"PARADIGMS OF PROCESS CONTROL"

by

A.S. MUKHERJEE*
and
R. JAIKUMAR**

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

** Professor at, Harvard Business School.

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Amit Shankar Mukherjee, INSEAD
Ramchandran Jaikumar, Harvard Business School

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1. *Introduction*

In recent years, the importance of statistical process control (SPC) for assuring the efficient use of a factory's resources and the quality of its output has been accepted without dispute. Virtually all the academic and managerial literature endorses its use and its absence is routinely taken to imply ineffective managerial practices. Interestingly, however, today, most discussions of the benefits of SPC are couched within discussions of Total Quality Control (TQC) and its attendant elements of cultural change, communication with employees and the like.

In this paper, we adopt a similar broad perspective and focus on the concept of process control *per se* - the science, technology and art of ensuring that a production system produces the desired output. We suggest that conventional implementation of SPC programs implicitly embody an internally consistent set of goals, tools and procedures which we call the Six Sigma paradigm and propose an alternative package of internally consistent goals, skills, tools and procedures for process control, which we call the Production Theory paradigm. The process control paradigm chosen by a plant influences the nature of the knowledge and information that it possesses/seeks, the infrastructural systems it creates, the skills that its personnel need, the goals for quality improvement and the distribution of manufacturing tasks.

The importance of the Production Theory paradigm stems from our empirical observation that the assumptions and implications of the Six Sigma paradigm make it inappropriate for manufacturing environments in which cause-effect relations are not firmly rooted in science/engineering knowledge. Such environments appear, for example, when technologies are new or very high levels of control are required. We analyze a matched pair of process control projects conducted by one firm to show that in such environments, the Production Theory paradigm can be substantially more effective for improving quality and productivity (13 other projects which support our conclusions are discussed in Mukherjee, 1992). However, we wish to emphasize that we do not intend to disparage the Six Sigma paradigm, but to explicitly discuss its assumptions and implications and define its domain of applicability.

The rest of the paper is organized as follows. In § 2, we introduce the two paradigms. In § 3, we describe the setting in which we developed of the Production Theory paradigm. In § 4, we use our field research data to define the differences between the two paradigms; the collective magnitude of the differences is so large enough to justify our use of the term 'paradigm.' In § 5, we discuss the generalization of our findings and the scope for future research.

2. *The Paradigms of Process Control*

In most firms, applications of the Six Sigma paradigm are rooted in attempts to institutionalize pervasive respect for quality. To this end, firms adopt policies/tools which presumably improve quality (Juran & Gyrna, 1980; Deming, 1982; Schonberger, 1982; Ishikawa & Lu, 1985).

In factories, ambitious goals are set for conformance quality; a widely adopted target is "six sigma capability," which seeks to reduce defect rates at *every production stage* to 3.4 per million. Such goals ensure that each stage treats the subsequent one as an 'internal customer.' To achieve them, managers must first identify and correct plant-wide problems. They organize 'breakthrough projects' which are guided by multi-function, multi-department steering committees. Specialist engineers oversee 'process characterization,' (i) decomposing processes in their jurisdictions into elemental tasks; (ii) selecting (on the basis of existing expertise) key variables; (iii) performing controlled experiments to determine optimal settings for these variables; and (iv) imposing SPC control on them. Subsequently, line operators, typically members of quality control circles (QCC), rectify out-of-control situations *in local work areas*. Their effectiveness may be enhanced by the use of the so-called Seven Statistical Tools: Ishikawa diagrams, Pareto analyses, flow charts, scatter diagrams, histograms, check-sheets and control charts. Powerful cross-functional steering committees coordinate actions across departments (Juran & Gyrna, 1980; Deming, 1982; Hall, 1983; Ishikawa & Lu, 1985; Imai, 1986; Gupta, *et al.*, 1987).

Firms at the cutting edge of the quality revolution also improve product design. To do so, they require detailed knowledge of product attributes, cause-and-effect relations which govern their products and processes and sources of noise which impair performance. Such knowledge is essential for applying highly recommended design quality improvement tools like Quality Function Deployment (QFD) and the Taguchi method (Kackar, 1985; Hauser & Clausing, 1988).

A hitherto unanswered question is whether the Six Sigma Paradigm is appropriate for production environments which are "dynamic" (Jaikumar & Bohn, 1992). Some plants often deal with new or poorly understood technologies, incompletely specified or imprecisely executed procedures, environmental disruptions and conflicting goals. Such conditions create environments characterized by ambiguity, uncertainty and complexity in which *contingencies* - unexpected events which disrupt production - occur routinely. These plants are not necessarily poorly managed. Their "dynamic" environment is often attributable to the lack of basic scientific or engineering knowledge or tools or the inability of R&D to provide detailed understanding of product or process technology (Sahal, 1981; Abernathy, Clark & Kantrow, 1983; Jaikumar, 1991).

Many contingencies are idiosyncratic, i.e., their occurrence is inextricably intertwined with their environment. They can only be studied *in situ* in the factory. Attempts to transfer them from their normal environment fail because their unknown and ill-understood causes do not survive passage to new settings (Sahal, 1981, discusses the related problem of scaling-up technology). Process control in such environments requires the simultaneous *creation* of new knowledge (about products, processes and contingencies) *and its incorporation* into control strategies. This *Production Theory paradigm* requires plant personnel to identify the inter-locking set of product, process and environmental variables which govern their product-process system. With help from R&D, they have to link product attributes at different process stages; product attributes and process parameters; and process parameters at the different stages, so that they can:

- Decide which variables to control. If variation did not adversely affect the productive unit or learning efforts, they could choose not to *actively* control it.

- Understand the potential impact of the variables which were *not* under control. This knowledge could not only help them identify strategies for tackling these variables, but in the intervening period, could also suggest how their effect could be counteracted.

- Determine economically optimal control strategies. Rather than focus on key, but expensive to control attributes, plant personnel could seek to change the levels of other related variables.

Key elements of the two paradigms are summarized in Table 1. In subsequent sections, we define the Production Theory paradigm in greater detail, discussing issues like necessary systems and tools. As an aside, note that the paradigms present alternative packages of knowledge for supporting TQC. This is because products are embodiments of information (Allen, 1977). Since TQC creates organizational conditions which enable the delivery of high quality products, it implicitly manages the quality of organizational knowledge.

Table 1 About Here

3. *Source of Empirical Data*

In mid-1988, we began studying how organizations learn to improve their understanding of process control. Since this was a question of procedural rationality, we adopted the case research methodology (Bonoma, 1985). Our subject necessitated our acquiring deep knowledge about the host firms' technology, organizational structure and information systems. So, the problem of assuring the confidentiality of proprietary information loomed large and we limited our study to one firm, N.V. Bekaert, S.A., with which one of us had an on-going advisory relationship.

Three of Bekaert's European factories, which primarily produced tire cord (i.e., wire used to make steel belted radial tires), participated in the study. Over a period of 2.5 years, we investigated the execution of 15 process engineering projects. We collected archival data and conducted over 200 hours of formal, semi-structured interviews with managers, engineers and technicians who had worked on them. We also accumulated 2000 hours of additional contact with company officials.

In this paper, we will only discuss two projects undertaken by one plant, Aalter. These projects dealt with similar problems at roughly the same point in time. Thus, they were undertaken under identical general management policies, used virtually identical raw materials, produced virtually identical products and served the same market (often the same customer). Consequently, it is relatively simple to make the claim that the one area of substantive difference between them was the philosophies of process control that they adopted. We emphasize, however, that the other projects in our database shared the characteristics we report here. Eight conformed to the Six Sigma paradigm, 5 to the Production Theory paradigm and 2 adopted both paradigms at different points in time (see Mukherjee, 1992 for details).

3.1 Production Process: Steel mills supply Aalter huge coils of thick steel wire (called 'rod') which had been created during one heating of a furnace. These coils have uniform, but not identical, properties. Aalter *pickles* the rod, i.e., dips them successively in acid and borax baths and dries them in ovens. The acid cleans the rod and the borax facilitates lubrication during the next stage.

Plant personnel load the coils on *dry drawing* machines. A coating of dry soap smoothens the passage of the rod through a set of dies (Figure 1). Next, in a process called *patenting*, the spools of wire are chemically treated and heat treated to improve attributes like ductility. A second stage of *dry drawing* reduces the diameter of the wire to 1.7 mm. At both drawing stages, the shape of die and the quality of lubrication determine the shape of the wire, critical physical properties and some types of wire fractures. Hence, plant personnel closely monitor the number of dies which wear out during the production of one metric ton of wire. The quality of lubrication significantly affects this measure, called *drawability*.

Figure 1 About Here

Many spools are then treated with chemicals and heat side-by-side on *'ISC' lines*. This process imparts strength, ductility, luster and a thin brass coating to the wire. Despite the use of advanced controls, even wires which are treated simultaneously do not have identical properties.

The wires are next drawn on *wet wire drawing (WWD)* machines. They pass through series of dies immersed in a soap solution and are progressively reduced to diameters less than 0.5 mm. The soap solution comes from two or three 'soap circuits' possessed by each plant. Each circuit has two swimming pool-sized soap pits. Several kilometers of outlet pipes from the pits lead to pumps which control the flow of soap, heat exchangers which control temperature and between 50 and 150 WWD machines. Outflow pipes from the machines lead back to the soap pits. The condition of the soap has long been believed to be important for assuring good drawability.

Next, *bunching* machines twist two or more filaments about each other and create tire cord. Many types of cord can be created by changing the diameters and properties of the filaments and the number of filaments combined. Some of these types are *spiral wrapped* for added strength. About 5% of all cord also have to be *rewound* from one spool to another when the original spool shows repairable defects. Finally, samples of the cord are tested prior to packing and shipping.

A process flow diagram appears in Figure 2. The variation in the number of machines used at the different production stages adds to the complexity of the plant. This fact, coupled with the presence of the soap circuits, precludes the adoption of conventional cellular manufacturing.

Figure 2 About Here

In the 1980s, the management of the soap circuits received considerable attention. Bekaert personnel subscribed to the industry-wide belief that 'soap steering' affected key process parameters (like drawability) and product properties. The state of a soap circuit at any point in time was specified by its 'fatty acid' concentration, temperature, pH value, composition of the 'ether soluble phase', phosphate ion concentration and the levels of several other ions and chemicals. Target values and control limits for these parameters differed for every soap circuit; tire manufacturers specified some and the plants set the others at levels at which, in the past, they experienced good drawability. The key technical problem was that with use, the chemical composition of the soap changed (in part because the wire deposits zinc, copper and iron ions). Unfortunately, no one understood this process of 'aging' very well. Thus, achieving the targets for, say, phosphate ions, did not necessarily assure good drawability and in fact, settings which gave good drawability on one occasion could give poor drawability on another. To deal with this problem, every plant employed a chemist as a 'soap specialist.' This person's ability to interpret data on soap was critical for making decisions like the amount of fresh soap (and other chemicals) to add and the amount of old soap to remove.

3.2 Plant Organizational Structure and the Flow of Technical Information Aalter, one of Bekaert's largest plants, had a traditional functional structure, with two minor exceptions: both dry drawing stages, pickling and patenting formed one meta-department - Half Products - and bunching and spiral winding formed another (Figure 3). All the production departments reported to a production manager who, in turn, reported to the plant manager. The department managers were supported by supervisors who, in turn, relied upon foremen to actually oversee production. In addition, the plant had a Technical department, which reported directly to the plant manager and had plant-wide responsibilities for Quality Assurance, SPC and improvement projects. Support departments included production planning, maintenance and electronic data processing (EDP); the last named collected and processed production and accounting data.

Figure 3 About Here

Aalter personnel routinely collected two types of process control data. First, at the end of the first dry drawing stage (when spools were first created), they attached to each spool a paper tag which accumulated basic information about its subsequent processing. Second, they collected SPC data at all production stages. Both types of data were processed overnight into departmental performance reports which included statistics such as fractures per ton of wire produced, scrap rates, C_{PK} values (Kane, 1986), volume of production and machine utilization. In all, the reports covered about 50 product properties and over 200 process parameters and performance measures.

Knowledge workers and machine operators used different aspects of these information. The SPC data were regularly fed back to operators. Each department displayed on large boards comparative data on goals and current and past performance on parameters for which it was responsible. First-line managers also used SPC data to identify operators who needed additional training. Knowledge workers received daily reports about events that occurred in their departments the prior day. They also received monthly plant-wide summaries of these data, as well as data about individual machines and products, standard costs and variances, Pareto analyses of major defects, inventory levels and sales, targets and average performance levels for prior periods and for other Bekaert plants. These 'Activity Reports' presented information in numerical and graphical forms. Typical structures of data on three departments are given in Figure 4.

Figure 4 About Here

3.3 The Six Sigma Paradigm at Bekaert: Aalter's Soap Steering & Drawability Project Aalter adopted a Six Sigma paradigm based SPC policy in 1981. Plant managers created an environment in which SPC/TQC would flourish, investing resources and managerial time in training, emphasizing the importance of internal customers, upgrading communications with workers, forming SPC

training cells, appointing TQC facilitators and improving information systems. Functional areas also characterized their processes and defined standard operating procedures (SOP).

However, SPC for soap steering was adopted late in the decade. Maurice, a chemist who had managed the chemical baths of ISC, became the soap specialist in 1987. Like his counterparts at other plants, he created flow-charts which codified his beliefs and specified appropriate actions for different conditions in the soap circuits (the charts did not refer to a key parameter - fatty acid concentration - since Aalter lacked a gas chromatograph necessary for its analysis). Once a week, he studied the drawability levels in WWD, the quantity of filament that WWD had produced and the expected production level for the upcoming week. He used four "correction factors" specified by R&D to ensure that the soap was neither too fresh nor too old. During periods of good drawability, he disliked taking any action for fear of affecting drawability adversely. At these times, he relied on input from his boss Nöel who, since 1981, had been the manager of the WWD department.

In March 1989, when Aalter experienced a period of poor drawability, plant management decided to introduce SPC-based soap steering. A team - consisting of Maurice, Nöel, André (SPC/TQC manager) and a Technical department engineer - tackled the task in a fashion similar to that described in § 2. It adopted a C_{PK} of 1.33 as an initial target. Since Aalter had just obtained a gas chromatograph, it created a new flow chart which incorporated this parameter. It chose targets and control limits based on the plant's recent experience of a 30 week stretch of good drawability. Finally, it developed control charts, checklists for data collection and a system for follow-up and monitoring. It did not analyze any wire-related variables, believing that (i) obtaining the necessary data from ISC would be difficult and (ii) by stabilizing the soap, SPC would improve drawability.

Over time, in response to new information from R&D activities, the project team changed its SPC-based policy several times. For example, at an R&D organized inter-plant conference late in 1989, Maurice learnt about a strikingly simple flow chart being used with great effectiveness at another plant. So, he eliminated several steps from the Aalter flow-chart. In May 1990, in response to criticism from an R&D soap expert that Aalter's daily steering actions did not allow the soap circuits to reach chemical equilibria, the project team modified the steering procedure.

Nevertheless, process characterization helped Maurice and André rectify significant operating problems. In December 1989, Pareto analyses of data collected enabled them to identify major deficiencies in the soap circuit pumps and led to the modification of the plant's preventive maintenance policies. During 1990, seeming inaccuracies in the fatty acid analyses led to R&D assisted changes in the analytical procedures for the gas chromatograph. Late in 1990, they tightened control over the maintenance and operation of the heat exchangers in the soap circuits.

Despite these efforts, the overall operation of soap circuits did not improve significantly during the twenty-one months for which we have data. Variability was hard to reduce and accuracy was hard to achieve except on the circuit (G3) equipped with the most sophisticated controls. However, the plant - through Maurice - learnt a lot about soap and improved the C_{PK} for some parameters. In December 1990, Maurice believed that given the types of controls he had on G3, he could achieve any reasonable C_{PK} value for any soap parameter - if he did not have to worry about production! However, neither he nor André were sanguine about their ability to use SPC to steer soap well. In fact, André believed that the theory and practice of soap steering were a long way apart. He had begun to doubt the utility of applying SPC in an area where the plant lacked fundamental knowledge.

3.4 The Production Theory Paradigm at Bekaert: The MLA Drawability Project In May 1988, Bekaert set up at Aalter an integrated line dedicated to the application of what we call the Production Theory paradigm. It named the line Model Line/Aalter (MLA) and appointed a senior R&D engineer, Paul, as its manager. Paul came from a highly functional unit - characteristic of firms which compete on the basis of product performance (Wheelwright & Clark, 1992), but had

atypically accumulated cross-functional experience. He was told to improve Bekaert's knowledge of its products and processes without sacrificing the production of saleable cord.

Bekaert formed the MLA very simply. First, Aalter nominally transferred operational control over specific equipment machines to Paul, allowing him to make decisions on issues ranging from rod supplies to preventive maintenance. Consequently, the operators who worked these machines now had to report to both their functional supervisors and the MLA engineers. Second, Bekaert gave the MLA adequate engineering resources - another engineer, two technicians, a few personal computers, a budget for experimentation, sensors and automatic data capture equipment and priority access to the laboratories which analyzed product and process samples. Third, in two stages (mid-88 and early 1990), Aalter transferred responsibility for the manufacture of a simple, but increasingly important, tire cord to the MLA.

Paul modified material flow patterns and data collection practices on the MLA, enabling it to routinely collect and process a vast and ever increasing base of process control related data, including about 500 process parameters and environmental variables. Data were collected through sensors, laboratory analyses and operator inputs. Daily audits of the MLA provided inputs on 'unusual events' normally ignored by the formal information system.

All the data were stored in the raw form. Thus, for each production batch, regardless of the date of manufacture, each element of data could be correlated with every other element. Besides, the monthly Activity Reports not only presented information similar to that reported by Aalter, but also what the MLA personnel knew (or did not know) about the data and what experiments they had planned or performed. Finally, the data and the experiments were discussed with Aalter personnel, visitors from other plants and R&D scientists during monthly 'State-of-the-Art' meetings.

In early 1990, the MLA attempted to improve WWD drawability by an order-of-magnitude. Paul initiated the effort, pulling together fragmentary knowledge created by unrelated experiments conducted over the prior 15 years by different R&D units. For example, an experiment with a soap similar to that used at Aalter had produced excellent drawability if the wire were drawn at low speed. Another experiment had shown that increased agitation of the soap reduced drawability. From these, Paul concluded that the duration of contact between the wire and the soap facilitated drawing and agitation impeded the formation of chemical compounds which were crucial for high drawability. He combined these hypotheses into a formal chemical model in which soap affected drawability only because its constituent chemicals reacted with the metals of the wire being drawn.

To this core, the MLA personnel added several factors (the geometry and heat transfer properties of dies; roughness of the wire and the quality of its heat treatment; the breaking load of the filaments produced; and the rod supplier) unrelated to soap or wire. Prior production experience and simple regressions on natural data had pointed to the relevance of these variables. The power of this expanded model lay in its seeming ability to explain why the soap specialists felt the need to monitor temperature, fatty acids and pH.

In March 1990, the MLA personnel designed a simple experiment to test the effects of temperature and the duration of the contact between soap and wire. They split 18.5 tons of ISC wire into two batches, dipped one in a tank of warmed soap solution and under essentially identical conditions, processed both batches on WWD machines. The pre-dipped wire showed a 73% improvement in drawability and a 65% decline in fractures. Buoyed by these results, they obtained a capital budget to conduct a larger scale test. During a scheduled preventive maintenance in May, they modified an ISC installation to include a pre-dip system. After one false start and subsequent re-engineering of the system, by September, they established the efficacy of the pre-dip.

In May, 1990, the MLA personnel validated their model with natural experiments based on data from 240 batches of cord. They then investigated the effects of various combinations of the soap, wire and die parameters on drawability. These experiments generated grossly contradictory

results and stimulated heated discussion at the State-of-the-Art meetings. However, after four months of concerted effort, the MLA personnel concluded that *none of the soap parameters had any statistically discernable effect on drawability,* but several ISC and dry drawing related factors - wire roughness, composition of the brass coating and filament breaking load - did.

Since soap steering did not affect drawability, the MLA personnel decided to make the steering process as simple as possible. In June 1990, they convinced Maurice to (i) limit intervention in the G3 circuit (which supplied the MLA) to once every three weeks and (ii) spread the steering actions over several days. During the first several weeks of trials, the new policy failed to stabilize the soap. Late in the year, the MLA personnel reviewed every step of the steering procedure and attributed the problem to the manner in which soap samples were being collected and the manner in which soap was transferred across the two pits in a circuit. In consultation with Maurice and André, they developed new operating procedures for these tasks.

Our formal data collection about the MLA effort came to an end in December 1990. At that time, most people seemed satisfied with the progress made, though no one could guarantee the long term success of the new policy. Through our subsequent contact with Bekaert executives, we found that (i) the MLA did sustain the sharply improved drawability performance and continued its efforts to understand and control the wire-soap interactions and (ii) Aalter adopted most of its counsel.

4. *Comparison of the Process Control Paradigms*

The Aalter and MLA projects suggest that both the Production Theory and the Six Sigma paradigms possess cohesive, inter-locking sets of characteristics which distinguish them from each other.

4.1 Reductionism Versus Holism *Reductionism* is the belief that "... a whole can be understood completely if you understand its parts, and the nature of their 'sum'" and *holism* assumes that "... the whole is greater than the sum of its parts" (Hofstadter, 1981, pp. 162). The Six Sigma paradigm is anchored on the former and the Production Theory paradigm, on the latter. This difference in perspectives lies at the root of all the differences between the two paradigms.

The Six Sigma paradigm makes the strong assumption that a firm can disaggregate the making of its products into relatively (if not completely) self-contained task units. This Tayloristic assumption itself relies on the belief that the firm's knowledge of its production task is relatively complete in the sense that all major tasks that have to be performed are known. There is no uncertainty or ambiguity about the means for producing good output; uncertainty only shrouds the optimum performance levels for the tasks. Thus, the planning of product/process control can be decoupled from the execution of control and improvement. The key managerial tasks are decomposing the process and ensuring that efforts to reduce uncertainty are undertaken.

In product development, the assumptions of complete knowledge/reductionism are embodied in tools like the Taguchi method and QFD. For example, the former requires knowledge of key sources of noise, the range of their intensity and the nature of their interaction with product and process attributes. Without such knowledge, parameter design experiments could not be conducted. We believe that this is probably a key reason why a field study of US firms employing QFD indicated that the method offered most benefits for simple products and incremental changes (Griffin, 1992).

In manufacturing, decomposition is effected during process characterization, when plant personnel identify tasks which might benefit from increasingly tighter control. Subsequently, they focus on reducing the variability (i.e., uncertainty) of known product attributes and process measures. The Seven Statistical Tools (Imai, 1986) are very well suited for this purpose: six of the tools provide the means for decomposing any problem into its constituent elements, while the seventh - control charts - provides the means for separately controlling each of the critical constituent elements.

The Production Theory paradigm embodies the holistic perspective. It assumes that in dynamic environments, poorly understood interactions among incompletely defined elemental tasks could impede decomposition of the product-process system. Knowledge workers must analyze the "nature of the 'sum'" and simultaneously, control its better understood elements. This effort would require the tracking and analyzing of a multitude of variables which could potentially affect a product-process unit. Thus, much of the analysis/control effort would have to be undertaken in the plant, where *natural and controlled experiments* would be the most important analytical tools.

The project team which imposed SPC on soap steering in the Aalter project followed this decompose-and-control strategy of the Six Sigma paradigm. It attributed the uncontrollable variability in drawability to the instability of the soap parameters. It imposed tight statistical control over soap parameters and created a system for monitoring, controlling and reacting to a wide range of possible contingencies. Subsequently, it reacted to problems - which it detected through the use of checklists and Pareto analyses - by imposing tighter control on the performance of key sub-systems like pumps, heat exchangers and the gas chromatograph. In contrast, by incorporating variables from dry drawing, ISC, WWD and soap steering and explicitly modelling the interactions among variables at different stages, the MLA team adopted a holistic approach. Its results indicated that each action of the Aalter team was a misplaced act of faith in the decomposability of soap from all other variables which could affect drawability.

4.2 Organizational Structure Under the Six Sigma paradigm, subsequent to decomposition, control over the constituent elements of a production system may be functionally decentralized. At the limit, one controller (a department, a machine, a computer or a person) can be made exclusively responsible for one element of a complex production task. In contrast, process control under the Production Theory paradigm cannot be decentralized. The task of determining the "nature of the 'sum'" in an ambiguous, complex and uncertain factory environment typically involves variables which have to be observed, measured and controlled at different stages of production. This poses a significant problem in conventional (i.e., not computed integrated) factories since people can only deal effectively with moderate amounts of integrative complexity (Streufert & Swezey, 1986). Hence, factories must create organizational structures which:

1. Eliminate sources of contingencies irrelevant for studying the "nature of the 'sum'" and thereby facilitate hypotheses formation and testing;

2. Facilitate product traceability (Juran & Gyrna, 1980) and give plant personnel *ready* access to data they need to study contingencies and the "nature of the 'sum.'" The importance of ready access is rooted in Allen's (1977) finding that R&D scientists do not acquire information they need if it is difficult to do so. It would be reasonable to expect similar behavior on the part of plant personnel, who have much shorter time horizons (Lawrence & Lorsch, 1967);

3. Set performance targets at product/plant levels in order to reduce the probability that conflicting departmental objectives will engender sub-optimal process control decisions;

4. Reduce the time needed to get useful information from experiments, since this ensures that more learning projects can be undertaken per unit time;

5. Ensure that learning/experimentation efforts are relevant to the needs of the factory; and

6. Ensure that the knowledge generated is applicable to a range of products.

Consistent with the needs of the Six Sigma paradigm, Aalter was structured into functional departments which managed sets of tasks which were believed to logically related. This assertion holds true even for the Half Products and the bunching/sprial winding departments. The former grouped dry drawing with two preparatory steps, while the latter linked related technologies.

Consistent with the needs of the Production Theory paradigm, Bekaert gave the MLA (i) a unified management structure which held one person responsible for both learning and production; (ii) a single important *and* representative product; (iii) every production stage necessary for making that product; (iv) at every manufacturing stage, the capability to track and correlate a wide range of product, process and environmental variables; and (v) access to excellent data processing, analytical and testing capabilities. Characteristic (i) supported goals (3) and (5); characteristic (ii), goals (1), (2) and (6); characteristics (iii) and (iv), goals (2) and (3); and characteristic (v), goal (4) and the ease of effort element of goal (2).

While it is conceivable that plants in other industries might create other organizational structures to achieve the goals listed above, we believe that the MLA, which we call a 'Learning Cell,' is a good model for implementing the Production Theory paradigm in conventional factories. (Shirley & Jaikumar, 1988, discuss related ideas about computer integrated manufacturing - CIM - plants.)

4.3 Contingency Recognition, Data Acquisition and Processing By requiring each production stage to treat the next one as its customer, the Six Sigma paradigm makes the strong assumption that *each stage (or its customer) can observe the contingencies it creates.* If this assumption is not met, no production stage can determine or correct the quality of its output. Hence, the literature on quality emphasizes the importance of "easy to see quality" (Schonberger, 1982; Hall, 1983).

An important corollary is that each stage does not require detailed information about its supplier or customer stages. All it needs are clear definitions of the inputs it will receive and the outputs it must produce. To these data, it must itself add detailed, specialized, local data on the product attributes, process parameters and contingencies it needs to control. Availability of summary performance statistics on other stages allow departmental personnel to keep abreast of key events.

A plant's information system (IS) can meet these needs since most production stages use the same tools for analysis and control (e.g., Pareto analysis and control charts). So, it can (i) process the data uniformly; (ii) reduce the amount of data it must store; (iii) provide feedback quickly; and (iv) reduce the amount of information that plant personnel have to review.

The Production Theory paradigm considers the "treat the next step as a customer" a desirable but not necessarily tenable ideal. It assumes that the lack of knowledge of all relevant variables means that data/information needs will routinely cross the boundaries of production stages. This implies that the IS system must routinely support the creation or acquisition of *new and different data* which could conceivably bring to light hitherto unknown facets of the process control problem. So, the IS must be flexible with regard to what data is acquired, in what form and how it is processed.

Consistent with these descriptions, Aalter's routine reports presented aggregated data and its project team collected and analyzed detailed, local and specialized data. Despite Maurice's (the soap specialist) background in ISC, the team could not obtain data from that department. In contrast, from the beginning, the MLA personnel routinely maintained raw, cross-functional and integrated product-process data on a very wide range of variables. During their drawability project, they had ready access to this database, which was fundamentally different from that readily available through the Aalter IS. Hence, they could readily test their model/hypotheses about the interaction of soap and wire variables.

4.4 Work Teams and the Scope of Problem Solving: The Six Sigma paradigm requires specialist engineers to conduct process characterization exercises and define the performance goals at each production stage. While doing so, they keep in mind the input/output specifications which link each department to its supplier and customer departments. Subsequently, departmental QCC correct the failures of their processes to meet output specifications. Cross-functional coordination is usually achieved through hierarchies of QCC or more commonly, steering committees (Juran & Gyrna, 1980; Schonberger, 1982; Hall, 1983; Ishikawa & Lu, 1985; Shea, 1986; Gupta, *et al.*, 1987).

The Production Theory paradigm relies on generalist engineers who have thorough knowledge of the overall process control task, but possibly lack deep, specialized knowledge about individual production stages. These process engineers head cross-functional problem solving teams which create and establish control policies after investigating their potential system-wide implications.

Since Bekaert formally introduced QCC in 1989, our evidence about the Six Sigma paradigm comes from the experience of quality leaders like Motorola (Gupta, *et al.*, 1987). However, the Aalter project did highlight the importance of the specialist: Without Maurice's knowledge, the project would have fallen apart at the process characterization stage. Subsequently, he and his team of operators also solved all soap-circuit related problems. In contrast, the manager of MLA, Paul, served as a process engineer in charge of the entire line. During the course of the Drawability project, he provided day-to-day technical leadership to his cross-functional group of engineers and technicians. (Mukherjee, 1992, presents evidence that other engineers associated with the MLA were expected to build similar cross-functional skills.)

4.5 The Distribution of Tasks in Plants In any plant, departmental personnel have two related tasks. First, they must create products and in order to do so, they must manage *process control* related activities. Second, they must sequence production and manage the flow of materials through their areas. We call this set of tasks '*production control*.' The two paradigms distribute these tasks differently and thus, pose different challenges of coordinating work.

The reductionist perspective of the Six Sigma paradigm ensures that the process control knowledge it creates needs to be possessed *first hand* only by the people who created it. These people can ensure that there is minimal conflict between the process control and the production control tasks executed within their functional areas. In other words, the two sets of tasks are well aligned. Plant managers have to oversee a system which is best represented as a *tree*.

The holistic perspective of the Production Theory paradigm is capable of creating knowledge which must be distributed to and acted on by personnel in many departments. Process parameters critical for the effective functioning of any production stage might be controlled by the personnel at other stages. Thus, even in ideal conditions, the degree of alignment between process and production control tasks executed in any department might be low. Thus, plant managers have to oversee a system which is best represented as a *network*. The degree of difficulty experienced in managing such a network might rise exponentially with an increase in the number of nodes.

Figure 5 describes the situation fostered by the two paradigms at Bekaert. The dotted lines mark the information flows associated with the Aalter project. The soap specialist interacts with SPC, the production section of WWD, maintenance and the planning departments. SPC helps establish controls and procedures, maintenance looks after the soap circuits, WWD provides input on drawability and planning provides estimates of actual and expected production levels. Only the soap specialist possesses fundamental knowledge of soap steering. He acquires information from the others and processes and acts on these.

Figure 5 About Here

The MLA project fostered information flows indicated by the dashed and the dotted lines in Figure 5. Dry drawing and the Technical department had to discuss process changes; SPC, ISC and WWD had to develop controls for soap pre-dip, heat treatment and brass coating; and Half Products and Quality Assurance had to monitor rod quality. While our research did not formally document these flows, our on-going contact with Bekaert managers indicates that the need to achieve such coordinated action among these players required significant effort, particularly as the results of this and other projects were diffused throughout Aalter.

4.6 Goals of Process Improvement Within the factory, the Six Sigma paradigm seeks to improve conformance quality. This implies that *the Six Sigma paradigm accepts the design quality as the*

ceiling for the level of quality achievable in the factory. This assumption directs process control efforts at minimizing problems that prevent the firm from delivering the product as envisioned by R&D. Thus, interactions between R&D and plants are dominated by the former. R&D decides what must be done, while the plants turn to it for help in dealing with producibility concerns and problems which fall beyond their competence.

Since it recognizes the idiosyncratic nature of contingencies, the Production Theory paradigm assumes that plants have to deal with situations which are not even apparent in the controlled environment of development laboratories (Sahal, 1981; Bohn, 1987). Thus, plants can create knowledge about issues which are not apparent to development engineers. This implies that design quality cannot define a performance ceiling. As such, R&D and plant personnel must interact with each other routinely, jointly defining improvement goals, generating and testing hypotheses and developing more effective process control strategies.

In the Aalter project, R&D directed the plants' management of soap circuits (e.g., by suggesting 'correction factors' and modifying analytical procedures). These inputs were largely based on theoretical analyses and laboratory-scale experiments. They were undoubtedly influenced by, but did not formally incorporate, production experience, since the plants lacked information systems which could provide necessary data. Had these infrastructural impediments not existed, R&D and the plants could have jointly improved soap steering if - and only if - R&D personnel actually acknowledged that plant personnel could contribute fundamental insights. In many firms, this key step might be a difficult cultural barrier.

In contrast, the manager of the MLA, Paul, was an ex-R&D engineer. He created an infrastructural systems which supported formal tests of hypotheses and organized monthly State-of-the-Art meetings which attracted scientists from R&D (and others). At the project level, by testing and applying knowledge created by R&D under conditions of full-scale manufacturing, the MLA avoided the problems associated with scaling-up experiments. Moreover, it formally incorporated into the project insights garnered from full-scale manufacturing experience. The interaction of these two bases of knowledge, a key concept of the Production Theory paradigm, enabled the MLA to point up serious short-comings in the received wisdom.

5. *Concluding Comments*

A summary of the differences between the two paradigms appears in Table 2. While the distinction on any one dimension, however profound, could be explained away as a tactical managerial choice, the use of the term "paradigms" is warranted by (i) combined magnitude of all the differences and (ii) inter-locking, internally consistent and mutually supportive nature of the goals, procedures and systems embodied by the two approaches. For example, generalist engineers can head truly cross-functional process improvement teams only if they have direct access to multiple stages (i.e., the organization is cellular) and can obtain cross-functional data. Under the circumstances, their proposed solutions might cross traditional departmental boundaries.

Table 2 About Here

However, we are not suggesting that the two paradigms are mutually exclusive. Indeed, a plant which embodied either of the paradigms would occasionally have to adopt pages out of the other's book. However, the experience of 2 of the 15 projects in our database suggests that the adoption of the Production Theory characteristics by a Six Sigma plant can be sustained only at the cost of disrupting normal production/process control activities. It would seem that Production Theory plants could adopt Six Sigma characteristics much more easily, but we wonder whether repeated adoptions would not endanger their base system. While we believe that the differences between the two paradigms are significant enough to make their simultaneous adoption in any plant (and indeed, any firm) a very difficult exercise, only empirical evidence can resolve this issue for certain.

A second issue concerns the domains of applicability of each paradigm. Earlier, we suggested that the Six Sigma paradigm might not be appropriate for "dynamic" production environments. From one perspective, dynamism might be considered a characteristic of specific industries. The Six Sigma paradigm was developed and applied effectively in fabrication-assembly industries, where the physics and mechanics of cutting, bending and joining metals were relatively well understood (e.g., performance curves for modern high speed steel cutting tools were developed by Frederick Taylor). So, the processes were readily decomposable and defects were generally observable by their producers or their customers. The paradigm was effectively adopted by other industries characterized by similar conditions of stability in technology and production environments. The Production Theory paradigm is more appropriate for industries which employ continuous production techniques (like paper and wire), deal with new or embryonic technologies (like ceramics) or cannot meet the challenge of immediate observation of contingencies (like semi-conductors and fiber optic devices). In fact, for semi-conductors, Fisher *et al.* (1983) called for the development of control strategies which emphasize system-wide control of production.

Another perspective on dynamism could be anchored on the idea of stages of knowledge (Jaikumar & Bohn, 1992). At the lower stages, when little is known about a product and/or its manufacturing process, the Production Theory paradigm could help firms recognize key variables and their effects. At the highest stages of knowledge, the search for complete procedural and algorithmic control - typically undertaken as a prelude to CIM - would necessitate studies of secondary, tertiary and higher order interactions among product, process and environmental variables. Here again, the holistic approach of the Production Theory paradigm could be beneficial (see, for example, Zuboff's (1989) description of work in CIM factories). At the middle stages of knowledge, a reductionist, Six Sigma paradigm, approach could probably be justified. This hypothesis is consistent with Jaikumar & Bohn's observation that most industrial processes operate at the moderate stages of knowledge. So, we would expect to - and do - observe many more examples of the application of the Six Sigma paradigm.

We readily acknowledge that our research is exploratory and limited by its focus on one firm. As such, our findings are no more than hypotheses about effective process control. Nevertheless, we would like the reader to note that in 1990, Bekaert's CEO won the European Forum for Quality Management Leadership award. The jury was believed to have been impressed by his vision for quality and process improvement as embodied by the MLA. In 1992, one of the other plants which hosted our study won the first European Quality Prize. Thus, while Bekaert might not be a well recognized name, it is not a laggard with respect to quality and process improvement.

Future research could follow two related but distinct paths. First, multiple small sample case studies in industries like ceramics and semi-conductors could be undertaken to substantiate and refine the characteristics of the Production Theory paradigm. Such studies could also examine critical procedural issues like: the difficulties experienced in simultaneously trying to apply both paradigms (at the level of the plant or the firm), effective means for transferring knowledge from a learning cell to the rest of the plant (firm), challenges of managing plants where production control and process control are not aligned and the difficulties of managing manufacturing and R&D as a team. Second, large sample, multi-industry, statistical studies could be undertaken to empirically explore the domains of applicability of both paradigms and the relative costs and benefits of applying them. Both streams of work would establish the degree of generalization of the concepts we have presented here.

Six Sigma Paradigm	Production Theory Paradigm
Plant managers select ambitious targets for conformance quality. Often, R&D managers set targets for design quality.	Plant and R&D managers jointly establish goals for improving products and processes.
Plant specialists decompose the production process into key steps and bring each step under SPC. Often, R&D personnel optimize designs against known sources of problems.	Plants collect data on product, process and environmental variables which could potentially affect quality or productivity.
High level cross-functional committees coordinate plant-wide tasks.	Plant and R&D personnel undertake integrated, cross-functional problem solving to understand how these variables affect each other.
Departmental QCC monitor day-to-day performance and manage problem solving.	Plant personnel impose control (statistical or otherwise) on important variables.

Table 1: Key Elements of the Paradigms

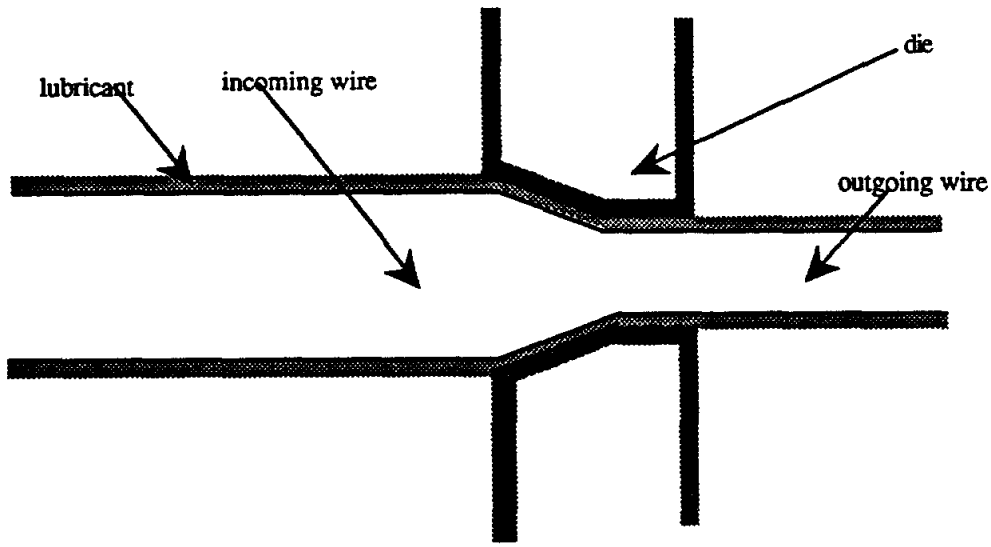

Figure 1: Schematic Cross-sectional View of the Drawing Process

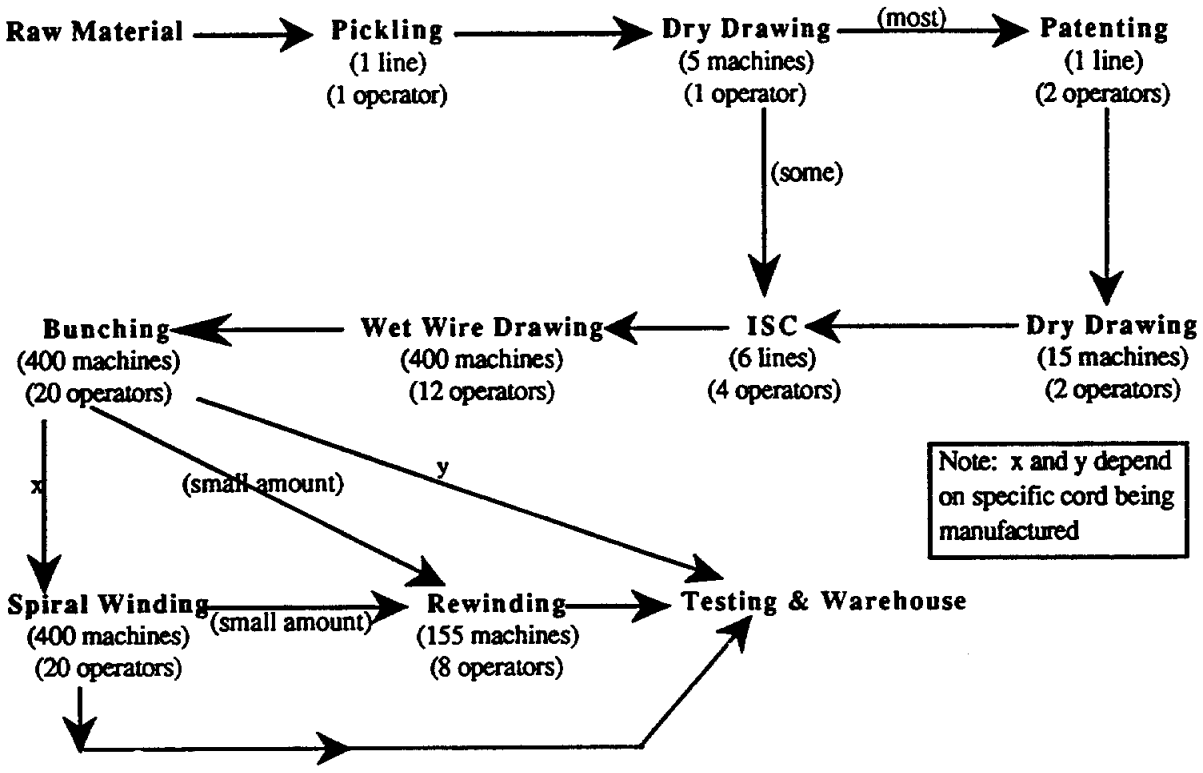

Figure 2: Process Flow Diagram for a Medium Sized Plant
(Numbers of people are given on a per-shift basis)

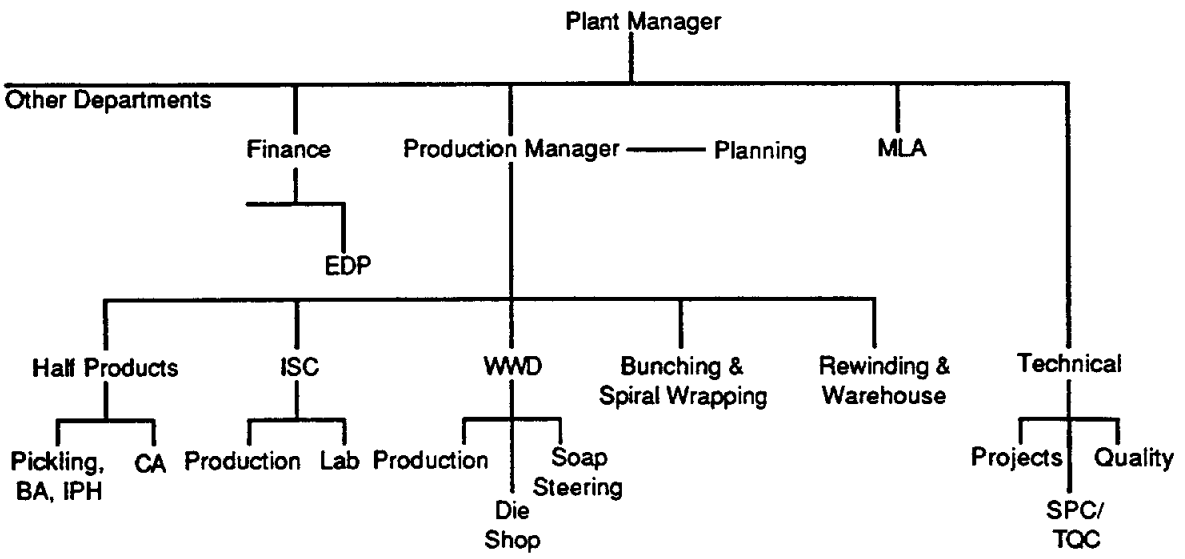

Figure 3: Partial Organization Chart of the Aalter Plant
(Note: Relative positioning of the departments bear no relation to their importance)

Dry Drawing	ISC	Wet Wire Drawing	Scope of Data
% Scrap	% Scrap	% Scrap	• Cumulative • Standard
% Rejected	% Rejected	% Rejected	• Cumulative • Standard
Fractures/ton	Fractures/ton	Fractures/ton	• Last 3 months • Cumulative • Target
Die consumption		Die consumption by filament size	• Last 3 months
	Lost people-hours	Lost people-hours	• Planned, actual • Reasons
	Lost tons	Lost tons	• Planned, actual
Number of machines	Number of machines	Number of machines	
Machine utilization	Machine utilization	Machine utilization	• Planned, actual • Cumulative
Lost machine hours	Lost machine hours	Lost machine hours	• Planned, actual • Cumulative
Work-in-process	Work-in-process	Work-in-process	• Planned, actual • Variance

Figure 4: Typical Structure of Data in Aalter's Monthly Activity Reports

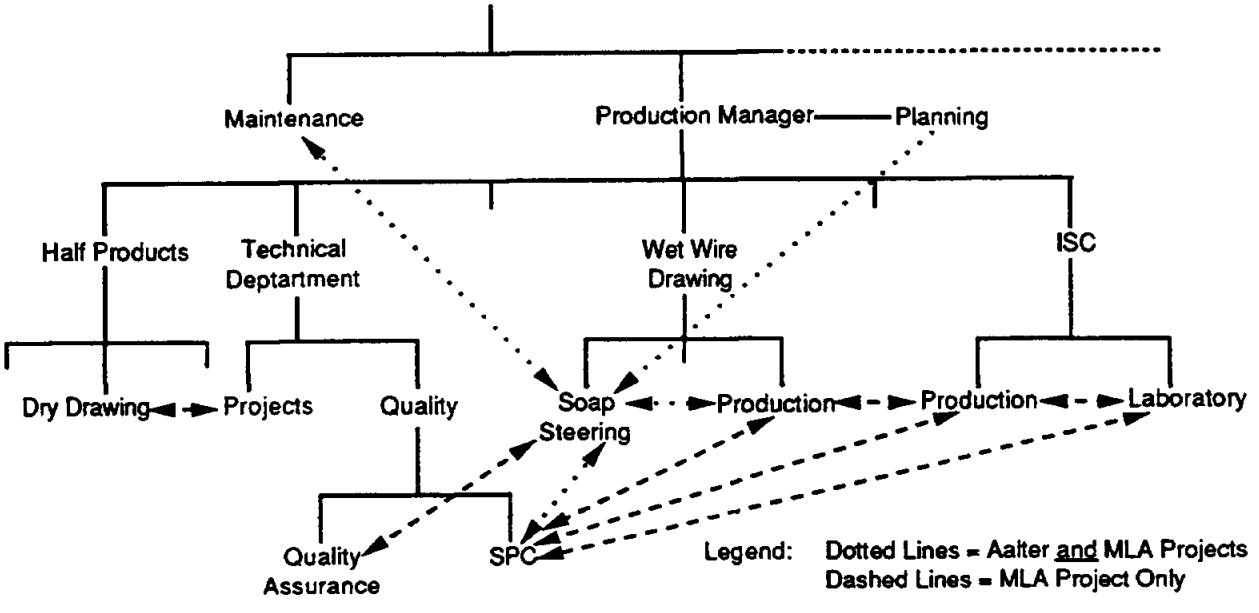

Figure 5: Information Flows Resulting from the Aalter and MLA Projects

Basis of Comparison	Six Sigma Paradigm	Production Theory Paradigm
1. Reductionism versus holism (fundamental distinction which drives all others)	Control over (known) individual production stages assures control over whole process. Manager's key tasks: reducing uncertainty about optimal settings. Key tools: Seven Statistical Tools, Taguchi Method, Quality Function Deployment, etc.	Appropriate decomposition of production process unknown. Manager's key tasks: determining relevant variables. Key tools: Natural and controlled experiments.
2. Organizational structure	Functional departments.	Cells (in conventional factories, a 'Learning Cell').
3. Contingency identification, data acquisition and processing	Contingencies identifiable by responsible departments or their customers. Departments have detailed, specialized, local data and easy access to summary data on others. Structured, efficient information systems.	No assumption about observation of contingencies. Cell personnel have access to detailed product-process data cross-linked within and across stages. Very flexible information systems.
4. Work teams/Scope of problem solving	Specialist engineers and departmental QCC tackle local problems; cross-functional committees integrate efforts across the plant.	Generalist engineers head cross-functional problem solving teams spanning all production stages.
5. Distribution of tasks	Process control and production control tasks are aligned and managed by individual departments within their domains.	Process control task might be divorced from production control and distributed across plant. So, plant management might be complicated.
6. Process improvement goals	Development engineers define design quality. Plants minimize/eliminate problems, improve conformance to the design specifications. Minimal communication between R&D and plants once specifications are set.	Since (many) contingencies are idiosyncratic, plants can generate data which designers lack. So, design quality is not an upper limit. R&D and plants must collaborate on knowledge creation/process control.

Table 2: Differences Between the Six Sigma and Production Theory Paradigms

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