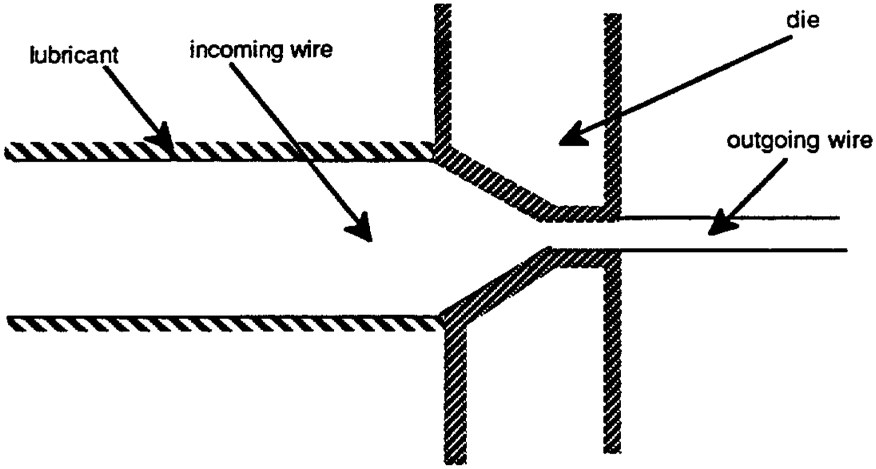

Figure 2: Schematic Cross-sectional View of the Drawing Process

Dozens of spools of wire were then unravelled simultaneously on *ISC lines*. A series of chemical baths, furnaces and cooling systems gave the wire properties such as strength, ductility, luster, resistance to rust and particularly, a thin coating of brass. Despite the use of sophisticated controls, all the wires which were processed together did not have identical properties.

Spools of wire were next drawn on *wet wire drawing (WWD)* machines. Here, the wires passed through a series of dies while they were immersed in a soap solution. The drawing progressively reduced their diameters to less than 0.5 mm. The fineness of these 'filaments' made the process particularly susceptible to interruptions, usually because of fractures. Another factor which made this process particularly complex was the difficulty in controlling the soap solution, which was supplied from two or three swimming-pool sized soap pits. Thus, while individual WWD machines were run independently, they were linked to each other because of the soap solution which flowed through them.

At the next manufacturing stage, the filaments were bunched: two or more filaments were twisted around each other to create cord. Depending on the number of filaments combined, the diameters of the filaments and the properties imparted to them, different types of cord could be constructed. The simplest tire cord had only two filaments, while complex ones had dozens.

Some cords had to be spiral wrapped. In this process, a fine filament was wrapped in the transverse direction around a core of bunched filaments. Spiral wrapping gave the cord great strength. Finally, about 5% of the spools were rewound, i.e., they were removed from one spool and loaded on to another. Typically, this was done when the wire on the original spool showed repairable defects. A sample of the cord was then sent for the testing and certification of cord properties and subsequently, all the cord was packed and shipped.

The process flow diagram is given in Figure 3. Two facts are important to note. First, the numbers of machines listed masked the real level of complexity that plant personnel had to face due to the many different types of machines used at each stage of production. For example, a typical plant could have ten distinct types of bunching machines. This variety could be attributed to technological constraints, differences in age of the machines and differences within specific types of machine because of subtle differences in components or sub-systems.

Second, the wide range in the numbers of machines used at the different production stages precluded the adoption of conventional cellular manufacturing. It was very difficult to create small flow shops for processing a limited number of similar parts all the way from the raw material stage to the finished goods stage (Vollmann, *et. al.*, 1988). The presence of the soap circuits compounded this difficulty.

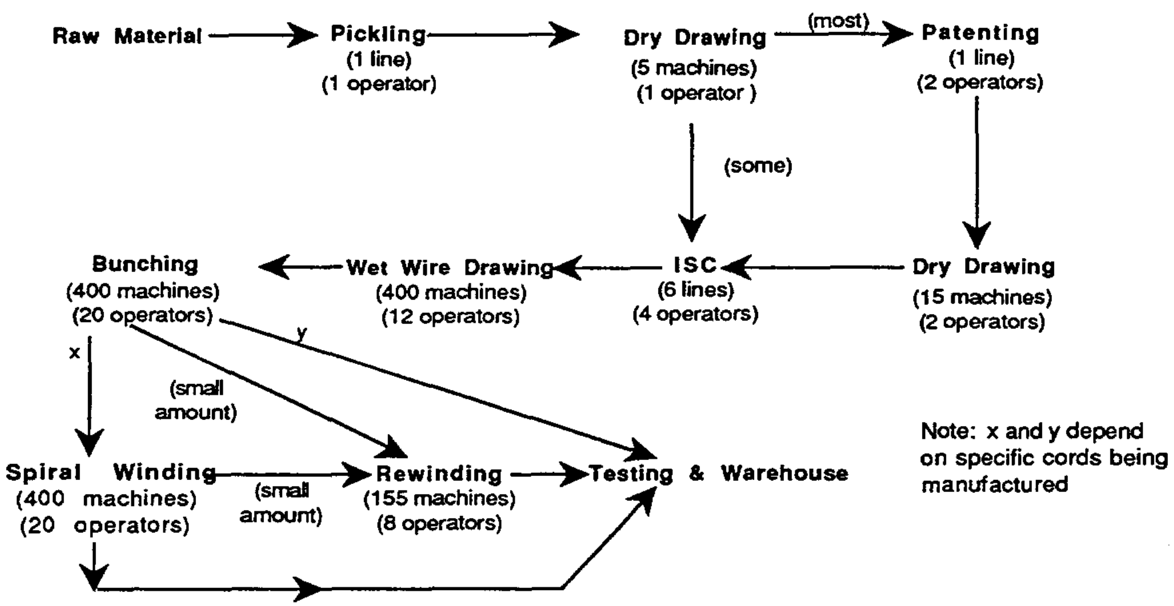

Figure 3: Process Flow Diagram
(Numbers of machines are for a mid-sized plant)
(Numbers of people are on a per-shift basis)

<u>3.4 Total Quality Control at Bekaert's Aalter Plant</u>: The *Orange Line* project undertaken in 1981 marked Aalter's and Bekaert's first real reliance on TQC concepts. The project was initiated to deal with a crisis: extraordinarily high levels of fractures in two complex spiral wrapped cords had brought on a slew of customer claims. The project team created, set and enforced Standard Operating Procedures (SOP's), educated the workers about the detrimental effects of variability and the basic elements of process capability, control charts and Ishikawa diagrams; and created an information system which fed back performance data to the workers on a daily basis. Within 6 months it reduced the level of fractures by a factor of 10.

That very year, Bekaert started a wider training program for its managers. They learnt about the Symptom - Cause - Remedy - Action (SCRA) concept and the need to undertake process characterization (i.e. ensure process capability). The SCRA concept was later adopted as a standard tool for TQC projects. Together with process characterization, it gained increasing acceptance over the following years.

Over the next few years, Bekaert:

- Created a functional TQC organization, consisting of a plant level TQC steering committee and departmental TQC teams. The TQC teams solved chronic problems relying on the experience of its members, brainstorming and the Seven Statistical Tools.

- Introduced SPC for the control of a few key parameters and attributes (1983). The use of SPC became widespread in 1986 and 1987 as customers demanded increasing levels of product quality and as the need to reduce costs attributable to defects became important.

- Added accuracy (C_A) and precision (C_P) indices to the existing Bekaert Quality Index (BQI), which was, till then, based on averages, standard deviations and out-of-specification values for key steps (1983). C_A measured the conformance of the average to the target, C_P the dispersion of achieved results. The use of C_{PK} indices - which combined C_P and C_A to give an overall perspective on process capability - began in 1986, when a C_{PK} of 1.33 (i.e. less than 6 rejects per 100,000) was adopted as a minimum acceptable performance level.

- Trained foremen in creating, establishing and monitoring SOPs. Rigorous implementation of SOPs yielded lower total product variance by diminishing operator variance (1984).

- Installed a new information system, which quickly provided standardized data (1985). The system enabled the economical follow up of daily, weekly and monthly production and quality data. A Cost of Quality system followed.

- Established a "model line" for an important, representative product and charged the engineer running it with the task of creating fundamentally new process control knowledge without sacrificing the production of saleable wire (mid-1988). The use of natural and controlled experiments became a way of life on the model line (Mukherjee, 1992).

- Set up quality control circles (QCC) with voluntary membership (1989).

In addition, throughout the decade, Bekaert's plants, including Aalter, also invested heavily in the training of plant personnel. In 1991, Aalter management started emphasizing the behavioral - rather than the technical - component of the TQC philosophy.

3.5 The Projects: Quality improvement projects at Bekaert are classified as follows:

1. Projects to hold gains or to make small improvements. These projects are typically focused on machine and operator level issues.

2. Projects to improve C_{PK} levels incrementally. These are managed at the foreman or supervisor levels.

3. Projects to improve procedures & systems. These are managed by engineers. They are similar in spirit to the process capability/process characterization studies described in the literature (Juran & Gryna, 1980; Gupta, *et. al.*, 1987).

4. Product line activities directed at the achievement of significant improvements in the quality attributes of specific products.

5. Key projects aimed at achieving order of magnitude improvements across the plant. They typically attract the attention and efforts of top managers and engineers.

In this paper, we will distinguish between projects of types 1 and 2 (which we will call 'TQC projects') and projects of types 3, 4 and 5 (which we will call 'key projects'). The TQC projects can also be characterized as continuous improvement, *Kaizen* or bottom-up projects (Imai, 1986), whereas the key projects can be characterized as breakthrough, stretch or top-down projects.

For most part, the TQC projects (see appendix A for an example) deal with problems of internal product failure and (process) capability. However, they also tackle issues like housekeeping, safety, ergonomics, maintenance and productivity. Typically intra-departmental in scope, they adopt the SCRA approach to problem identification, which they combine with the Deming Plan-Do-Check-Act (PDCA) circle. Project participants first define the problem and agree upon a goal. They then collect and analyze data using the Seven Statistical Tools, brainstorm about their experiences and knowledge and determine the issues they should tackle. Finally, they act on their decisions, cycling back to refine their analyses whenever necessary.

The key projects meet the criteria used in the literature to identify unstructured or poorly structured problems. For example, well defined problem solving methods often do not exist, conflicting trade-offs have to be made, solutions cannot be recognized until they are reached and not all problem transformations and states are known (Mintzberg, *et. al.* 1976; Gerwin, 1981; Mason & Mitroff, 1981; Daft & Macintosh, 1981; Mason & Mitroff, 1981; Smith, 1988). These projects are often interdepartmental. They attempt to improve product attributes and resolve internal failure and reliability issues[4].

<u>3.6 Data Collection</u>: We aim to acquire data on a large number (possibly 100) of the quality-related projects that Aalter undertook during the 1980s. These data are of two types. First, we are collecting archival data from the firm's management information system. Second, where necessary - and this is really relevant only for the key projects - we are interviewing the participants in these projects both to triangulate the archival data and to get a richer, deeper perspective on the knowledge creation efforts.

---

[4] Wire fractures, which have an impact on both internal and external measures of quality, are often the target of both types of quality improvement efforts.

Figure 4 illustrates on a time line 52 projects we have studied so far. It is important to note that only 45 of these projects are from the Aalter plant; within this subset 37 are TQC projects undertaken in the BA, IPH, CA, ISC, WWD and Bunching departments and 8 more are key projects. Also included in the figure are 7 key projects executed at two of Aalter's sister plants. We have included them in this study purely as a control for our statistical analyses (§4 and §5); this point is discussed in §4.3.

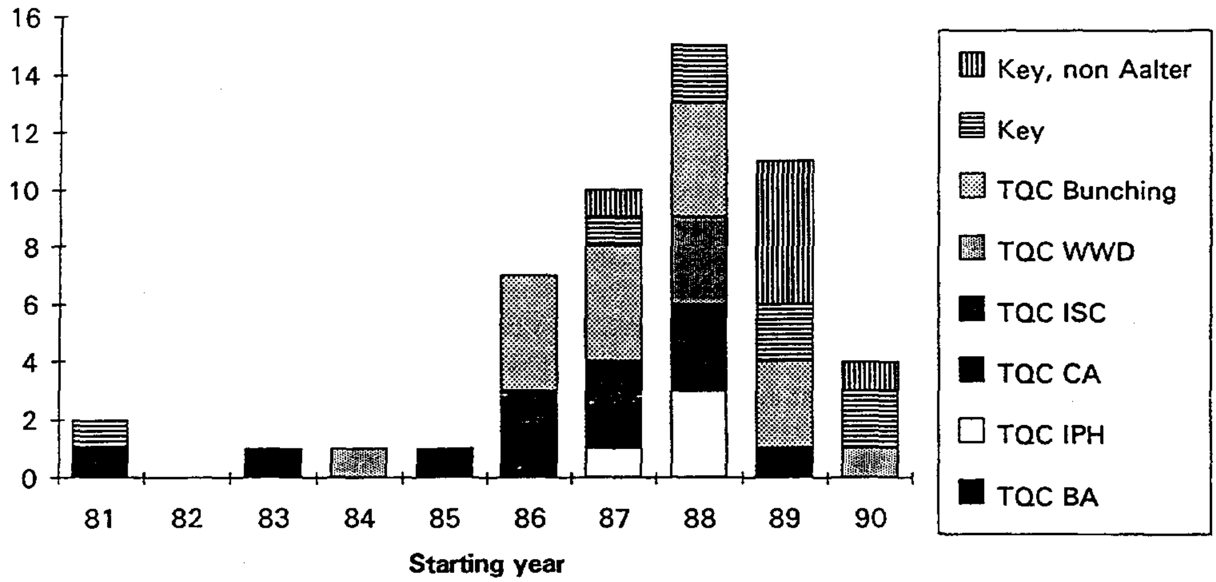

Figure 4: Distribution of Projects Studied Over 1980s

The TQC projects in our database include all projects which (i) were past the testing, but not necessarily full scale implementation, stage; (ii) had an identifiable quality component (i.e., were not exclusively related to housekeeping, safety, ergonomics, maintenance and productivity); and (iii) had been adequately documented. Figure 4 shows that the number of these projects rose sharply from 1986 to 1989. During those years, plant management required foremen to undertake defined numbers of such projects as a part of their training in the use of the SCRA/PDCA methodologies. Currently, plant personnel undertake TQC projects whenever there is a need and the foremen have more freedom in applying the SCRA method.

The key projects from Aalter and the other plants are described in Mukherjee (1992). With one notable exception of the Orange Line project mentioned earlier they were executed between 1987 and 1990[5]. In all other respects, these projects form a heterogeneous group:

- Engineers played the lead roles in some and technicians in others;

---

[5] In particular, 5 of the Aalter projects were executed on its "model line."

- Line personnel managed some while technical service (staff) personnel managed the others.

- Well-defined teams executed some while individuals, working in loose confederations with their colleagues inside and out of the plant, managed others.

- Some had passed the testing stage, while others had been implemented in full scale production. For some of the latter, project completion was an arbitrary milestone, for these were truly continuous improvement efforts.

We coded both the TQC projects and the key projects using the protocol given in Appendix B. The questions in the protocol fell into three groups and required responses on a five-point Likert scale. The first set of ten questions (Set A) dealt with how the projects were executed. It covered issues like whether or not project goals had changed; the degree to which the project environment approximated the mass manufacturing environment and the extent to which project results were followed up. The second set (Set B) focused on the impact the projects had. The twenty two questions in this set rated issues like actions taken, confidence and understanding engendered, complexity of the solutions advanced and the use of formal knowledge. The third set (Set C) focused on project level performance of the projects. We discuss in §5 the reasons why we used project level measures instead of product or plant level measures.

One person on our research team coded the TQC project data. For most part, he relied on the final reports of the TQC projects (see Appendix C). For example, in order to code a question like "the degree of objectivity in the problem solving process", he looked at sample sizes, variability of tests and explanations why tests did not work. However, he could not always get all the data he needed from these reports. For example, most reports did not discuss "the depth of understanding of the issues solved," because understanding could have been common knowledge, or irrelevant to the problem on hand. In such cases, he sought the help of the TQC facilitator who had assisted many of the TQC work groups in tackling problems systematically.

Another member of the project team coded the data on the key projects. In a prior research effort, he had conducted over 200 hours of formal, semi-structured interviews with knowledge workers in three plants - Aalter, Lanklaar (Belgium) and Burgos (Spain) - the corporate R&D and the central engineering staff. In these interviews, he had acquired background data on interviewees and their plants as well as detailed information on the projects in which the interviewees had participated. He had also collected archival data on the projects and cross-referenced these with the interview data. He coded these key projects on the basis of this extensive data set.

4. Dimensions of Knowledge

<u>4.1 Preliminary Principal Component Analysis</u>: In §2, we discussed the need to identify the characteristics of knowledge which drive quality performance. We relied on the statistical

technique, called *Principal Component Analysis*[6] (PCA) to reduce our data on project impact to a reasonable number of basic - and possibly latent - characteristics.

We began our PCA with the 37 TQC projects undertaken by Aalter. The set of projects was so homogeneous that our scales picked up very few differences on several questions (see Appendix B). Consequently, we were forced to drop 7 questions from Set B. The SAS statistical package (Allen, *et. al.*, 1990) we used generated (i) 4 eigenvalues larger than one and (ii) a Scree-test which could support up to five components. It retained 4 using the more formal eigenvalue criterion and generated the analysis reported in Table 1.

4.2 Assigning Meaning to the Components: An analysis such as this would be of little value if we could not relate the Components to understandable conceptual constructs. This discussion, which will temporarily take us out of the domain of statistical analysis, is best presented with the help of the schematic representation of cause-and-effect relationships (Figure 5). Assume that 'B' is some attribute, variable or measure of quality, 'A' is a variable which affects it directly and 'C' is a variable which affects it indirectly. We will refer to 'A' as the 'primary action variable,' to 'C' as the 'higher order variable' and to '-->' as the 'association (between 'A' and 'B'). For ease of exposition, we will consider the components in the order 1, 3, 2 and 4.

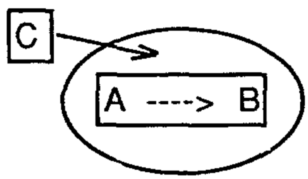

Figure 5: A Simple Schematic Cause-Effect Model of Quality

The four questions (B6, B3, B5 and B2) that loaded onto Component 1 essentially deal with how much understanding the project engendered (or reflected) about 'A' and the association between 'A' and 'B.' Such base-level knowledge of cause-and-effect is commonly acquired through experience of working routinely on production problems. For example, the TQC projects were organized by experienced foremen or supervisors. In virtually all the projects, the team members relied on brainstorming to capture their collective wisdom. They then codified their experience and wisdom in the form of Ishikawa fishbone diagrams which guided subsequent problem solving activity. In other words, they acquired *cognitive* knowledge about process control through "learning by doing" (Arrow, 1962; Dutton, *et. al.*, 1984) and applied this knowledge in the solution of quality related problems. Clearly, this is a recurrent, cumulative

---

[6] We also analyzed the data using a related methodology, Factor Analysis. Some analysts believe that Principal Component Analysis is a more reliable technique, citing issues such as the stability of factor scores (Wilkinson, *et. al.*, 1992). So, we have reported the PCA data here. However, the choice of techniques did not affect our findings.

Unrotated Data:

	Component 1	Component 2	Component 3	Component 4
Eigenvalue	4.89	2.46	1.86	1.44
Variance (%)	32.6	16.4	12.4	9.6
Cum. Var. (%)	32.6	49.0	61.4	71.0

Varimax Rotated Component Patterns:

Questions*	Component 1	Component 2	Component 3	Component 4
B6	**0.88**	0.12	0.11	0.03
B3	**0.87**	0.13	0.07	-0.15
B5	**0.86**	0.24	-0.08	-0.02
B2	**0.85**	0.21	-0.07	-0.27
B21	0.03	**0.85**	0.18	-0.12
B1	0.32	**0.73**	0.27	0.09
B22	0.27	**0.69**	0.28	-0.06
B18	-0.04	**0.68**	0.09	0.06
B14	0.28	**0.62**	-0.03	-0.18
B4	0.27	**0.60**	-0.21	0.07
B7	-0.04	0.09	**0.96**	-0.00
B8	0.06	0.22	**0.91**	-0.04
B20	-0.07	0.18	-0.19	**0.83**
B19	-0.14	0.01	0.19	**0.83**
B16	-0.06	-0.23	-0.05	**0.66**

Final Communality Estimates (CE) for the Questions:

Questions	CE
B1	0.71
B2	0.85
B3	0.80
B4	0.49
B5	0.81
B6	0.80
B7	0.93
B8	0.88
B14	0.50
B16	0.50
B18	0.48
B19	0.75
B20	0.77
B21	0.77
B22	0.64

Table 1: PCA (Varimax Rotated) of the Data on 37 TQC Projects

phenomena: the understanding engendered by one project is utilized in the next. In recognition of the role of learning by doing in generating the understanding, we have labelled Component 1 '*Experience Knowledge.*'

The two questions (B7 and B8) that loaded onto Component 3 dealt, respectively, with whether the project had engendered (or reflected) an understanding of impact of higher order variables and whether the project had attempted to affect them. For example, a TQC project in which the participants worried about the effect of dust on some key performance measures would score high on B8[7]. Such variables are often relevant for extending the domain of process control beyond "local control of contingencies" (Bohn & Jaikumar, 1992). In other words, they help define the conditions necessary for the primary relationships (like 'A --> B') to hold. If plant personnel lack knowledge of such higher order variables or fail to control for them[8], they might not be able to achieve their desired goals even if they manipulate the appropriate primary action variables and associations. For example, plant personnel often explained seemingly irreducible differences in a key product attribute (adhesion) across two products on the basis of the amount of brass dust produced by the different models of the machines used to produce these products. Hence, we have called Component 3 '*Domain Knowledge.*'

It is worth mentioning here that although the TQC projects were not highly sophisticated, this Domain Knowledge Component turned out to be very robust. In an attempt to see whether we were picking up a spurious Component, we ran the PCA without one or the other question that had loaded on this Component. Instead of loading onto another Component, the remaining question inevitably loaded onto a separate Component.

The questions which loaded on to Component 2 made for an interesting mix. Three (B4, B1 and B14 respectively) related to the modification of 'A', the association, 'A --> B,' and changes in the monitoring of variables like 'A' and 'C,' while the others (B22, B21 and B18 respectively) related to the importance of scientific knowledge, the ability to specify the effect of variability among causal variables and the formality (Jaikumar & Bohn, 1986; Mukherjee, 1992) of the final knowledge produced. That each of these sets was internally consistent and mutually supportive was not surprising; the strong link between the two sets was harder to appreciate.

Our explanation draws upon a well-established idea from the literature: organizational learning usually involves incomplete learning cycles (March & Olsen, 1976; Hedberg, 1981). In Hedberg's words, the term 'incomplete learning cycles' refers to the fact that learning efforts "... are often interrupted or disturbed. Organizations have difficulties in tracing which actions caused environmental responses. Individuals in organizations sometimes form their beliefs on

---

[7] Similarly, a key project, in which participants worried about the impact of changing the model of a machine on a hypothesized cause-effect relation would score high on B8.

[8] Failure to control might be due to lack of knowledge or lack of the appropriate technology. A substantive discussion of the reasons for the lack of knowledge is beyond the scope of this paper. Suffice it to say here that it could arise from a condition as trivial as the lack of exposure (of plant personnel) to alternative production environments.

mis-interpretations of cause-effect relationships or even through influences from outside sources. This gives room for theories of action - myths - with low or no validity to the concerned organizations. Schools of thought substitute for first-hand experience. Myths are created on spotty evidences" (pp. 11). One wide-spread effect of incomplete learning cycles is that received wisdom is hard to challenge.

In the present context, received wisdom could be that a particular choice of 'A' produces a specific desired (or undesired) effect 'B.' In this case, a project which sought to change the choice of 'A' could potentially run into very strong opposition, both within the TQC project group during the brainstorming phase or later, when the group made its recommendations for implementation. In either case, the factor which determined whether or not the challenge to the received wisdom was indeed successful could well be the nature of the evidence brought to bear on the issue. In such situations, scientific, statistical and otherwise formal types of knowledge might prove to be very valuable because such knowledge is rigorously codified and difficult to deny[9]. Hence, we characterized Component 2 as *Formal Knowledge* .

Finally, the three questions (B20, B19 and B16) which loaded onto Component 4 dealt with the number of distinct elements of 'B,' the number of links among them and the degree of communication the management of these elements and links would engender among supplier/customer departments. We had included these questions in order to get some idea of the *complexity* of the projects; the statistical analysis captured our intent.

Complexity was a control Component. We did not really expect it to influence our understanding of the characteristics of knowledge which affect quality. In fact, it has nothing remotely in common with the other components described above. *Ex ante*, we would expect it to affect quality only to the extent that high complexity output would take longer to develop and longer to implement successfully.

Given the identifiably different nature of this Component, we re-ran our analysis without questions B20, B19 and B16. Our objective was to see if it made any difference to the other dimensions of knowledge that we had identified. The results (which we will not report here) were interesting. Three components were retained by the program and among them, they explained the same 71% of the variance in the data. Moreover, the questions loaded onto these components exactly as they had under the four-component analysis (only minor re-shuffling of the loading patterns occurred). Finally, the communality estimates remained very stable.

---

[9] It is worth noting that the organizational learning literature actually asserts that in the face of incomplete learning cycles, it is usually difficult to overturn received wisdom on the basis of empirical data alone. Mukherjee (1992) and Mukherjee & Jaikumar (1993) pointed out that this assertion does not necessarily hold for organizational learning about scientific and engineering issues in technology and operations management. They attribute this to the fact that scientific and engineering phenomena are governed by unambiguous laws of nature and not by the whims of man. So, well-crafted empirical evidence can challenge myths by shifting the burden of proof from the creators of new knowledge to the supporters of the myths.

4.3 Extension of the Domain of Applicability of the Components: On the basis of 37 TQC projects, we had identified four types of project output - Experience Knowledge, Formal Knowledge, Domain Knowledge and Complexity. Could the characterizations of knowledge produced by such a homogeneous group be applicable to a wider range of quality efforts?

To answer this question, we broadened the scope of our analysis in two stages. First, we added 8 key projects undertaken at Aalter to our basic data set on 37 Aalter TQC projects. Second, we augmented this expanded data set with another 7 key projects which were executed at Aalter's sister plants at Lanklaar (Belgium) and Burgos (Spain). At this point, the data set covered 52 projects. Since we had asserted earlier that we wanted to study the evolution of quality at one plant, this last extension warrants an explanation. In fact, the 7 non-Aalter key projects are simply meant to act as a control. We were concerned that the data on the 37 TQC projects could drown out the data on the 8 Aalter key projects and thereby defeat our attempts to explore the robustness of the four components of knowledge. Since we do not have as yet the complete data set we hope to collect at Aalter, we relied on the 7 non-Aalter projects to increase the proportion of key projects in our data base to 29%. We felt that if the set of 52 projects (37 Aalter TQC projects, 8 Aalter key projects and 7 non-Aalter key projects) corroborated the results we obtained from analyzing the 45 Aalter projects, we could be reasonably sure that the results were not simply due to the larger number of TQC projects in our database.

How could we be sure that the TQC projects formed a homogeneous group and the key projects were in fact, basically different? We had extensive qualitative data to support this position, but could we support our assertion with less subjective data? The answer to this question is a *qualified* "Yes", for we knew of no single statistical technique which would give an unequivocal answer. Cluster Analysis (Jackson, 1983) was the obvious choice, but unfortunately, it requires the analyst to specify the number of clusters he or she desires. So, the best we could do was to see if the statistical procedure could reproduce the distinctions we had made on the basis of qualitative data.

The application of Cluster Analysis posed two more problems. First, the literature gave many different methods for creating clusters (e.g., Allen, 1990) and *ex ante*, we had no theoretical rationale for using any particular method. Second, these methods are generally best suited for analyzing large volumes of data, which we did not have. So, we adopted the advice offered by Aaker & Day (1990), to the effect that "... analyst ... might look for clusters that are stable over a relatively large range of clustering criteria" (pp. 589) and proceed with the assumption that we would obtain less than ideal results.

We performed Cluster Analysis on the data from Set A in our protocol, which dealt with how the projects were executed (Appendix B). As shown in Table 2, several clustering methods gave consistent results in response to our attempts to produce two clusters. These results show that the TQC projects formed a relatively homogeneous set. The key projects differed from them at least according to some of the statistical criteria. Thus, while we cannot make an airtight case that these projects were very different, we have some evidence supporting this contention.

Clustering Method	Cluster 1	Cluster 2
45 Aalter Projects:		
Average Linkage	37 TQC projects 6 key projects	2 key projects
Ward's Method	37 TQC projects 3 key projects	5 key projects
EML	37 TQC projects 3 key projects	5 key projects
Fast Cluster	34 TQC projects	3 TQC projects 8 key projects
All 52 Projects:		
Average Linkage	37 TQC projects 12 key projects	3 key projects
Ward's Method	34 TQC projects 2 key projects	3 TQC projects 13 key projects
EML	37 TQC projects 9 key projects	6 key projects
Fast Cluster	33 TQC projects 2 key projects	4 TQC projects 13 key projects

Table 2: Summary of Results of Cluster Analysis

4.4 Analysis of the Expanded Data Sets: Tables 3 and 4 show that despite the incorporation of the key projects into our data base, the four components that we had identified on the basis of the TQC data remained robust. Moreover, the cumulative variances and the communality estimates remained stable. All that changed was (i) the order of the component loadings and (ii) the appearance of a somewhat higher degree of cross-loadings for some of the questions. The first issue is of little consequence here and we have not yet analyzed the implications of the second change. Finally, removal of the questions relating to Complexity made no difference to the analysis; the other three Components remained stable in every respect (we will not report these results here).

Having reduced the probability that these results are merely artifacts of the proportionately high number of TQC projects in the data, what explanations can we offer for these results? One explanation could be that unknown and unintentional biases affected the coding of the data. Again, while this possibility cannot be ruled out entirely, it is important to re-emphasize that the TQC projects were largely coded by one member of the research team, who was assisted by the TQC facilitator at Aalter, whereas the other projects were coded independently by another research

Unrotated Data:

	Component 1	Component 2	Component 3	Component 4
Eigenvalue	5.48	2.73	1.45	1.24
Variance (%)	37.5	18.2	9.7	8.3
Cum. Var. (%)	37.5	54.7	64.4	72.7

Varimax Rotated Component Patterns:

Questions	Experience Knowledge	Formal Knowledge	Domain Knowledge	Complexity
B5	**0.87**	0.25	-0.05	0.00
B2	**0.86**	0.16	0.01	-0.21
B6	**0.84**	0.17	0.04	0.02
B3	**0.83**	0.25	0.21	0.02
B18	0.01	**0.78**	-0.17	-0.08
B22	0.31	**0.72**	0.33	0.08
B21	0.18	**0.71**	0.47	0.22
B1	0.34	**0.65**	0.42	0.15
B14	0.33	**0.59**	0.21	-0.05
B4	0.36	**0.58**	-0.05	0.22
B7	-0.05	0.03	**0.94**	0.13
B8	0.12	0.23	**0.88**	0.15
B20	-0.01	0.23	-0.03	**0.84**
B19	-0.12	-0.03	0.21	**0.82**
B16	0.01	-0.00	0.13	**0.72**

Final Communality Estimates (CE) for the Questions:

Questions	CE
B1	0.73
B2	0.81
B3	0.79
B4	0.52
B5	0.83
B6	0.74
B7	0.90
B8	0.87
B14	0.50
B16	0.53
B18	0.65
B19	0.73
B20	0.76
B21	0.80
B22	0.73

Table 3: PCA on Data on All 45 Aalter Projects

Unrotated Data:

	Component 1	Component 2	Component 3	Component 4
Eigenvalue	5.41	2.71	1.41	1.22
Variance (%)	36.1	18.1	9.4	8.1
Cum. Var. (%)	36.1	54.2	63.6	71.7

Varimax Rotated Component Patterns:

Questions	Experience Knowledge	Formal Knowledge	Domain Knowledge	Complexity
B5	**0.87**	0.25	-0.06	0.00
B6	**0.86**	0.11	0.08	0.04
B2	**0.85**	0.22	-0.01	-0.18
B3	**0.84**	0.22	0.21	0.01
B18	0.02	**0.79**	-0.12	-0.11
B21	0.23	**0.63**	0.52	0.25
B4	0.34	**0.62**	-0.02	0.21
B14	0.33	**0.61**	0.20	-0.03
B22	0.38	**0.60**	0.41	0.09
B1	0.35	**0.54**	0.48	0.17
B7	-0.08	-0.05	**0.91**	0.13
B8	0.11	0.17	**0.89**	0.15
B20	-0.03	0.26	-0.01	**0.84**
B19	-0.13	-0.08	0.19	**0.81**
B16	0.06	-0.02	0.16	**0.71**

Final Communality Estimates (CE) for the Questions:

Questions	CE
B1	0.67
B2	0.80
B3	0.80
B4	0.54
B5	0.82
B6	0.76
B7	0.86
B8	0.85
B14	0.52
B16	0.53
B18	0.65
B19	0.71
B20	0.77
B21	0.78
B22	0.68

Table 4: PCA on Data on All 52 Projects

team member, who relied on detailed clinical data. Moreover, if anything, consistency of coding across the breadth of the data is normally considered a virtue in empirical research.

The second - and certainly, our preferred - explanation is that the Components are indeed stable over different types of projects and capture significant, latent characteristics of the projects. Undoubtedly, we bear the burden of substantiating this explanation as we continue our research efforts at Bekaert. Nevertheless, for the present we will proceed on the assumption that we have identified a few of the characteristics of knowledge that we discussed in §2.

5. The Impact of Knowledge on Quality Improvement

We next turn to the question of the impact the projects - specifically, the Components - had on performance. Since we do not as yet have the plant-level or even department-level measure of quality that Bekaert uses, we will not tackle this issue at the level of generality suggested in §2. Instead, we will focus on the much more limited question of how the projects affected the contingencies (Bohn & Jaikumar, 1992; Mukherjee, 1992) they were meant to control.

The term 'contingencies' refers to the occurrence of unexpected events during production. For example, a machine might break down or a microscopic flaw may exist in the raw material. Such contingencies result in the non-conformance of a product to specifications or the use of excessive resources and make for an unreliable production system. The term may also refer to the unexpected occurrences of favorable events, though unfortunately, the literature ignores this possibility.

Plants which seek to improve their performance on quality must undertake efforts to control the occurrence of contingencies. Ideally, they must try to eliminate or minimize contingencies which have adverse effects. If this is not possible, they must at least try to limit the impact of such contingencies. Plants must also try to make routine those contingencies which have beneficial effects. Each of the projects in our data base had at least one of these goals.

We used two different project level measures (Set C Appendix B) of the degree to which individual projects were able to resolve contingencies. One measure assessed the achievement of a project's stated contingency control goal on a 5-point Likert scale. The second measure used a similar scale to assess the success of the project in consistently changing the frequency of occurrence of contingencies. These two performance measures are related, but distinct. At one level, the two measures would differ for two projects which dealt with the same contingency if one attempted to modify the frequency of its occurrence and another tried to determine how to respond when it did occur. At another level, a project could consistently change the frequency of occurrence of a contingency without achieving its stated goal.

We tried to explain these two performance measures using the Component Scores of the projects. Specifically, we wanted to see if any of the four Components of knowledge had statistically discernable effects on the two measures. In other words, we wanted to obtain the estimates for β in the following equation:

$$y = \mathbf{X}\beta + u, \quad \text{where}$$

y = Measure of achievement of stated goals or measure of achievement of consistent changes
u = Error term
X = n X 4 matrix of Component Scores of the n projects for (i) Experience Knowledge, (ii) Formal Knowledge, (iii) Domain Knowledge and (iv) Complexity
β = 4 X 1 vector of coefficients of the four Components

To the best of our knowledge, there exists no statistical model which simultaneously handles polytomous dependent variables (like Likert scales) and truncated distributions of independent variables (the Component Scores ranged from -2.25 to 2.28) (Johnston, 1984; Kmenta, 1986; Jackson, 1983). Therefore, we used ordinary least square (OLS) regression for our analysis. We justify our decision on the basis of the following: (i) it conforms to common practice (see for example, Lehmann, 1985, pp. 572); (ii) the resultant models passed the basic conventional tests of validity (e.g. unbiased distribution of residuals); and (iii) prior research on dichotomous dependent variables and unrestricted independent variables has indicated that in situations involving relatively small data sets, the OLS regression model generally performs as well as logit or probit models (Aldrich and Nelson, 1984; Noreen, 1988). The results of our analysis appear in Tables 5 and 6.

	Constant	Experience Knowledge	Formal Knowledge	Domain Knowledge	Complexity
TQC Data:	Adjusted R^2	= 0.22			
Achieve Goal	**3.5**	**0.57**	**0.32**	**-0.13**	**0.02**
t - stats		3.2	1.8	-0.7	0.1
P > |T|		0.003	0.083	0.468	0.895
All Aalter Data:	Adjusted R^2	= 0.24			
Achieve Goal	**3.5**	**0.55**	**0.33**	**-0.10**	**0.03**
t - stats		3.57	2.14	-0.67	0.20
P > |T|		0.001	0.038	0.508	0.843
All Data:	Adjusted R^2	= 0.28			
Achieve Goal	**3.5**	**0.58**	**0.36**	**-0.06**	**0.02**
t - stats		4.14	2.61	-0.42	0.13
P > |T|		0.000	0.012	0.678	0.900

Table 5: OLS Regression of Achievement of Goals on the Component Scores

As in the case of the PCA, what is striking is the consistency of the results reported in the two tables. In particular, the following points are worthy of note:

1. For both performance measures, the explanatory power (i.e., the *adjusted* R^2) of the models increased with the addition of the key projects to the data base.

2. In Table 5, the coefficient of Experience Knowledge essentially remained unchanged as the basic TQC data set was augmented with key projects. Simultaneously, the coefficient of Formal Knowledge became marginally more positive and the significance levels for both variables improved sharply.

	Constant	Experience Knowledge	Formal Knowledge	Domain Knowledge	Complexity
TQC Data:	Adjusted R^2 = 0.36				
Consistent Change	**2.7**	**0.95**	**0.36**	**0.11**	**0.15**
t - stats		4.52	1.71	0.51	0.69
P > |T|		0.000	0.096	0.617	0.499
All Aalter Data:	Adjusted R^2 = 0.37				
Consistent Change	**2.9**	**0.91**	**0.38**	**0.23**	**0.21**
t - stats		4.79	2.00	1.19	1.10
P > |T|		0.000	0.052	0.242	0.28
All Data:	Adjusted R^2 = 0.39				
Consistent Change	**2.8**	**0.90**	**0.42**	**0.18**	**0.17**
t - stats		5.35	2.52	1.09	1.00
P > |T|		0.000	0.015	0.28	0.322

Table 6: OLS Regression of Ability to Make Consistent Changes on the Component Scores

3. In Table 6, the coefficient of Experience Knowledge dropped and the coefficient of Formal Knowledge became relatively more important as the TQC data were augmented with key projects. Simultaneously, the significance levels for Formal Knowledge improved sharply.

4. Domain Knowledge had little impact on performance in both models, perhaps because none of the project results were applied in domains other than those for which they were generated.

These results suggest that as quality projects become increasingly less structured, effective performance requires that Experience Knowledge be augmented with Formal Knowledge. In fact, the relative importance of the latter tends to rise. Why might this be so? What roles do the two types of knowledge play in the TQC and the key projects?

Our preferred explanation of our findings draws on the qualitative data we have gathered at Bekaert (see also Mukherjee, 1992). Virtually all quality improvement efforts undertaken in plants focus on the control of contingencies, which often have multiple causes. As such, plant personnel who seek to control them have to know where to find their source and/or what forces could ameliorate their effect. When projects are limited in scope - as are most TQC projects - the decision usually boils down to listing all possible variables on an Ishikawa diagram and then honing in on some of these. Experiential knowledge is extremely valuable for this process. Usually, once the key variables have been identified, control action can be readily defined.

In contrast, when the projects are less structured, experiential knowledge, though even more important for suggesting avenues to explore, is no longer sufficient for defining solutions. Often, the variables involved in the occurrence of the contingencies (as well as the links among them) are shrouded in ambiguity, equivocality and high uncertainty. In such situations, Formal Knowledge tends to become essential for isolating cause-effect relations.

An alternative explanation could be that engineers and operators traditionally rely on different approaches to problem solving. In particular, engineers tend to use Formal Knowledge (e.g., based on careful statistical experimental designs) even in situations where Experience Knowledge would be just as effective. Pending further data collection and analysis, we cannot rule out this possibility completely. However, we believe that this explanation is inappropriate for our data. In spite of Bekaert's long history of commitment to the TQC philosophy in general, its plant level engineers have only recently begun to adopt regular use of formal statistical experiments. Even today, the predominant experimental tool is *ad hoc* experimentation. In fact, eight of the fifteen key projects we studied (including 4 of the Aalter key projects) did not rely on statistical experimental techniques.

One interesting aspect of Table 5 which we have ignored so far is the near-zero coefficient values and the near-one p-values of Component 4, Complexity. Together, these values indicate that from a statistical perspective, Complexity is an irrelevant variable in this model (Johnston, 1984) and can be dropped. Such a decision could also be justified conceptually by reference to the fact that Complexity has little in common with the other components of knowledge identified in this paper. The results of the analysis performed without this variable are presented in Table 7[10].

---

[10] Similar questions could be raised about Component 3 (Domain Knowledge) in Table 5 and about Components 3 and 4 (Domain Knowledge and Complexity, respectively) in Table 6. In these cases, however, the conclusion is not as clear cut, particularly because there clearly are conceptual reasons for retaining Domain Knowledge in our analysis. Our analysis of the data without these variables did not reveal any interesting insights.

The 3-Component OLS models had comparable explanatory power to the 4-Component models. However, the coefficients and statistical significance of the Formal Knowledge component became stronger, while the coefficients of Experience Knowledge (and Domain Knowledge) essentially remained unchanged. Thus, the model supported the hypothesis we offered about the comparative roles of these two explanatory variables.

	Constant	Experience Knowledge	Formal Knowledge	Domain Knowledge
TQC Data:	Adjusted R^2	= 0.24		
Achieve Goal	**3.5**	**0.56**	**0.34**	**-0.13**
t - stats		3.17	1.91	-0.71
P > |T|		0.003	0.065	0.480
Aalter Data:	Adjusted R^2	= 0.26		
Achieve Goal	**3.5**	**0.54**	**0.36**	**-0.10**
t - stats		3.55	2.37	-0.66
P > |T|		0.001	0.022	0.513
All Data:	Adjusted R^2	= 0.30		
Achieve Goal	**3.5**	**0.56**	**0.40**	**-0.06**
t - stats		4.05	2.92	-0.41
P > |T|		0.000	0.005	0.685

Table 7: OLS Regression of Achievement of Goals on Three Component Scores

If these findings are substantiated by our continuing research, we will need to think very carefully about the relative effectiveness of various problem solving tools as the nature of quality improvement efforts change. In particular, a cursory review of the quality improvement literature will show that the Seven Statistical Tools are often suggested as a panacea for most of a firm's quality problems. Such a position would not remain tenable.

6. Future Work

We have repeatedly emphasized that in this paper we are reporting preliminary results from what is clearly an exploratory study. Much work remains to be done. In particular, we will build on the work reported here in two ways: by acquiring more data and by doing more - and different - types of statistical analysis. We will briefly discuss both in turn.

We are currently in the process of acquiring raw data on (i) about 50 more projects, most of which will be key projects and will relate to Bekaert's earlier quality improvement efforts; (ii) department, plant and product level quality indicators relating to internal failures, reliability and product attributes. In addition, we will rely on our experience of the PCA we have reported to refine our protocol. Such a refinement will enable us to generate additional data.

With regards to analysis, we expect to follow two related paths. First, we will use the tools we have used in this paper on the larger data sets. *Ex ante*, we expect such analysis to help us refine the variables and relationships we have discussed in this paper and rigorously explore the alternative explanations that we have advanced for our results. Second, we expect to use path analysis and related structural modelling tools to map out the process by which Bekaert implicitly created the knowledge which affected its quality levels. In particular, data on Bekaert's decade-long effort will also allow us to address questions like:

- Did the degree of reliance on the different components of knowledge change over time?
- Were the learning efforts cumulative or were the projects independent?
- Did the tools and training provided by Bekaert's managers affect the nature of projects undertaken?
- What was the role of production departments with different process characteristics in generating quality improvements?

Our efforts to address these questions will be the first important steps towards the goal (established in §2) of linking the knowledge which affected quality to the conditions and tools which produced the knowledge.

7. Concluding Remarks

In this paper, we did three things. First, we suggested the need to study the creation and use of quality related knowledge in order to avoid the confounding of issues of "quality culture" with issues of "quality tools." Second, we presented some preliminary results (from one firm) to the effect that: (i) it is possible to identify three robust characteristics of knowledge (Experience Knowledge, Formal Knowledge and Domain Knowledge) and an important control (Complexity); (ii) Experience Knowledge and Formal Knowledge are both very important for explaining project-level performance on quality; and (iii) as projects become less structured, the relative importance of Formal Knowledge increases. Third, we described how we are going to expand the scope of our work in the months to come.

When all is said and done, in the language of decision theory, what is the "Expected Value of Perfect Information (EVPI)?" In other words, what do we expect to get out of the research agenda we have laid out? We believe that our research, when complete, will contribute to the understanding of the sources of quality, not at the functional level that concerned Garvin (1987), but at the more fundamental level that we framed as the chicken-and-egg question in §2. To elucidate our position, we have to go back to the old saw about quality being free (Crosby, 1979).

The point that is often missed in the discussions about this belief is that while doing quality work might indeed seem free because a firm does not have to tie up its resources in rework and damage control, the process of getting to that point certainly is not. If anything, the cost to a firm of evolving from a state in which people pay lip service to quality to a state in which quality is the key element of each task is potentially enormous. Today, firms which wish to improve quality have no choice but to accept the conventional wisdom. They have to change their existing culture and they have to indoctrinate their people about a whole array of tools which might or might not be relevant to the business. The only alternative is a long drawn out process of trial-and-error (Goodman & Chew, 1990). They also have many difficult decisions to take. Should they first implement culture building policies like the abandoning of Management by Objectives and incentive payment schemes (Deming, 1990) and the creation of education programs (Wiggenhorn, 1990)? Alternatively, should they adopt SPC, Taguchi Methods and Design for Manufacturability? Within each set of alternatives, which should come first? How should conflicting objectives be resolved? The list of such questions is potentially long.

Our research will - hopefully - generate insights which can help practitioners and researchers alike to deal with such questions. If we are successful in identifying the knowledge based sources of quality, we will be able to offer firms normative advice on what works and under what conditions and, possibly, even on the impact of alternative implementation strategies. Given the stage of our work, success is not assured and certainly will not come easily. However, we believe that the potential value of this work justifies the commitment of our resources.

It is in this respect that questions about the generalizability of our work is particularly important. Clearly, unless we reproduce our research design in a few other industries, we cannot establish to everyone's satisfaction the applicability of our findings. Nevertheless, we can offer two reasons for being very sanguine about our work:

- While the products produced and the technologies used by Bekaert are specialized, the organization of technology is not. Production follows a batch process. If we rate Bekaert's factories against the idealized characteristics of the different types of production processes (Hayes & Wheelwright, 1984, Table 6-3), we would find lots in common with both pure batch processes and pure assembly line processes (Mukherjee, 1992).

- The tools and systems used for quality improvement at Bekaert are by and large those used by most quality-minded firms around the world. Moreover, while Bekaert came to adopt the TQC philosophy late by global standards, it was one of the first to do so in Europe and it probably has worked at it at least as long (if not longer) as most well-managed American firms. So, Bekaert is not a laggard in the area. Hence, the insights that we can obtain by studying its experiences can inform firms which are way behind in the quality race and can serve as a benchmark (or at least an important point of comparison) for the others.

We have repeatedly suggested that we are only scratching at the surface of research possibilities linking the management of knowledge to the management of quality. We hope that other researchers will come to mine this field with us.

References

Aaker, D.A. & G.S. Day, *Marketing Research*, Wiley, New York, 1990.

Adler, P.S., *When Knowledge is the Critical Resource, Knowledge Management is the Critical Task*, IEEE Transactions on Engineering Management, vol. 26, #2, May 1989.

Aldrich, J.H. & F.D. Nelson, *Linear Probability, Logit, and Probit Models*, Sage University Paper #45, Sage Publications, 1984.

Allen, J.F., *et. al.*, *SAS/STAT User's Guide, Version 6*, 4th ed., SAS Institute, Cary, NC, 1990.

Allen, T.J., *Studies of the Problem Solving Process in Engineering Design*, IEEE Transactions on Engineering Management, vol. EM-13, #2, June 1966.

Arrow, K.J., *The Economic Implications of Learning by Doing*, Review of Economic Studies, April, 1962.

Badaracco, J.L., *The Knowledge Link: How Firms Compete through Strategic Alliances*, Harvard Business School Press, Boston, 1991.

Bhote, K., *Motorola's Long March to the Malcolm Baldrige Award*, National Productivity Review, vol. 8, # 4, Autumn 1989.

Bohn, R., *Learning by Experimentation in Manufacturing*, Harvard Business School Working Paper 88-001, 1987.

Bohn, R. & R. Jaikumar, *The Dynamic Approach: An Alternative Paradigm for Operations Management*, Harvard Business School Working Paper 88-011, 1987.

Byrne, D.M. & S. Taguchi, *The Taguchi Approach to Parameter Design*, 40th Annual Quality Congress Transactions, American Society for Quality Control, Inc., Milwaukee, 1987.

Bolwijn, P.T., *et. al.*, *Flexible Manufacturing: Integrating Technological and Social Innovation*, Elsevier Publishing, Amsterdam, 1986.

Clark, K.B. & T. Fujimoto, *Product Development Performance: Strategy, Organization, and Management in the World Auto Industry*, Harvard Business School Press, 1991.

Crosby, P.B., *Quality is Free*, McGraw-Hill, New York, 1979.

Daft, R.L. & N.B. Macintosh, *A Tentative Exploration into the Amount Equivocality of Information Processing in Organizational Work Units*, Administrative Science Quarterly, vol. 25, 1981.

Deming, W.E., *Quality, Productivity, and Competitive Position*, MIT Center for Advanced Engineering Study, Cambridge, 1982.

Drucker, P.F., *The New Realities*, Mandarin, Great Britain, 1989.

Drucker, P.F., *The Emerging Theory of Manufacturing*, Harvard Business Review, May-June, 1990.

Dutton, J.M, *et. al., The History of Progress Functions as a Managerial Technology*, Business History Review, Summer 1984.

Eccles, R.G., *The Transfer Pricing Problem: A Theory for Practice*, Lexington Press, Lexington MA, 1985.

Gabriel, L.K. & M. Beer, *Westinghouse Commercial Nuclear Fuel Division*, Harvard Business School case 9-492-026, 1992.

Garvin, D.A., *Operating Strategy: Competing on Quality*, Harvard Business School case 5-688-044, 1987.

Gerwin, D., *Relationships Between Structure and Technology* in Handbook of Organizational Design, edited by Nystrom & Starbuck, Oxford University Press, New York, 1981.

Goodman, S.L. & W.B. Chew, *Design for Manufacturability at Midwest Industries*, Harvard Business School case 9-690-066, 1990.

Gupta, P., *et. al.*, *A Systematic Approach to SPC Implementation*, Quality Progress, April 1987.

Hall, R.W., *Zero Inventories*, Dow-Jones Irwin, Homewood, 1983.

Hauser, J.R. & D. Clausing, *The House of Quality*, Harvard Business Review, May-June, 1988.

Hayes, R. & R. Jaikumar, *Manufacturing's Crisis: New Technologies, Obsolete Organizations*, Harvard Business Review, September-October 1988.

Hayes, R. & S. Wheelwright, *Restoring Our Competitive Edge*, John Wiley & Sons, New York, NY, 1984.

Hedberg, B.L.T., *How Organizations Learn and Unlearn*, in Handbook of Organizational Design, edited by Nystrom & Starbuck, Oxford University Press, New York, 1981.

Imai, M., *Kaizen, the Key to Japan's Competitive Success*, Random House, New york, 1986.

Ishikawa, K. & D.J., Lu, *What is Total Quality Control?* Prentice-Hall, Englewood Cliffs, 1985.

Jackson, B.B., *Multivariate Data Analysis, An Introduction*, Irwin, Illinois, 1983.

Jaikumar, R. and R. Bohn, *A Dynamic Approach to Operations Management: An Alternative to Static Optimization*, International Journal of Production Economics, October 1992.

Jaikumar, R., *Intelligent Manufacturing Control*, in The Competitive Edge: Research Priorities for U.S. Manufacturing, National Research Council, National Academy Press, 1991.

Johnson, A.B., *et. al.*, *Xerox Corporation: Leadership Through Quality*, Harvard Business School case N9-490-008, 1989.

Johnston, J., *Econometric Methods*, 3rd Edition, McGraw-Hill Book Company, New York, NY, 1984.

Juran, J.M., & F.M. Gryna, *Quality Planning and Analysis*, 2nd. ed., McGraw-Hill, New York, 1980.

Kackar, R., *Off-Line Quality Control, Parameter Design, and the Taguchi Method*, Journal of Quality Technology, vol. 17, # 4, October 1985.

Kmenta, J., *Elements of Econometrics*, 2nd. ed., Macmillan, New York, 1986.

Lehmann, D.R., *Market Research and Analysis*, 2nd. ed., Irwin, Illinois, 1985.

March, A. & D.A. Garvin, *A Note on Quality: The Views of Deming, Juran, and Crosby*, Harvard Business School case 9-687-011, 1986.

March, J.G. & J.P. Olsen, *Ambiguity and Choice in Organizations*, Universitetsforlaget, Bergen, 1976.

Mason, R.O. & I.I.Mitroff, *Challenging Strategic Planning Assumptions*, Wiley, New York, 1981.

Mukherjee, A.S., *The Effective Management of Organizational Learning and Process Control in the Factory*, Unpublished Doctoral Dissertation, Harvard Business School, Boston, 1992.

Mukherjee, A.S. & R. Jaikumar, *Managing Organizational Learning: Problem Solving Modes Used on the Shop Floor*, INSEAD Working Paper 92/63/TM, 1992.

Noreen, E., *An Empirical Comparison of Probit and OLS Regression Hypothesis Tests*, Journal of Accounting Research, vol. 26, # 1, Spring 1988.

Sahal, D., *Patterns of Technological Change*, Addison-Wesley, Reading, 1981.

Schonberger, R., *Japanese Manufacturing Techniques: Nine Hidden Lessons in Simplicity*, The Free Press, New York, NY, 1982.

Scott-Morton, M.S., *The Corporation of the 1990s: Information Technology and Organizational Transformation*, Oxford University Press, New york, 1991.

Smith, G.F., *Towards a Heuristic Theory OF Problem Structuring,* Management Science, vol. 34, #12, December 1988.

Vollmann, T., *et. al., Manufacturing Planning and Control Systems,* 2nd Edition, Dow-Jones Irwin, Homewood, IL, 1988.

Wadsworth, H.M., *et. al., Modern Methods for Quality Control & Improvement,* Wiley, New York, 1986.

Walleigh, R., *Product Design for Low-Cost Manufacturing,* The Journal of Business Strategy, July-August, 1989.

Walton, M., *Deming Management Method,* Mandarin, London, 1986.

Wiggenhorn, W., *Motorola U: When Training Becomes an Education,* Harvard Business Review, July-August, 1990.

Whitney, D.E., *Manufacturing by Design,* Harvard Business Review, July-August 1988.

Wilkinson, L., *et. al., SYSTAT: Statistics, Version 5.2 (Systat Manual),* Evanstan, Illinois, 1992.

Appendix A: Summary of the Final Report of a Typical TQC Project

Project Name: Inversions 3x0.22 + 9x0.20 + 1 HT
When Executed: December 1988 until May 1989
Project Team: Supervisor, foreman, an engineer and 4 workers.

Symptom
Inversion means that one of the three 0.22 mm core filaments which should have been in the core of the cord had switched places with one of the 0.20 mm which should have been on the outside. In November 1988, 2.85% of the production was rejected because of inversions. The team set a goal of 0%. The problem was believed to have occurred because of a rapid introduction of the (new) cord. Normally, new cord were tested for long periods before being mass manufactured.

Cause
Data analysis showed that 78% of the inversions were caused by two 0.20 mm filaments which got entangled before entering the cabling die. Brainstorming produced an Ishikawa diagram which listed eleven main causes. The team voted to rank incorrect pay-off tension as the principal cause of the problem and the shape of the distribution piece as the second cause.

Remedy
The team proposed dealing with the pay-off tension by securing the pay-off tension more often and increasing the pay-off tension by 20%. It chose to recommend a new design for the distribution piece.

Action
Operators on machines KGLT 24 to 33 secured the pay-off tension every week. After five weeks, rejects were still at 2.79% (compared to 3.56% for the other machines). On machines KGLT 29 to 46, the team increased the pay-off tension for the 0.22 mm filaments by 20%. Reject rates averaged 3.69%, compared with 3.56% for the other machines. The team abandoned all actions related to pay-off tension.

A test on a single machine equipped with the new distribution piece yielded 0% rejects. When 18 machines were modified, 0.06% rejects occurred against 1.25% on the other machines. Finally implementation on all 39 machines resulted in 0% rejects for three consecutive months.

In October 1992 there were 0.38% rejects due to inversion.

Appendix B: The Protocol

Part A: Execution of a Project

A1. Degree of change in goals during the project
A2. Degree of change in attention during the project
A3. Degree of change in search procedure during the project
A4. Degree of objectivity in problem solving process
A5. Degree of explicitness of relation between hypothesized problems and proposed solutions
A6. Degree of association between the project environment and mass-manufacturing
A7. Degree of involvement of other production departments in implementing results
A8. Degree of follow-up of test results
A9. Degree of follow-up of implemented results
A10. Scope of impact of project output

Part B: Impact of a Project[11]

B1. Degree of modification of an association
B2. Degree of confidence in the final association
B3. Depth of understanding of this association
B4. Degree of modification of primary action variables
B5. Degree of confidence in the final values of the primary action variables
B6. Depth of understanding of these primary action variables
B7. Degree of modification of higher order variables
B8. Degree of confidence in the final values of the higher order variables
B9. *Depth of understanding of higher order variables
B10. *Degree of modification of environmental variables
B11. *Degree of confidence in the final values of environmental variables
B12. *Depth of understanding of these environmental variables
B13. *Degree of change in goals as a result of the project
B14. Degree of change in attention as a result of the project
B15. *Degree of change in search procedure as a result of the project
B16. Degree of importance ascribed to communicating project results to customer/supplier department
B17. *Degree of importance ascribed to communicating project results to other departments
B18. Degree of formality of results
B19. Number of distinct elements in the proposed solution
B20. Number of links among the elements in the proposed solution
B21. Ability to specify impact of variability of known causal variables
B22. Degree of identifiable scientific knowledge in the project

Part C: Performance Measures

C1. Degree of achievement of stated goal
C2. Ability of output to consistently change the level of contingencies on an ex ante basis

---

[11] Questions marked with asterisks were dropped due to low variability of responses across projects.

Appendix C: Format for the Final Reports of TQC Projects