A Systems View of Quality

by

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Submitted to the Sloan School of Management

in partial fulfillment of the requirements for the degree of

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at the

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ABSTRACT

Caterpillar, a leading manufacturer of construction and mining equipment, diesel and natural gas engines and industrial gas turbines, is committed to continually improving the quality of their products. Caterpillar currently employs many of the well-known quality techniques, such as statistical process control, yet experience varying levels of quality improvement success across the enterprise. This thesis explores possible causes of the variation amongst the business units. Benchmarking and a literature search are used to identify possible variables and provide frameworks and a basis for comparison. The problem is explored from a systemic perspective with a focus on market served and organizational learning. Conclusions regarding the sources of differences and recommendations for the enterprise and business units are included.

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TABLE OF FIGURES

TABLE OF CONTENTS

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Accomplishments are only possible with help of others, as no man (or woman) is an island. We live in a system composed of familial, social, intellectual, and organizational elements. I am fortunate to have a supportive system full of positive reinforcing loops.

My husband, Kent, is my soul mate. We have supported each other for 22 years through turbulent and calm times. This thesis is an accomplishment for us both. My daughter, Lauren, is my pride and joy. A college student herself, she has provided me with inspiration to learn and stretch myself.

My thesis advisor, Nelson Repenning, has allowed me the flexibility and intellectual freedom to conduct this work while providing steady guidance and thought provoking input.

Caterpillar has given me with the opportunity to work for a great company. It has provided challenging assignments, a rewarding culture, and the invaluable opportunity to become a Sloan Fellow. Caterpillar is a quality company in all dimensions. I am grateful for the opportunity to conduct this thesis as part of their quest to continuously improve quality.

INTRODUCTION

Much has been written about product quality. Ideologies and methodologies have emerged, evolved, and commingled over the past several decades. The abundance of academic research, formal processes, business books, and consulting businesses revolving around quality is staggering. Yet companies still seek the perfect recipe for improved product quality. What is the root of this conundrum?

Do companies know how to improve quality but lack the will? Is it possible that quality-minded leadership is the magic ingredient companies need? These questions were the genesis of this thesis. Research partially validated the hypothesis. Leadership establishes the company's objectives, strategies, structure, and operational practices. Leadership also nurtures and guides the culture. In the broadest sense, leadership is at the root of quality. Then, is quality-minded leadership in an environment of good quality practices sufficient to deliver industry-leading and continuously improving quality?

Simply put, the answer to the question above is "Yes". Yet this simplistic answer is insufficient to provide direction. What specific actions do successful leaders take to improve quality? Leaders establish priorities. They create organizational structures to carry out their objectives. They measure, monitor, and reward performance. Leaders set the pace for process improvement and design the systems that generate improvement. They establish training programs and personnel policies that influence organizational learning. They determine how the organization will interact with customers, suppliers, and competitors. They bring outside thought and experts into the organization. The list goes on and on. Leaders are at the root of quality improvement. They continually adjust controls and evolve the organization to ensure their objectives are achieved. Successful companies make these adjustments over time to adapt to the ever-changing business environment.

We live in a dynamic world: Competitors evolve; Suppliers come and go. Industry structures morph. New products are introduced. Workers retire and new employees are hired. Customer expectations change. Demand rises and falls. Emerging economies provide opportunity. To benefit from change, the corporation's management must provide a steady long-term direction and solid foundation of values along with intermediate goals and operational mechanisms to achieve the goals. The intermediate goals, operational processes, organizational structure, governance, and resource allocation and effectiveness determine near-term performance and lay the groundwork for achieving the long-term vision. Quality is a measure of near-term performance, an intermediate goal, part of the long-term vision, and is often incorporated in values. Product quality is omnipresent and continually evolving element of the ever-evolving state of the corporation. Leadership attempts to manage quality as one of the elements of a complicated dynamic system.

Quality, then, must be viewed from a systems perspective. To view it from a single dimension such as leadership, while convenient, is narrow and simplistic. Quality is the result of a complex system composed of numerous factors. Not only is it complex in terms of the quantity of elements, it also varies over time. Some processes, such as manufacturing output, are measured in days while other processes, such as organizational learning, are measured in years.

This thesis explores quality from a systemic view using comparative analysis. Benchmarking with other companies and comparisons amongst CAT business units were made. This work, when coupled with the literature, provides a basis for defining the characteristics of successful and unsuccessful product quality initiatives. Quality metrics are also compared. Metrics drive behavior and reflect management's view of quality. A more in-depth analysis is conducted on the value of quality to CAT, as this is necessary to prioritize quality improvement with competing initiatives.

In the analysis section, the major organizational level factors influencing quality are identified and comparisons are drawn from the benchmarking, research, and CAT interviews. The factors include market served, learning effects, and governance. Cultural analysis receives special attention as leadership was the genesis of the hypothesis. Finally, conclusion and recommendations are made.

CHAPTER 1: BACKGROUND AND IMPORTANCE OF ANALYSIS

Importance of Quality to Caterpillar

Caterpillar (CAT) is the world's leading manufacturer of construction and mining equipment, diesel and natural gas engines and industrial gas turbines (CAT, 2005). Customers rely on Caterpillar equipment to operate their businesses. Equipment uptime influences their profitability. For the purposes of this study, quality will be defined as the two factors that heavily influence vehicle uptime:

1) Reliability – Uptime in the first 1000 hours of the vehicle's life
2) Durability – Life of the components and vehicle

The above-mentioned characteristics are a derivative of those mentioned in the article "Investigating the Association Between Productivity and Quality Performance in Two Manufacturing Settings" by Kontoghiorghes and Gudgel (Kontoghiorghes & Gudgel, 2004).

Caterpillar has long recognized the importance of quality. Uptime influences customer productivity and therefore influences the price he is willing to pay for a new vehicle. Healthy prices yield attractive margins for CAT dealers. Dealers invest the profits in customer service which further increases customer uptime or productivity. Product support reinforces CAT product desirability and price. This is one of four reinforcing loops reflected in figure 1.

The role of dealer support is illustrated in the loop denoted "product support". Dealer support positively influences uptime, which increases customer productivity. Increasing customer productivity increases Caterpillar equipment value proposition. Increasing value proposition increases price realization which yields profit. As of 2006, CAT has 182 dealers around the world (CAT, 2005). The breadth and capability of Caterpillar's product support organization is regarded as a competitive advantage.

The role of uptime in brand is illustrated in the loop denoted "brand". Increasing uptime increases customer satisfaction which enhances brand value. The CAT brand is widely recognized and is associated with words like "durable" and "rugged" (Smith, 2005). It contributes to the price premium Caterpillar equipment enjoys in many market segments(Utley, 2007).

The third reinforcing loop in figure 1 is denoted "product development". Product development, in an environment of continuous quality improvement, increases quality which increases uptime and subsequently price. Increasing price increases profits which provide investment for product development Product development requires several years to complete, thereby introducing a long delay into the system. Product improvement initiatives or, conversely, poor quality product introductions do not impact the field for several years.

The fourth reinforcing loop in figure 1 is denoted "warranty". Higher quality yields lower warranty which improves profit, thereby enabling more investment in product quality. Warranty is a lagging measure of quality. It can create a liability that lasts for several months.

The four reinforcing loops capture how quality influences profitability. A minimalist's value of quality would consider only the warranty. This expense alone is large enough in most durable goods businesses to justify quality improvement. Yet many companies face stalled quality improvement. They have pursued various methodologies over the years, only to discover their latest initiative has become a fad.

Quality Management Methodologies

Quality has been the subject of numerous management methodologies. Each methodology has its own recipe and terminology. Examples include Juran, TQM, Malcolm Baldridge, and the Toyota Way. Many such methodologies follow the classical management fad pattern in which the methodology produces results, gains notoriety, and is widely adopted. Balancing forces eventually limit growth and may ultimately kill the initiative. In the latter case, the methodology becomes a fad. Figure 2 depicts factors that influence quality methodology adoption.

Quality has been a pressing concern for numerous industries as they face global competition. Responding to the need for improved quality, consultants and professional societies promote the use of a quality improvement methodology, which increases adoption rate and creates a pool of adopters. Adopters implement the methodology and become practitioners, thereby increasing the quality improvement rate and stock of quality improvements. Consultants and professional societies watch the stock of improvements grow and continue to promote the methodology. This reinforcing loop is denoted as "external support" in figure 2.

Positive word of mouth also reinforces quality methodologies. Increasing stock of quality improvements increases positive word of mouth, which increases consultant support. This increases adoption rate, which increases the number of practitioners and the stock of quality improvements. This reinforcing loop is denoted as "positive results" in figure 2.

Management is similarly influenced by the increasing stock of quality improvements. Eager to gain additional improvement, they may increase the number of projects, which reduces focus on any given project, thereby slowing the improvement rate. This frustrates management, who reduce their support of the initiative. This balancing loop is denoted as "overzealous implementation" in figure 2.

A supportive management team may foster implementation by limiting competing initiatives. The resulting focus increases quality improvement rate, which positively impacts results and reinforces management support. This reinforcing loop is denoted as "competing initiatives" on figure 2.

Management is influenced by competing business needs and customer quality demands, also shown on figure 2. As such, the priority management places upon quality improvement will vary. A competing business need, such as a demand spike, may decrease management's relative emphasis on quality. Likewise, increasing customer expectations will increase relative emphasis on quality.

As management increases their support for quality improvement, they increase quality training. This promotes organizational learning. Organizational learning, which is also influenced by the lessons learned from failed initiatives and quality improvements, ultimately increases the improvement rate and reduces the failure rate. The influence of learning on quality improvement is denoted in the loop reinforcing loop "learning effects" on figure 2.

The success of a quality improvement initiative depends upon system design and the relative strength of the reinforcing and balancing loops mentioned above. The remainder of this thesis will be devoted to identifying the factors that influence an organization's ability to sustain continuous product quality improvement.

Benchmarking Methodology

Benchmarking provides a broader frame of reference and specific application experience than can be obtained through internal interviews or a literature search alone. It unveils how market requirements impact quality metrics and governance mechanisms. Further, benchmarking provides insights on how companies design their organization and engage their employees in improving quality.

Benchmarking also helped to put in perspective how companies are employing practices and techniques prevalent in the literature. Companies are employing several elements of popular quality methodologies in their quality management systems. The companies appear to have avoided the quality management fad trap.

Caterpillar largely provides capital goods to quality sensitive customers. Other capital goods manufacturers and aerospace manufacturers were selected for benchmarking. The capital goods comparison is helpful because the relevance of quality to the end-user is likely similar to Caterpillar's. The aerospace comparison is relevant because quality is a non-negotiable product requirement with huge potential liability.

The interviews provided a broad yet relevant view of how capital goods companies govern quality. The following companies were benchmarked:

1) General Dynamics
2) Gerdau Acos Especiais SA
3) Lockheed-Martin
4) Pratt & Whitney
5) Schlumberger

Benchmarking was conducted via face-face and phone interviews. The interviews were semi-structured. The interviewees received a preparatory email that contained a short list of questions. The interview was roughly patterned from these questions. The questions focused on governance, metrics, organizational structure, and culture. The conversation was guided to leverage the interviewee's expertise. Seven interviews were conducted.

Importance of Literature Search

Quality has been widely studied for decades. Early experts such as Deming developed tools and espoused the virtues of quality-oriented culture. His methodology was adopted widely by Japanese manufacturing companies. Many of Deming's practices, such as statistical process control, are now commonplace in Western businesses. Other practices, such as his proposed personnel evaluation practices, have not been widely adopted. In understanding quality from a systems perspective, it is relevant to understand how Deming's methodologies are used in modern quality systems and why companies create unique systems rather than adopting his.

Deming noted the influence of metrics on behavior. Later, Kaplan promoted a balanced set of metrics that measure business performance through multiple dimensions in both rearward and forward looking fashion. He maintains "The objective of any measurement system should be to motivate all managers and employees to implement successfully the business unit's strategy (Kaplan, 1996)". Quality is a common element in business unit strategies. In understanding quality from a systems perspective, it is relevant to understand how metrics are used to impact quality performance.

A subsequent wave of management thought arose in the 1990's with Peter Senge's learning organization. Senge describes a culture in which employees individually and collectively continuously grow and deepen their understanding of the business system. The learning organization facilitates continuous quality improvement. In understanding quality from a systems perspective, it is relevant to understand the influence of organizational learning on quality.

Knowledge-based product development methodology embodies learning organization concepts. Popularized by Toyota, the methodology emphasizes individual and organizational skills applied within a structured development process. It is important to understand how the design process influences quality and fits within the quality system.

The works of Deming, Kaplan, and Senge provided frameworks for improving and measuring quality. Scholarly studies and business writings supplement these readings by providing a linkage between theory and practical application. Case studies on quality improvement and systems dynamics papers were especially helpful. Business press writings on organizational culture and quality were also referenced.

CHAPTER 2: LITERATURE REVIEW

The literature review focused on quality governance and the role of organizational culture and learning. It concentrated on governance and execution. The literature review is divided into two sections: 1) Classical schools of thought, and 2) Systems dynamics and learning organization. Findings from scholarly text, business press, and benchmarking are included where they reinforce the literature.

Classical Schools of Thought

Deming is perhaps the most widely recognized quality expert. He published "Out of the Crisis" when the U.S. economy was in a recession and American companies were facing new competition from Japan. Deming was infamously critical of Western management and proposed specific improvements. Although it was written in 1982, the book enumerates some findings and recommendations that are as relevant and controversial today as they were then.

Deming proposed 14 points for transforming management. An abbreviated version of these points are (Deming, 1986):

1) Create constancy of purpose toward improvement of product and service, with the aim to become competitive and to stay in business, and to provide jobs.
2) Adopt the new philosophy. Western management must awaken to the challenge, must learn their responsibilities, and take on leadership for change.
3) Cease dependence on inspection to achieve quality. Eliminate the need for inspection on a mass basis by building quality into the product in the first place.
4) End the practice of awarding business on the basis of price tag. Instead, minimize total cost. Move toward a single supplier for any one item.
5) Improve constantly and forever the system of production and service, to improve quality and productivity, and thus constantly decrease costs.
6) Institute training on the job.
7) Institute leadership. The aim of supervision should be to help people and machines and gadgets to do a better job. Supervision is in need of overhaul.
8) Drive out fear, so that everyone may work effectively for the company.
9) Break down barriers between departments.
10) Eliminate slogans, exhortations, and targets for the work force asking for zero defects and new levels of productivity.
11) Eliminate work standards (quotas) on the factory floor. Eliminate management by numbers. Substitute leadership.
12) Remove barriers that rob the worker of his right to pride of workmanship. The responsibility of supervisors must be changed from sheer numbers to quality.
13) Institute a vigorous program of education and self-improvement.
14) Put everybody in the company to work to accomplish the transformation.

These points, taken together, present the following themes: quality minded leadership sets the tone for the organization; continuous improvement applies to everything from shop processes to individual learning; workers want to create high quality products, employee engagement is essential in accomplishing change; teamwork across the supply chain; build quality in; and don't buy on price.

Some of Deming's recommendations have been adopted by industry. Employee engagement is a top-tier metric in many corporate scorecards, as is encouraged in Kaplan's "The Balanced Scorecard". Kaplan also validated Deming's high regard for the customer by devoting one of the four boxes in his model to the customer. Many modern corporations also embrace Deming's desire for teamwork across functions. Business unit structures incorporating all functions have replaced functional organizations. Finally, Deming's desire to building quality into a product rather than inspecting it in is also widely understood and has spawned in-process verification and stop-and-fix.

While the importance of supply chain integration is integral in the Toyota Production System, many companies are still seeking transformation. Incoming supplier inspection remains commonplace. Material cost has been a primary buying criterion in many industries as companies strive to improve operating margin. Focus on earnings has increased since the time of Deming's writings. Deming sited focus on short-term earnings as one of the seven deadly diseases of Western management. Deming's seven deadly diseases are (Deming, 1986):

1) Lack of constancy of purpose to plan product and service that will have a market and keep the company in business, and provide jobs.
2) Emphasis on short-term profits; short-term thinking, fed by fear of unfriendly takeover, and by push from bankers and owners for dividends.
3) Evaluation of performance, merit rating, or annual review.
4) Mobility of management; job hopping.
5) Management by use only of visible figures, with little or no consideration of figures that are unknown or unknowable.
6) Excessive medical costs.
7) Excessive costs of liability, swelled by lawyers that work on contingency fees.

In presenting the deadly diseases, Deming cited economist Carolyn Emigh's assertion that "cure of the deadly diseases will require total reconstruction of Western management (Deming, 1986)". This leaves little wonder as to why they haven't been solved. It also provides a relevant thought for this thesis: The system that generates quality is complex, dynamic, and large. In an absolute sense, even market pressure on earnings per share should be considered a forcing function.

For the scope of this thesis the relevant themes in the seven deadly sins are: focus on a long term strategy; select relevant metrics; and facilitate employee learning through less frequent job rotations. These themes are recognized by managers as within their scope of control.

The Toyota Way emphasizes the importance of management (Liker, 2003). Lean production techniques emphasize the role of the supervisor as an interactive member of the production team. Some industries, especially those that are highly regulated, recognize the importance of manager and employee skill and have an incentive to keep mobility low. This finding has been proven repeatedly. In a study of engineering teams, Allen found team productivity peaks with tenure of approximately 3.5 years (Allen, 1988).

Interestingly, modern management philosophy regarding management performance appraisals has moved even further away from Deming's recommendation since the time of his writing. GE, under Jack Welch's leadership, popularized the notion of up-or-out management. In his book "Winning", Jack Welch discussed GE's rating structure of 20/70/10 (Welch, 2005). The top 20% of performers receive rich economic rewards and increasingly challenging assignments. The bottom 10% is eliminated. Deming would likely fault the system rather than the employees for poor performance.

The purpose of this thesis is not to resolve this debate. Rather, it recognizes the quality system, organizational and individual performance, governance, and metrics set the stage for delivering quality.

Kaplan's Balanced Scorecard is a preeminent work regarding metrics. Kaplan proposes measurements in four categories: 1) Customer, 2) Processes, 3) Financial, and 4) Employee. He takes a systems view of the business. Results in one category are causally linked to other categories. Financial performance is viewed as an outcome of performance in the other dimensions. This is intuitively obvious. Novel to Kaplan's approach, though, is the equally balanced measurement system.

Kaplan's scorecard is also temporally balanced. It includes forward-looking and rearward-looking metrics. Forward-looking metrics are performance drivers. Quality examples include carry-over problems in new product launches and statistical product control metrics. Rearward-looking, or lagging, metrics measure outcomes. Quality examples include warranty and dealer repair frequency.

Kaplan's methodology requires companies to address their objectives in a systemic way by viewing the relationship between causal factors and outcomes amongst four dimensions. Deming was also a systems thinker, though the nomenclature post-dates his work. For instance, he identified management skill as a causal factor in worker skill which influences quality (Deming, 1986). The science of systems dynamics has grown over the past 20 years and provides analytical frameworks for understanding cause and effect in complex systems.

Business Dynamics and Learning Organization

Business dynamics uses systems thinking and modeling to understand complex business problems and evaluate solutions. The field extends systems engineering concepts to the business world. Stocks, flows, and auxiliary variables are used to model a system. As with mechanical systems, business system performance is often too complex to understand without a model (Sterman, 2000). System performance is determined by the characteristics of stocks, flows, and relationships between auxiliary variables. It is nearly impossible to predict the performance of a complex system without a model.

Even the most intuitive, intelligent manager may lack the capacity to single-handedly drive a complex initiative. Nobel Memorial Prize winner Herbert Simon introduced the "principle of bounded rationality" as follows: "The capacity of the human mind for formulating and solving complex problems is very small compared with the size of the problem whose solution is required for objectively rational behavior in the real world or even for a reasonable approximation to such objective rationality (Sterman, 2000)." It is no wonder a complex systems problem such as quality improvement sometimes becomes a management fad. The principle of bounded rationality implores us to look beyond mere leadership to understand why some quality initiatives fail where others succeed.

Sterman and Repenning studied the system dynamics of two process improvement programs in their paper "Capability Traps and Self-Confirming Attribution Errors in the Dynamics of Process Improvement" (Repenning & Sterman, 2002). The authors studied two improvement initiatives conducted in one business by one manager. One initiative succeeded and the other failed. The successful initiative's system response was more immediate than that of the failed effort. The successful initiative, which was directed towards improving factory operations, had a cycle of time of less than one year. Improvements were quickly realized and fostered subsequent improvements. The failed initiative, which was directed towards new product introduction, had a cycle time of 1-3 years. The longer time period allowed entry of new, independent variables and fundamental attribution error (Repenning et al., 2002).

Through systems modeling, Repenning and Sterman demonstrated the bias towards short-term problem solving. Their model compared rework to process improvement. Rework and working harder immediately reduced defects. Working smarter, otherwise known as process improvement, reduced defect introduction after training and process experimentation were complete. The system delay in implementing process improvement made it a fundamentally less attractive effort, perhaps due to cognitive biases or organizational dynamics. The delays also made it difficult to assess progress. Hence, less effort was devoted to process improvement than rework. The defect introduction rate was not reduced (Repenning et al., 2002). Figure 3 reflects the system model. This work illustrates the value of leading indicators and systems thinking in quality improvement.

Repenning and Sterman explored unanticipated consequences of quality improvement programs. Analog Devices dramatically improved their quality and subsequently suffered from poor financial results. This paradox was caused by excess capacity that resulted from improved factory efficiency. Lackluster market conditions exacerbated the problem (Sterman, Repenning, & Kofman, 1997). Employee engagement, which had been instrumental in improving quality, suffered when improved efficiency led to lower employment rates. Quality improvement became associated with unemployment. This dynamic may fuel union officials' reluctance to participate in quality improvement initiatives (Sterman et al., 1997).

The Analog Devices study underscores the importance of addressing quality improvement initiatives from a systems perspective. This is in contrast to the time-honored practice of solving problems via decomposition (Sterman et al., 1997). Decomposition techniques, such as FMEAs and fishbone diagrams, are very good in defining elemental cause and effect. Yet these techniques do not account for the interactions between the elements of the system. In the words of Repenning and Sterman, "Decomposition in complex, tightly coupled dynamic systems optimizes the parts at the expense of the whole and the present at the expense of the future (Sterman et al., 1997)." The Analog Device case provides yet another argument for addressing quality improvement from a systems perspective. The Analog Devices study also makes the case for considering organizational and human factors in quality improvement.

Peter Senge, in his book "The Fifth Discipline", introduced the idea that a firm's competitive advantage lies in its ability to continuously learn and evolve (Senge, 1994). Senge identified five learning disciplines that influence an organization's ability to learn. These disciplines are (Senge, 1994):

1) Shared vision: What we want to create together.

2) Systems thinking: Understand the whole and how its parts interact.

3) Team learning: Learn from others' perspectives.

4) Mental models: Our internal picture of the world.

5) Personal mastery: Expand our personal capacity and development.

These disciplines are relevant to the quest for continuous quality improvement. Shared vision is essential in rallying the organization to understand the importance of improved quality. Systems-thinking enables one employee to understand how his work influences the quality of the machine. Team learning helps a workgroup understand how they can change the way they work together to improve quality. Each of us acts in accordance with our mental model of how quality should be improved, not recognizing that our model may be missing some causal elements. The very act of understanding that our mental models are incomplete or perhaps even incorrect is important. A manager who does not understand the limitations of his mental model might unwittingly impose an ineffective, incomplete, or even damaging solution to the quality challenge. The personal mastery of every individual on the team influences quality.

Kennedy's book "Product Development for the Lean Enterprise" acknowledges the importance of personal mastery in product development. He likens the Toyota chief engineer to a winemaker (Kennedy, 2003). Toyota chief engineers have a recipe for product development which they tailor as the project evolves to yield the desired product performance. Chief engineers are product development experts. Similarly, Toyota engineers become experts in their components and contribute both to platform development and to the component design portfolio for use in future platforms.

Kennedy acknowledges the presence of certain powers in a product development organization. Like Deming's seven deadly diseases, these are statements rather than specific calls for actions. Kennedy's powers are paraphrased below (Kennedy, 2003):

1) The power of bureaucracy. Beware of a "process czar" who values the process more than the outcome.

2) The power of engaged leadership. Expect leaders to be engaged in product development.

3) The power of assessment. Be brutally honest in evaluating the organizational effectiveness.

4) The power of vision. Vision must provide a clear discontinuity in order to create compelling motion towards the goal.

These powers create the backdrop for what Kennedy called the knowledge-based development (KBD) environment. Like Deming's fourteen points, they are more tactical and actionable than the powers listed above. The elements of KBD are (Kennedy, 2003):

1) Engaged, expert workforce at all levels. This element aligns with Senge's personal mastery and team learning.

2) Set-based concurrent engineering. Begin the program with several design sets. Eliminate them one by one as flaws surface. Carry the most robust set to production. Set-based concurrent engineering is reportedly more costly upfront but yields lower total cost, higher quality, and more timely delivery than linear concept development.

3) Responsibility-based planning and control. Chief engineers conduct integration events. They coach their team members in product development and make product development decisions. They do not manage the detailed plans of their engineers. Engineers and program teams maintain their own detailed plans with the guidance of the chief engineers.

The above-mentioned elements characterize lean product development at Toyota. The "Toyota Way" is the phrase Toyota uses to describe their culture. The Toyota Way is not a process or a manufacturing methodology. It describes organizational rules and norms. One such norm that supports quality is Toyota's expectation they will be a learning organization through relentless reflection and continuous improvement (Liker, 2003). Reflection requires people to relive mistakes and to identify means of preventing the mistakes in the future. This exercise is exhaustive and would be tempting for all but the most dedicated to skip. The documentation and communication required are voluminous.

Another principle in the Toyota Way calls for businesses to grow leaders who thoroughly understand the work, live the philosophy, and teach it to others (Liker, 2003). This principle mirrors the lean product development principle of chief engineers. Toyota leaders are expected to develop exceptional people and teams who follow the company's philosophy. The principle calls for social systems and technical systems that complement and reinforce each other. This principle is not unique to Toyota. Jack Welch also calls for a good fit between the individual and the company (Welch, 2005). These writings emphasize the importance a knowledgeable and competent leader.

CHAPTER 3: BENCHMARKING

All benchmarked companies indicated quality is the top priority behind safety. They view quality as a non-negotiable customer expectation. Quality was once a possible source of competitive advantage for some companies, though the advantage is dwindling due to globalization. US, Japanese, and European manufacturers have expanded operations to low cost countries. This has created a high quality, low cost supply base that can serve indigenous manufacturers, thereby leveling the quality playing field.

The benchmarked companies have developed a means of overcoming policy resistance. Large organizations with stringent quality requirements instituted complex control structures and a strong culture to deliver high quality. Past quality excursions or financial results provided impetus for change. The companies were successful in their quality efforts and provided rich information.

Five factors characterize the quest for continuous quality improvement as illustrated in figure 4. Market expectations are exogenous and drive the need for design and manufacturing quality. Increasing manufacturing quality increases positive results which reinforces a culture of quality. The feedback to the manufacturing process is relatively quick and is denoted as "short term results". The culture of quality promotes increasing design quality which further supports manufacturing quality. This loop is denoted as "learning". The culture of quality increases governance capability, which increases manufacturing quality, positive results, and organizational learning. Similarly, increasingly governance effectiveness increases design quality. Increasing design quality increases manufacturing quality, which increases positive results and strengths the quality culture. The loops describing the influence of governance are denoted as "governance".

The market establishes quality expectations. Companies will invest in quality when the customer or shareholders value it. Once those needs are met, the company will place its improvement efforts elsewhere. Competing initiatives will impose a balancing force on the quality system.

Marketplace and Partners

Customers establish quality expectations. Three categories of quality-related customer requirements were evident in the benchmarking: 1) Mission-critical safety, as in the case of aerospace, 2) High product availability, as in the case of equipment, and 3) Performance versus a specification, as in the case of steel. Caterpillar falls into the second category, though safety and performance versus specification are also important. Most companies will face customer expectations from all categories, though one category is likely to be dominant.

Products in which safety is mission-critical have stringent quality requirements. Quality requirements are reflected in specifications, design procedures, and manufacturing procedures (Seidel, 2007). They require specific prove-out and reduce the opportunity for management discretion. Management does not have the option to trade-off quality and commercial issues. Quality at a specified level is a condition of sale.

Aerospace defense contractors, such as Lockheed-Martin, have no discretion in setting quality targets but face low commercial pressure once a contract is awarded (Seidel, 2007). Their improvement focus is directed towards further risk mitigation or increasing process yield. Commercial aerospace suppliers also face mission-critical quality requirements. Yet they do so in a highly competitive commercial environment in which they are competing against another engine manufacturer for OEM business (Tarnacki, 2007). They compete on price, service, and features. Pratt & Whitney direct quality improvement attention towards reducing the cost of quality.

Cost of quality is a consideration for specialty steel manufacturer Gerdau Acos Especiais SA. Specialty steel is a premium commodity used in automotive applications such as bearings and engine components. Quality is Gerdau Acos Especiais SA's top priority, only behind safety (Heineck, 2007). Excursions are expensive and damage reputation, providing an incentive to ship high quality. Gerdau Acos Especiais SA measure progress on all fronts with financial metrics (Heineck, 2007).

Construction equipment and on-highway diesel engines face a market in which safety is critical but is less regulated than aerospace. Safety-related quality is non-negotiable. Quality is the top product priority behind safety. Management is heavily influenced by customer and competitive pressures when setting quality targets. The focus of quality efforts is on uptime.

One interesting contrast of the two Caterpillar markets is the distribution channel. Caterpillar machines are distributed through independent dealers. The dealers are certified by Caterpillar, sell only Caterpillar parts, and repair and conduct maintenance per Caterpillar procedures. The dealer is a partner in delivering quality to the customer. In contrast, on-highway diesel engines are sold through OEMs. Commercial pressure, as at Pratt & Whitney, is high as manufacturers compete for chassis business. Frequent emissions regulation changes force major product updates every four years. The updates provide companies with the opportunity to gain market share through superior product launch. Quality improvement efforts are therefore directed towards continuously improving uptime and launching the next generation product with superior quality.

Market requirements trickle down to the supply base which responds accordingly. Aerospace companies select suppliers who understand what is required to meet exacting requirements. At the other end of the spectrum, specialty steel is a commodity business served by raw materials suppliers. The suppliers focus on delivery and price. Construction equipment specifications fall between the aerospace and commodity. The supply base competes on delivery, price, and ability to meet specification. The diesel engine business is largely served by the automotive base that also competes on delivery, price, and ability to meet specification. There are spillover effects in process improvements from the automotive base to the industrial base (Heun, 2007). Likewise, manufacturers benefit from spillover between companies.

In summary, benchmarking revealed the market and its structure play a strong role in a company's approach to product quality. The market determines whether quality is mission-critical or a commercial issue. The customer base and distribution channel establish the competitive landscape and relative importance of quality. The supply base responds and may benefit from spillover. The quality structure that evolves as the result of the market dynamics influences where a company will focus improvement efforts. The following table summarizes the findings.

Table 1: Influence of Market Served on Quality Demands

	Aerospace – Defense	Aerospace – Commercial	On-Highway Diesel Engines	Construction Equipment	Specialty Steel
Quality requirement	Mission Critical	Mission Critical	Safety related Important to uptime	Safety related Important to uptime	Customer specified
Regulatory involvement	High	High	Moderate	Moderate	Low
Customer	Government	Commercial	Commercial	Commercial	Industrial
Discretion in finished quality target	Very little	Very little	Some	Some	Some
Distribution	Direct	OEM	OEM	Dealer	OEM
Supply Base	Aerospace	Aerospace	Automotive	Industrial	Raw materials
Quality improvement focus	Risk mitigation Process yield	Risk mitigation Process yield	Uptime New product launch	Uptime New product launch	Customer acceptance Process yield

Seminal Processes

Product design and manufacturing establish the quality of a product. All companies interviewed had formal design and manufacturing processes. Product introduction processes employ stage gates and reviews. Manufacturing processes employ standards, procedures, and control mechanisms. Numerous authors have commented that processes are rarely the root cause of quality differentiation. Rather, it is execution that differentiates performance (Bossidy, 2002). Execution will be discussed in the governance section of this chapter.

While the processes are similar between the companies, the environment in which processes are executed differs. The interviews revealed differences in product line complexity, product line age, and engineering change management. Some of these differences may be attributed to the industry.

Aerospace companies operate in a highly regulated environment in which changes are tightly controlled. Designs have very long shelf lives. For instance, aircraft engine designs are often current for over 20 years. Quality is more dependent upon design maturity than most other factors (Tarnacki, 2007). Changes are tightly controlled and validated. Other variables, such as business unit structure or manager, are thought to be neutralized by stringent process controls such as engineering change management. The weaknesses in an aerospace company's quality process are not reflected in the quality figures. Quality is non-negotiable. Rather, improvement opportunity manifests itself in operating cost reduction.

In contrast, Caterpillar does not operate in a highly regulated environment. Their managers have more freedom in managing the product line. Product groups are encouraged to be entrepreneurial. They are free to change the design per market or business needs. They may also simultaneously product several generations of product in order to finely segment the customer base. The strength of this approach is that it provides freedom to maximize business results. The weakness of this approach is that it drives complexity.

To reduce complexity associated with ongoing consist change, batch changes are being implemented at Caterpillar. Batch change processing and validation facilitate process stability and enable process improvement. Aerospace and automotive company quality benefits from tightly controlled change (Murphy, 2007; Seidel, 2007). The economic benefits of controlling complexity and engineering change are difficult to quantify. The difficulty in creating a business case can create a barrier for commercial producers whereas highly regulated producers are required to control change and complexity.

Complexity is also controlled through standards. Standards facilitate process stability which is a critical factor in improving quality (Deming, 1986). The tightly regulated aerospace environment forces a more rigorous standards maintenance process than a less regulated industry might adopt. Updating engineering and manufacturing standards drives overhead costs which, in down cycles, could be postponed. Postponing updates can lead to out-of-date standards which are ignored, thereby jeopardizing process control (Miles, 2007). The causal loop diagram on figure 5 illustrates the phenomena.

Environment, market, and process changes generate a gap in the currency of a standard. The out of date standard loses relevance, thereby decreasing the degree to which it is employed. Interest in the standard wanes and management allocates fewer resources, thereby pushing the standard even further out of date. The "irrelevancy" loop could doom standards to dusty microfiche if it were not for their impact on quality. If standards are not employed, quality will eventually suffer, which will increase interest in quality governance and, consequently, standards. This will eventually reduce the gap in standards. This balancing loop is denoted as "standards can help". Several companies employ internal auditing and certification to ensure standards are kept current (Miles, 2007). Pratt & Whitney is one such example (Tarnacki, 2007).

Governance

The term governance implies authoritative direction and control. Management establishes control through organizational structure and metrics. The power structure embedded in the organizational design provides direction. Metrics provide management with a means of measuring progress towards the desired direction. Benchmarking interviews focused on the role of metrics and organizational structure in delivering quality.

The interviewees agreed metric and incentive selections influence quality improvement through driving behavior. Each company's metrics are tailored to their operating system and culture. Despite the differences in metrics amongst the companies, two common themes emerged:

1) Metrics should be easily understood by all employees.

2) Metrics should be common across the enterprise.

Pratt & Whitney measures quality progress by monitoring the cost of complying with rigid standards. P&W consistently measures cost of quality (COQ) monthly at all divisions. Performance is compared to a targeted improvement trajectory. Top executives review the results monthly. They discuss the targets, results, remedial actions, and how well the units are leveraging experiences across the company (Tarnacki, 2007).

P&W include the following expenses in their COQ figure (Schiveley, 2004; Tarnacki, 2007):

1) Warranty
2) Scrap and rework
3) Terminating purchase orders
4) Excess and obsolete inventory
5) Engineering rework

Tracking COQ aligns well with Kaplan's balanced scorecard methodology. He asserts that "Ultimately, causal paths from all the measures on a scorecard should be linked to financial objectives (Kaplan, 1996)". The methodology similarly adheres to Deming's fifth principle of continuous quality improvement which reduces cost (Deming, 1986). Further, it provides a singular frame of reference for prioritizing quality improvement initiatives to other business priorities

Motorola was once an advocate of this approach (Schiveley, 2004). In their quest to improve quality in the 1990s, their executives developed a "shadow P&L" to ensure quality-related cost reductions were not merely the result of shifting expenses from one account to another. They ultimately abandoned the "shadow P&L" because financial tracking and reporting created transparency issues (Schiveley, 2004).

Some interviewees prefer first-order quality measurements, thereby avoiding translation into another metric. A repair metric which relates direct to the customer and is easily understood by employees can be powerful. A statement such as "The customers who own this product must repair it 2 times per year" is clear and compelling (Coffey, 2007). All companies interviewed use easily understood metrics.

Metrics, according to Deming, should transparently cascade and be relevant and actionable by the audience (Deming, 1986). Cascading metrics, leading metrics, lagging metrics, and summary metrics can add up to an astounding figure. This is the consequence of the complex, multi-layered system that generates product quality. While the metrics should be periodically reviewed for relevance, an equally important issue is how the metrics are used in the governance process. Are the metrics reviewed by those who can take specific corrective action? How are employees encouraged to improve performance?

Incentives are designed to promote behavior which improves business results. Performance is measured against some objective stated as a metric. Rewards, usually financial, are granted based upon performance versus a target.

Most companies interviewed link financial rewards to quality performance. This linkage generates employee interest. In the words of a Schlumberger executive, "As you may know, incentives play a great role in shaping behavior. Quality targets are part of management performance incentive plans (Okoro, 2007)". The linkage between employee pay and quality underscores the importance of clear metrics and goals.

Some executives cited rigorous annual planning sessions in which goals are negotiated. While time consuming, the executives felt the process gives them a voice in setting their quality objectives. In the words of Nelson Repenning, "If students could take away just one lesson from the social sciences, it is that change initiatives are only successful when employees have a hand in crafting them (Repenning, 2007)".

Incentives encourage employees to improve performance against select metrics. Employees work together to improve performance through a set of rules defined by the organizational structure.

Each organizational structure has strength and weaknesses. Centralized organizations foster technical competence at the expense of business focus. Decentralized organizations encourage entrepreneurial zeal at the risk technical competence (Schiveley, 2004). In reality, most organizations are a "matrixed" blend of centralized and decentralized units. The centralized functions are created where technical competence and common process benefit the enterprise. All benchmarked companies operate via a matrix.

The aerospace companies have strong, centralized quality organizations that own quality related processes, ensure common application across the enterprise, and establish corporate-level quality strategy. Each business unit has a quality executive who is a peer of the top executives. Business unit quality executives report to the business unit manager with dotted line accountability to the central quality organization. The business units clearly own quality.

Quality executives own all quality related processes within their business unit. Processes span from cradle (new product introduction) to grave (issue resolution). Business unit quality executives conduct quality reviews and track issue resolution throughout the business unit. The reviews are rigorous, highly structured, and conducted consistently throughout the enterprise. They are held at each of the functional levels and at the program level. Quality executives have sign-off authority. While they have a powerful and equal role to the program manager, they are not accountable for the program quality. The program manager is ultimately accountable for all aspects of the program. It is important to clarify roles and responsibilities in a matrix organization.

Schlumberger clarifies roles and responsibilities in a corporate-issued document. As Monday Okoro, VP of Human Resources said "At the corporate level, we have a CEO-issued policy on accountability called 'we are each accountable'. In this policy is a matrix referred to as the accountability matrix. We use it to determine the level of accountability of each person in an incident. It does not only apply to quality, it applies to every kind of breach of practice (ethics, code of conduct, HSE, quality). Quality and Health, Safety, & Environmental are managed through our QHSE management System which consists of policies, standards, best practices, training and certification, audits and reviews. We monitor and bench-mark year on year performances (Okoro, 2007)".

Aerospace organizations had the most complex quality organizational structures of the benchmarked companies. Stringent product and process quality requirements and the need to interface with regulatory agencies likely drive this complexity. In contrast, the specialty steel manufacturer had a streamlined organization in which the plant manager is responsible for quality. Quality affects process yield, an important measure of performance and is a strong determinant of incentive compensation. Though the organization is simple, the corporation sets clear expectations and encourages sharing. Fabio Heineck, an executive with Gerdau Acos Especiais SA explained it as so: "At the corporate level, the mission of the whole company clearly prioritizes quality. Strategic quality projects are spread across the company (Heineck, 2007)".

All benchmarked companies establish quality as a priority, hold business units accountable, and encourage sharing across business units. The more complex structures employ a centralized process owner to facilitate common practices. Benchmarked companies agreed sound practices, business unit ownership, sharing across business units, and employee skills are critically important in improving quality.

Culture and Learning Organization

Ambroz defines culture as "the shared beliefs and values guiding the thinking and behavioral styles of employees (Ambroz, 2004)". This simple definition will suffice for this paper.

It is well-established that culture impacts business results. "An organization's culture has a significant impact on a firm's long-term economic performance and productivity (Ambroz, 2004)". Culture has repeatedly surfaced in quality movements as in important determinant in an organization's success or failure.

Lin takes this assertion even further. He indicates "Most features associated with TQM – such as quality training, performance improvement, and benchmarking – do not generally produce advantage, but that certain tacit, behavioral, imperfectly imitable features – such as open culture, employee empowerment, and executive commitment – can produce advantage (Lin, Madu, Kuei, & Lu, 2004)".

Lin acknowledges the value of culture and that it is "imperfectly imitable" (Lin et al., 2004). Culture is the personality of a corporation. Like an individual's personality, it rarely changes. Behavior changes are slow to occur in the absence of a high impact event. The same can be said of corporate culture.

Tragedy or misfortune can play a role in changing corporate culture. It shakes the foundation upon which employees' beliefs are based. Old paradigms may fall and the opportunity arises to instill new beliefs. New beliefs may be needed for survival. As we look into our personal lives, we see evidence of this in people who have faced a tragic loss. Likewise, organizations face tragedy and emerge changed.

Space Shuttle disasters have rocked the foundation of the US space program. The earliest failure, that of the o-ring on the Challenger, prompted increased scrutiny at NASA and the contractors. Engineers had questioned the basic design and some had warned the o-ring could fail. Yet the launch proceeded. As a result of this breakdown in governance, NASA redoubled focus on transparency and decision-making. A few years later, NASA faced another shuttle disaster. This time, foam from the external fuel tank flew off and damaged the wing, resulting in reentry failure. Engineers had been openly tracking the problem but assumed it would not cause significant damage. This failure, though handled much more openly than the o-ring, provided yet another sobering reality to the contractors. All parties were reminded that quality is mission-critical (Scearce, 2007).

As a party to the disaster, Lockheed Martin dissected their quality management processes. They implemented numerous process and controls improvements. Lockheed also reflected upon its culture. The leaders recognized process controls alone will not deliver flawless quality (Seidel, 2007). Employees must own and deliver quality.

A Lockheed Martin quality executive explains the role of culture and procedures with the symbols "big Q" and "little Q". The "big Q" represents a culture of quality. The "little q" represents quality processes. This executive stressed the importance of culture when he said "The more 'big Q' you have, the less 'little q' you need (Seidel, 2007)". This statement quite simply captures why executives resort to burdensome processes when they feel the culture lacks quality focus. The Lockheed quality executive views his role as facilitating both the "big Q" and the "little q".

Another affirmation of the tight linkage between culture and quality is evident in corporate values and other strategy-related statements. Schlumberger's aforementioned accountability policy "we are each accountable" is a call for employees to accept personal responsibility for quality. A 20-year Caterpillar employee made a similar statement when explaining his experience leading a team to resolve a quality problem. He said, "I have decided that quality is personal (Coldren, 2007)".

This assertion illustrates the challenge and opportunity in creating a quality-oriented culture. It is a challenge because it requires the personal conviction of each employee. Yet the power of individual and collective conviction is so strong it can overcome great hurdles. This explains the importance of and the quest for a quality-oriented culture. Anything so critical to performance must surely be measured.

Pratt & Whitney, and all business units in parent company United Technologies, uses a comprehensive and consistent measurement system (Tarnacki, 2007). Achieving Competitive Excellence (ACES) is an operational system which measures performance in six areas: customer, quality, delivery, financial, environmental / health / safety, and employee engagement.

Of the six ACES measurements, culture is the most difficult to measure (Tarnacki, 2007). P&W assess culture through interviewing people at all ranks and by observing manager behavior and response to quality issues. P&W also gauges culture by the degree of visual management on the shop floor. Visual management, an element of lean manufacturing, is an interactive communication tool which captures actionable process metrics that are leading quality indicators. Employees know how to improve quality using this information. P&W relies on manager and formal training to improve workforce capability (Tarnacki, 2007).

Lockheed Martin has an engineering certification program with the objective to improve product quality and the quality of all engineering program work. The training includes 12-15 hours of training in quality, drawing, and cost accounting. It culminates in an exam and certification. Certification yields a pay increase and is important for those seeking advancement. Encouraging team learning is a more difficult task.

Team problem solving is necessary when the problem extends across organizational boundaries. Even a relatively focused problem in a steel plant frequently involves multiple departments. The specialty steel executive commented as follows: "Problems are always treated from an inter-area perspective in order to define the best solutions for the company and not for one specific area (Heineck, 2007)". Cooperation becomes more difficult as problems span multiple plants, business units, or even time zones. Some benchmarked companies used the central / business unit quality structure to address this challenge.

Most quality executives agreed one role of the centralized process owner is to facilitate learning across the organization. This differs from a policing role, which is a paradigm some employees have regarding a centralized organization. Business unit quality executives also claim a role in creating a learning organization. One business unit quality executive tidily summarized his role is "to create an error-free environment through practices, procedures, and training."

Formal policies and procedures are used by most organization to share practices. How well the procedures are used is a function of process rigor and individual decision. Highly structured organizations with rigid sign-off criteria may choose to incorporate new practices into standards as a means of codifying best practices. Even these organizations may employ incentives to share best practices. Such is the case with Pratt & Whitney's ACES certification. Less structured organizations rely more upon the personal mastery and team learning to share quality improvement practices.

Personal mastery is built through formal education and on-the-job experience. Highly experienced employees play a key role in team learning and in delivering quality products. An engineer with 20 years of casting design experience is adept in creating and maintaining designs that are easy to manufacture and meet quality targets. He is experienced in working with the foundry and the machine shop to design high quality processes. He is also capable of making ship or stop-shipment decisions when a deviation occurs. Such a high level of personal mastery is attained over several years. Senior engineers mentor less experienced engineers. This example underscores the importance of personnel policies and reward mechanisms that encourage personal mastery and team learning.

The importance of personal mastery and team learning extends to leaders. Some interviewees emphasized the importance of having business unit leaders who have deep knowledge of their business and quality. In fact, some companies make a practice of keeping a leader in one business segment throughout their career. Lacking experience across multiple business units, these leaders must be encouraged to collaborate with their peers in other business units. Jack Welch insisted upon sharing best practices across General Electric business units. One of the questions he asked most frequently as he visited business units was "How many other business units have you shared this with? (Welch, 2005)".

CHAPTER 4: IMPORTANCE OF UPTIME

Caterpillar products are capital goods used in production. Machine uptime is critical because it influences the customer's revenue stream.

Mining trucks are especially sensitive to uptime. They are used in a wide range of mining applications such as diamond mines and oil shale mines. Mining operations are highly sophisticated. The trucks are equipped with payload management systems that enable the operations manager to continuously monitor productivity. A 797B truck operating in an oil shale mine hauls approximately 1900 barrels of oil per hour. At $65 per barrel, this equates to $124,000 revenue per truckload per hour. The resultant loss in gross profit is approximately $78,000. Further stressing the importance of uptime, the operators expect 7000 hour per year uptime, which translates to 19 hours per day (Frese, 2007). While an extreme case, the mining truck example properly frames the importance of construction equipment uptime. Figure 6 illustrates availability is the second most important factor in operating cost, falling only slightly behind operator productivity (Frese, 2007).

The value of a few weeks of uptime can quite easily exceed the cost of equipment. Uptime and customer support are often more important buying criteria than price. An equipment manufacturer can price their vehicles at a premium if they provide superior uptime. The dealer's pricing power with a repeat customer increases if that customer has experienced superior uptime with CAT equipment. Uptime also increases customer satisfaction which, over time, increases the brand power thereby supporting pricing power. This is reflected in the reinforcing loop labeled "brand" in figure 1.

Price elasticity to quality varies by application, market, and competition. The broad range of application and factors influencing quality make it difficult to precisely determine the relationship between product quality and price. However, a simple model was created in which prices of various machine models were traced as a function of the machine reliability (Sieck, 2007). Care was taken to remove known commercial and market issues, such as buying aberrations prior to model change and difficult market conditions. This analysis indicates significant price elasticity to reliability. These results suggest reliability improvements will yield top line growth and improved bottom line.

CHAPTER 5: ANALYSIS OF FACTORS INFLUENCING CATERPILLAR PRODUCT QUALITY

This chapter will explore the role of market served, learning effects, and governance in product quality at Caterpillar. Comparative analyses will be used to deduce the influence of causal factors on product quality. These lessons will support recommendations.

Market Served

In understanding the attention given to quality improvement, it is helpful to understand the impact on financial results. Warranty directly impacts bottom line profit. Warranty policy is driven by the marketplace.

Warranty is an important factor in the on-highway engine market. Trucking companies operate on relatively thin margins, with an average return on sales of 5.5% (West, 2006). Expansive warranty policy insulates the trucking company from unforeseen expenses that erode thin margins. Heavy-duty on-highway truck engines are often guaranteed for 500,000 miles. Construction equipment is typically warranted for 12 months. The outcome of these differing policies is on-highway truck engine warranty (as a percentage of sales) is higher than machines, even though engine repair frequency is lower than machine repair frequency.

High on-highway engine sales volume heightens the importance of quality. An engine quality problem quickly becomes a large field and warranty problem. Further, engine business margin is typically lower than machinery business margins (CAT, 2005). A costly engine warranty problem would deteriorate engine business profitability and overall quality of earnings. High volume, generous warranty policy, and challenging margins create a compelling case for risk management.

One means of managing this risk is to closely manage reliability. On-highway engine reliability has, on average, improved at a more dramatic rate over the past 4 years than has average machine reliability. Differing business models contribute to the difference.

Caterpillar equipment is sold to CAT dealers, who sell and service the products. Service contracts, in which the customer pays the dealer to manage vehicle service, are common. The resulting good maintenance practices and opportunity to proactively solve known quality problems increase uptime and customer satisfaction. Lexus' model is not unlike Caterpillar's. Lexus is well-known for customer service and proactive repair. While Lexus likely has very good reliability from the factory, the dealer further shields the customer from problems (Muller, 2006). Caterpillar machine customers enjoy the same protection.

The dealer provides a buffer between the factory and the customer. While this is helpful in providing the highest reliability to the customer, it also insulates the factory from direct customer input. Direct customer input provides unfiltered, timely data to management and engineers. Dissatisfied customers create an uncomfortable social situation. Absent the dealer buffer, company employees are exposed to the emotion of unhappy customers.

Personal dissatisfaction is the result of a gap between a person's desired state and the current situation. Psychologists have shown that events have more impact on humans when emotion is involved. A gap between the current reality and desired state creates tension. The tension can be used as a driving force for improvement. This is the rationale behind the Toyota Production System principle #14. "Become a learning organization through relentless reflection and continuous improvement (Liker, 2003).

Market Served Case Study: Contact with Customer Increases Quality Focus

A personal experience reinforces the value of relentless reflection and emotion associated with an event. As a young engineer, the author accepted an assignment to lead validation improvement efforts directed to improve an unreliable engine. This product caused extreme customer dissatisfaction. Over a period of years, this engine moved from the least reliable to the most reliable engine in the product line. During this period, various members of the design team met with customers to communicate problem resolution status. Customers shared stories of the pain the unreliable engines inflicted upon their business. They lost revenue due to downtime. Freight was stranded. Produce spoiled. While the customers heralded Caterpillar's product support, they were disappointed in the product. These customer encounters were priceless in instilling the importance of quality in the design team and their management.

End-user relationships expose management to customer problems, thereby increasing management's focus on quality. Management then increases problem resolution and prevention resources. These resources are invested in improving validation and quality processes, which contribute to successful product release, thereby increasing customer satisfaction, desirability, sales, and field population. A greater field population increases the opportunity for end-user relationships. This dynamic is reflected in the reinforcing loop "relationships reinforce quality" on figure 7.

Warranty also increases management focus on quality. A higher field population will result in more field failures, which increases warranty, thereby increasing management focus on quality, which invokes investment in quality, and improves customer satisfaction, sales, and field population. This is reflected by reinforcing loop "warranty increases attention" in figure 7.

One more advantage of customer feedback warrants discussion. Third party evaluation, such as J.D. Power and Associates Customer Satisfaction study, provides independent analysis of customer satisfaction. Mid-range and heavy-duty on-highway truck engines are included in J.D. Power surveys. Caterpillar engines have won the award for several years. The third party evaluation provides an annual reminder of the importance of quality.

As illustrated by figure 7, the positive reinforcement mechanisms of relationships and warranty are balanced by quality improvement itself. Successful product releases reduce field failures. Fewer problems are routed to validation and quality processes. In the theoretical limit, a zero failure system robs the organization of its ability to react to a new failure mode. This is denoted by the loop "improved releases reduce failures".

On-highway truck engines benefit from relationships that form as the result of the distribution model. Engines are marketed to the end-user, who specifies a Caterpillar engine to the OEM. The engine is then shipped directly to the OEM with no dealer involvement. Any defect will result in a complaint from the OEM or the end-user. The direct shipping model eliminates the dealer buffer and ultimately drives close attention to quality shipped from the factory.

Market Served Case Study: Business Model Influences Process

The second case, a single machine model manufactured in two plants, provides an example of how business model influences process. The machine model to be discussed is commonly used in construction. During the period of this study, both plants manufactured the same design at similar volumes. The most notable difference between the two plants was that plant A shipped machines to dealers while plant B shipped machines directly to customers. Plant B performed the pre-delivery inspection in house. Plant A relied upon the dealer for pre-delivery inspection.

To study the influence of manufacturing processes on quality, it is useful to break the vehicle's early life into 3 distinct phases which are illustrated on figure 8:

1) Very early hour reliability (VEHR) 0-20 hours
2) Dealer repair frequency 1 (DRF 1) 21-200 hours
3) Dealer repair frequency 2 (DRF 2) 201-1000 hours

Very early hour repair frequency (VEHR), a measure of reliability from 0-20 hours, differs between the plants. Defects uncovered in this period are attributable to manufacturing. Plant A machines were shipped to the dealer, inspected by the dealer, and delivered to the customer. The dealer discovered and reported VEHR failures. Plant B machines were shipped directly to the customer. Plant B performed post-assembly inspections. Repairs were made in the plant and communicated upstream to the assembly processors. Data taken from both plants shows plant B machines had markedly fewer VEHR defects than plant A, as reflected in figure 9.

After leaving the very early hour phase, the machine completes its infant mortality in the DRF1 phase which spans from 21 to 200 hours. Defects in the phase are caused primarily by manufacturing processes. By the end of this phase, the machines enter the useful life phase in which defects are driven primarily by design. One would expect the average quality in the transitory DRF1 phase to differ between plants A and B, but to a lesser degree than the difference exhibited during VEHR phase. Indeed, this was the case, as reflected in figure 9.

The reliability difference between plant A and B becomes insignificant as the machines accumulate hours and leave the infant mortality phase of machine life. Early hour manufacturing defects have been resolved by this phase. Failures are predominantly driven by design problems and occur randomly. Caterpillar assesses reliability in this phase by measuring dealer repair frequency in the period 201-1000 hours. This is denoted as DRF2. Plant A machines and plant B machines demonstrated very similar DRF2 reliability because the designs were identical. DRF2 is exhibited in figure 9.

This example proves a relationship between factory inspection and infant mortality. The root of this process difference was the business model. Plant A relied upon the dealer for pre-delivery inspection. Plant B performed the inspection themselves. This facilitated rapid upstream process improvement in addition to reducing very early hour failures.

Recognizing the benefit of inspection and feedback per this example and others, Caterpillar implemented pre-shipment quality inspections at all plants. In addition, plants inspect incoming parts and employ in-process verification. Data gathered at the inspection points is captured and communicated to the upstream sources, who own permanent corrective action. The centralized quality organization defined and communicated this standard process across the enterprise. Local quality organizations own implementation and quality improvement.

Case Study: Innovation Type and Learning Effects Influence Quality

This section will study the influence of product development process execution on quality. The influence of innovation type and learning effects will be explored by comparing two engine product launches. Both were developed in the same business unit, managed by the same executive leadership, and manufactured in the same plant.

Engine A was launched in the late 1980's. It was Caterpillar's first fully electronic engine. Electronic controls and fuel systems were key building blocks for meeting upcoming emissions regulations while improving fuel consumption and response. Engine A was planned to ultimately replace an older, mechanical engine.

Electronics and electronically controlled fuel systems were new to the diesel engine industry. This constituted a radical innovation, per Clark and Henderson's innovation matrix reflected in figure 10. A radical innovation involves an overturned core concept and a changed architecture (Clark, 1990). The overturned concept, in this example, was the electronically controlled fuel injector, which required a new architecture. The radical nature of the new system created a challenge for the organization. "Incremental innovation reinforces the capabilities of established organizations, while radical innovation forces them to ask a new set of questions (Clark, 1990)".

The new control system and fuel injector increased the performance development and validation challenge. New performance development tools and validation techniques were needed to ensure the fuel system and electronic system performed acceptably. The high new content and the nature of the content, in retrospect, warranted a sophisticated and well-executed development program.

The program team was composed the most talented engineers in the business unit. The chief engineer had over 20 years of design experience and was highly regarded. They expected it would be difficult to validate the new architecture because they lacked a transform between validation exercises and field experience. Field tests were performed, but were capable only of catching gross component quality problems because sample sizes and failure rate target were low. Additionally, late fuel system validation delayed other component validation. The program yielded an engine whose reliability prove-out lagged the original program plan.

The team could have either delayed the introduction, at the expense of business commitments, or maintained the launch date while attempting to manage the risk. They selected the latter path. As the engines accumulated experience at the customers' hands, it became clear the engine was unreliable. Competitors' first electronic engines faced a similar fate.

The product group entered rapid problem resolution mode as the reliability crisis became clear. The product health section watched dealer repair reports daily and communicated with engineers. They quantified the magnitude of the problems and prioritized the need for fixes. The design group tackled the problems quickly and thoroughly. Each problem was quantified, the root cause was identified, a design improvement was proposed, and the proposed fix was validated. Structured problem solving tools were applied. If a validation simulation or test did not exist to assess the situation, a new method was invented. In order to facilitate rapid problem resolution, the product group personnel were kept in place.

The product group resolved the reliability issues over a few years of structured problem solving. The engine reliability became very good and performance was excellent. However, the engine never achieved the original annual sales goal. Poor reliability spoiled the engine model's brand early in its life.

The silver lining in this cloud is organizational learning. All engineers working the problems increased their product development personal mastery. Team learning was facilitated by the close interactions of the various product group functions. The group also learned how to work closely with manufacturing and the supply base. Finally, they learned how to engage dealers and customers in understanding and resolving the problems. This team was kept in tact to develop engine B, the successor to engine A.

Engine B was designed to broaden the product offering and resolve the last open structural design issues of engine A. It was an incremental innovation, per Clark and Henderson's terminology. This is reflected on figure 10. The incremental nature of this product development and the strong base from which it was built created a higher probability of success than the team faced for engine A.

The team further increased their chances of success by further improving the validation and development processes used in resolving engine A reliability problems. They used the Caterpillar New Product Introduction process as an umbrella for the program. Having felt the sting of poor execution, they were stringent in their adherence to the process and made improvements where they felt it was insufficient.

They began the process with a thorough review of the market strategy. Marketing conducted a conjoint study to evaluate several different product derivative concepts. The analysis provided a multi-year forecast of rating demand from the customer. The development team validated both displacements of engine B at the power settings to be offered several years in the future. This forethought saved future engine programs validation expense and increased the current development team's confidence in the design.

The product design team selected suppliers immediately after they completed the concept design. They realized the importance of supplier involvement through their experience with engine A. Early supplier involvement enabled suppliers to provide detailed component design advice and begin their own process development. The suppliers were asked to provide production processed components for field reliability testing, which drove them to install production processes earlier than they normally might have.

Some aspects of engine B design stretched traditional design limits or introduced features with which they had no experience. The team employed advanced simulation techniques to conduct quantitative analyses rather than simply relying upon pass-fail tests. They also conducted probe testing, which tested the engine and key components beyond their design limits. The team's objective was to predict the failure rate and the failure mode of the major components prior to field experience.

Their quest to quantify risk was extended to field testing. Engine A field experience illustrated the importance of application experience. Sometimes the most seemingly benign application would demonstrate the highest occurrence of a serious failure mode. The field test quantities, locations, and timing were chosen so that product reliability could be predicted within a specified confidence interval by critical product design deadlines. The leadership team closely followed the design drop dead dates and ensured product development activities were progressing in a coordinated fashion. They acted as today's Toyota chief engineers do in conducting integration events (Kennedy, 2003).

Desiring high confidence before the product was released to high volume production; the team initiated a long, slow ramp that enabled close field follow. The skilled engine A product health team frequently visited the engine customers, proactively looked for problems, and brought data back to the engineers. This close field follow enabled the product design team to resolve those few problems which had escaped their validation process or were introduced as the result of production process changes.

The team won the Chairman's Annual Quality Improvement award for their achievement. Team members, who had been together for approximately four years, became mobile. Research from Allen and Katz suggests optimal team performance occurs when the mean tenure of members is between 2 and 4 years, suggesting this team had likely reached its maximum performance (Allen, 1988). Several team members moved to other groups, bringing with them their experience and process improvements.

The team members and engine B benefited from organizational learning. The causal loop diagram on figure 11 illustrates how organization learning influences quality. Engine A was an unsuccessful product release which drove high field failures. This increased management's focus on quality, which increased problem prevention and resolution activity, thereby increasing quality process development and execution, which increased probability for a successful engine B launch. This loop is denoted as "process improvement". As management increased their focus on quality, they recognized the need to reduce employee mobility in order to increase individual and team learning. The skilled team improved process and execution, thereby promoting a successful release, which increased sales and warranty exposure, thereby reinforcing management focus on quality. This loop, denoted as "freezing the team", is balanced by a "promote competency" loop in which a successful program increases the promotability of key employees. This reduces the team's knowledge and ability to execute the process. The interplay between these reinforcing and balancing loops underscores the importance of coordinating personnel moves in concert program needs.

<u>Governance</u>

Governance is a broad topic that cannot be comprehensively covered in this thesis. Rather, this section will focus on timely topics for Caterpillar quality: 1) The role of centralized and local control, 2) the role of bureaucracy, trust, and team learning and 3) The continuous product improvement process.

The balance between centralized and local control is periodically called into question. Caterpillar has been known for functional excellence and entrepreneurial zeal. The former was predominant when the organization was functionally focused. The latter is recognized as a current strength. As the company embarks upon the next generation of quality improvement, it is important to assess means of governing the matrix organization.

The very existence of the matrix suggests central coordination is necessary. Hundreds of cross-organizational touch points exist to develop, market, manufacture, and sell a Caterpillar product. Common processes, metrics and values help business unit leaders manage these touch points.

The corporate quality organization is positioned to drive common metrics, training, linkage with other corporate initiatives, and standard processes. Business units are positioned to implement and manage quality processes with the aid of local quality organizations. The experience of the benchmarked companies suggests roles and responsibilities between the central group and local groups must be well-understood and commonly applied, as should key roles such as Product Manager and Plant Manager. An efficient organization structure will facilitate quality improvement. The objective is to achieve high quality via sound processes and employee engagement rather than bureaucracy.

Figure 12 illustrates the relationship between bureaucracy, learning, and trust in delivering quality improvement. Employee commitment drives favorable quality results, which reduces the quality gap, which increases management trust in people (conveyed by word of mouth), and ultimately reinforces quality. This reinforcing loop is denoted as "results generate trust". Similarly, employee commitment reduces the need for bureaucracy. Employee commitment drives favorable results, which reduces the quality gap, thereby increasing management's trust of the process and reducing metric proliferation and bureaucracy, and increasing word of mouth support for quality and employee commitment. This reinforcing loop is denoted as "results reduce bureaucracy". Seidel from Lockheed Martin verbalized this loop as follows: "The more big Q you have, the less little q you need (Seidel, 2007)". As management realizes the benefits of employee skill, they invest in education and training which reinforces employee commitment and positive results. This is denoted as "training".

Organizational learning is also reinforced by employee commitment, as illustrated in the loop "team learning". Employee commitment promotes sharing, which yields best practices that contribute to quality results, thereby reducing the gap and promoting trust in people, word of mouth support, and greater individual commitment to quality. Visionary leadership and values also facilitate employee commitment to quality. The strong reinforcement loops in this diagram typify organizational inertia to changing the direction of quality. Management inserts a balancing force into the system through imposing quality goals.

As management increases the desired quality result, the gap increases, perhaps even if quality is improving. This can reduce management trust in the process, leading to an increase in metrics and bureaucracy, which decreases word of mouth support, thereby decreasing employee commitment to quality, which slows quality improvement progress. This progression demonstrates the management tool of stretch objectives can backfire if it generates frustration and a loss of trust in people or process. This causal loop diagram is a simplified characterization of factors that influence employee commitment and the linkage between commitment and results. Other factors, such as incentive compensation and personnel policies can introduce additional loops.

Process effectiveness also influences quality improvement. Caterpillar has a formal product quality improvement process which employs 6 Sigma methodologies. A centralized office owns the process, establishes metrics, and sets targets for all business units. The local process owners are responsible for implementation.

The process is effective in resolving product problems, as is shown by the very low number of recurring problems once they have been addressed using the process. The process, named Continuous Product Improvement (CPI), prioritizes problem resolution activities across the enterprise per a scoring mechanism entailing failure rate, dealer repair hours, and warranty cost for a given part number. This generates a score which can be compared for any part across the enterprise. Business units are expected to resolve all problems that hit a certain threshold value, and more, if needed to meet their reliability improvement target. The reliability improvement target for each business unit is equal to the enterprise reliability improvement target.

The CPI scoring mechanism accomplishes some of the objectives of a balanced scorecard. Balanced scorecard methodology promotes metrics that reflect multiple stakeholder points of view (Kaplan, 1996). It also promotes common metrics across the enterprise. However, the score is not a first-order performance measure. The literature search and benchmarked companies unveiled first-order metrics such as failure rate and warranty are commonly used. The only second-order metric found in existence was cost of quality (COQ). The CPI scoring mechanism, while effective in prioritizing enterprise problems, lacks intuitive relevance to most employees. They relate much better to repair frequency, warranty, or cost of quality.

Employee efficiency is a key factor in quality improvement. Research from Clark and Wheelwright indicates the most efficient number of active projects per engineer is two, as shown in figure 13. Excessive workload reduces engineer value-added time due to switching and coordination costs. Therefore, any metric that unwittingly promotes a high number of projects per engineer in the hopes of accelerating implementation may, in reality, retard implementation. Overzealous implementation, as reflected in figure 2, can contribute to the migration of a good initiative into a management fad.

Care should be taken in selecting improvement metrics to ensure maximize organizational efficiency in problem resolution. The targets should vary by business unit with sensitivity to current product reliability and customer satisfaction. Those products with the poorest reliability impose the greatest risk to brand and price realization. Their reliability improvement goals should be greater than those of the most reliable products. The most reliable product groups may need to address another critical area of their business, such as operations improvement or new product development. Jack Welch stresses the importance of using discrimination, not homogenization, in setting targets

(Welch, 2005). The benchmarked companies that set homogenous improvement objectives were not as successful in meeting their quality improvement goals as those companies that discriminated.

Finally, with regard to CPI, it is important to view this process and these objectives as one element of a complicated organizational system composed of numerous parties, processes, capabilities, and priorities. The system has stocks and flows. The implications of some process changes may manifest immediately, while others may take years to surface. While it is difficult to model such a complicated system, it is important to bear in mind the system exists and to rationalize the possible side effects of policy change. Policy resistance is a well-documented fact of organizational life that managers must consider when inventing and implementing processes. A systems view of quality and the factors that influence it are critical in order for continuous product improvement to thrive.

CHAPTER 6: RECOMMENDATIONS

Caterpillar has demonstrated ability to improve quality. Their challenge is to apply this skill across the globe and broad product line. This thesis has focused on the importance of governance and organizational learning in continuous quality improvement. Recommendations will be broken into these two categories.

Governance

Metrics should be easy for the average employee to understand and relevant to the customer's business. A first-order quality metric such as dealer repair frequency should be used to monitor progress. This metric should be broken into actionable pieces and communicated to the appropriate levels in the organization. For instance, engineers should know the repair frequency of their components, the failure modes, and the design characteristics responsible for the failure. Similarly, manufacturing people should understand which features are subject to quality excursions, where those features are generated in the manufacturing process, and how to monitor process performance. Metrics should be used as feedback tools for those controlling the process. They should not be used as a detailed scorecard to judge organizational performance. In short, metrics should be tailored to be relevant, clear, and actionable. At a high level, they should reflect the most important impact of quality: customer impact.

The centralized organization should define quality processes, establish enterprise goals, drive common metrics, establish standards, share best practices, and facilitate organizational learning. The local quality organizations should own implementation, establish local goals and standards, and should be responsible for maintaining quality core competencies and process excellence for the business unit. The local quality organization should report to the business unit manager and should coordinate with other quality organizations through their involvement with the centralized quality organization.

The centralized organization should frame quality improvement within the context of other strategically important initiatives, such as production system improvement. The local organization should integrate quality improvement into various aspects of the business. A systems approach to quality at the centralized and local levels will facilitate cultural engagement and will prevent overwhelming the organization with seemingly unrelated objectives.

Organizational Learning

Governance facilitates quality but does not guarantee it. The skills and capabilities of the people who execute and improve the process are critical. Continuous quality improvement relies upon continual learning. Learning can be promoted through formal training and on-the-job experiences.

Formal quality training should be required of all product engineers and manufacturing supervisors. This training extends to management, who is ultimately accountable for quality and is responsible for asking the right questions of their staff. The objective of training is to: 1) Increase employee awareness of the impact of quality on the customer, 2) Help employees see the systems nature of quality through providing a clear linkage to their other work, 3) Train employees in the relevant tools and process, and 5) Specifically train employees regarding their unique metrics, methodologies, and role. This training should be developed on a small scale for a pilot business unit and improved based on employee feedback and impact on implementation success.

Caterpillar has the structure to conduct quality training through Caterpillar University and 6 Sigma. For instance, 6 Sigma DMEDI provides numerous tools for integrating quality into product design. Leveraging 6 Sigma is a means of linking quality improvement to existing initiatives. The linkage will help employees understand quality is an element of the work they do and not an initiative of its own. The formal training will provide employees with a basal level of knowledge to apply to their jobs. It is only a beginning in improving the skills and capabilities of individuals and teams.

Product development and manufacturing employees should have job experiences that enable them to improve proficiency in their craft. This will entail coaching by managers and longer tenure on a job. Management jobs may need to change to accommodate the need to spend more time coaching employees. Engineers should generally remain with a new product development program from inception to production. Employees will ultimately realize competency is valued and will expect fewer job rotations. In the meantime, managers must signal competence is important through appointing technical stewards and rewarding manufacturing knowledge.

Quality must be addressed from a systems perspective. A singular change in policy, process, governance, or people will not improve quality. The system that produces quality is complex and dependent upon human behavior. Leaders must take this mature perspective and must nurture the organizational processes and people to improve quality. Formally, they implement governance structures to maximize efficiency and effectiveness. They must also establish the organizational structures and personnel practices to promote organizational learning. As stated in the hypothesis, leadership is at the root of quality. Leaders have the power to treat quality as an initiative or as a complex systems problem to be addressed in a holistic fashion. Only this approach will yield sustainable quality improvement.

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Figure 1: Importance of Vehicle Uptime

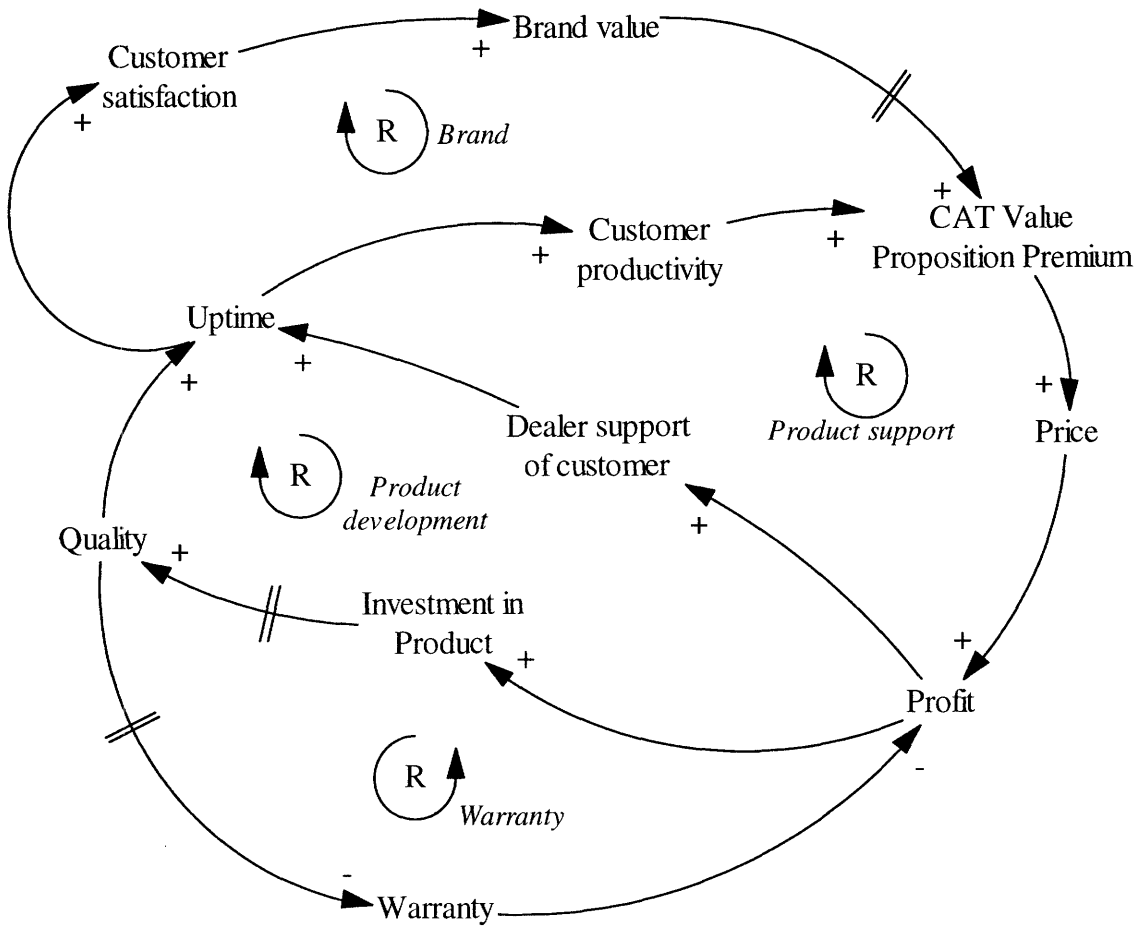

Figure 2: Factors Influencing Quality Methodology Adoption

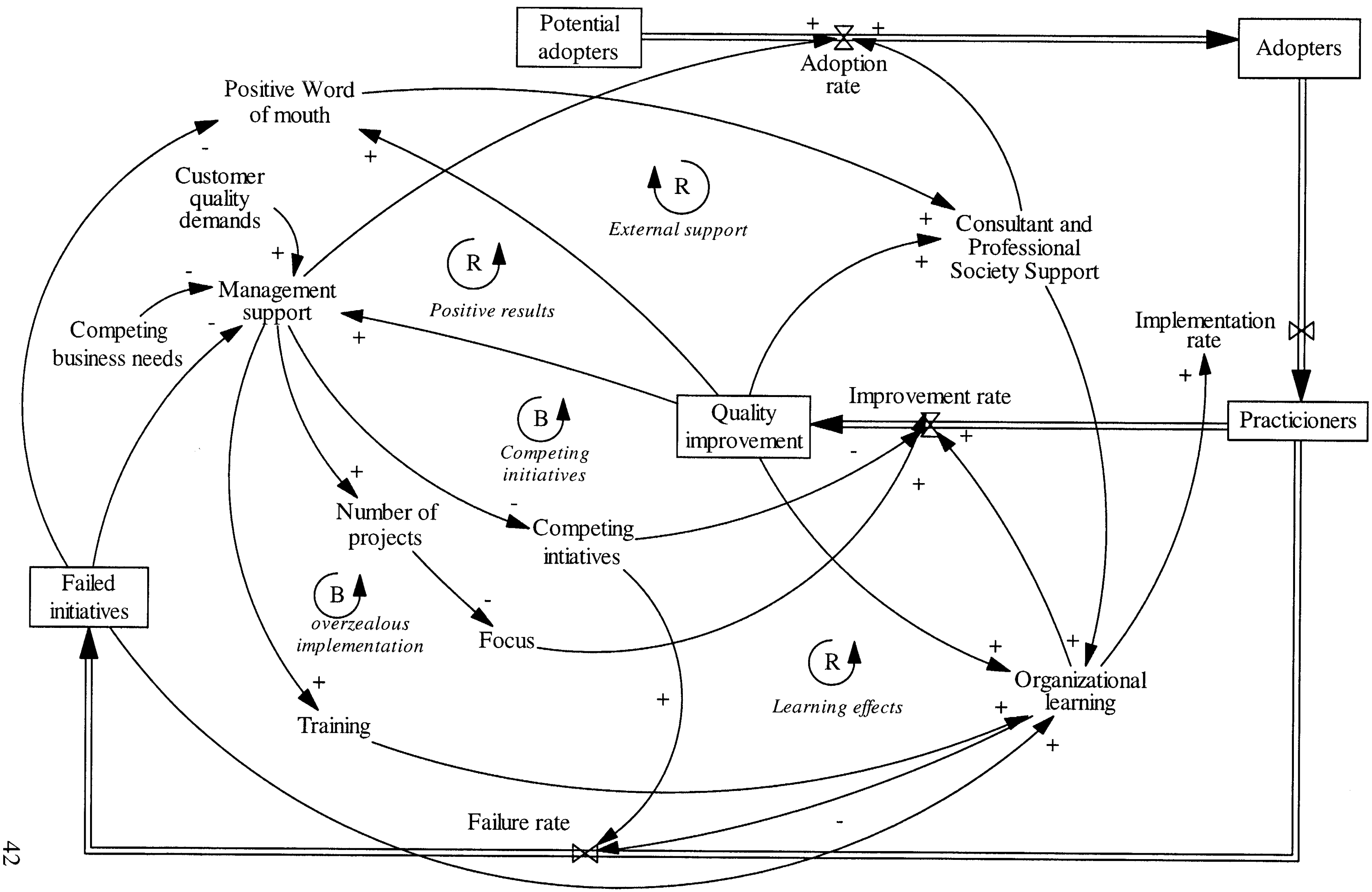

Figure 3: Reinforcing Feedbacks Driving Improvement

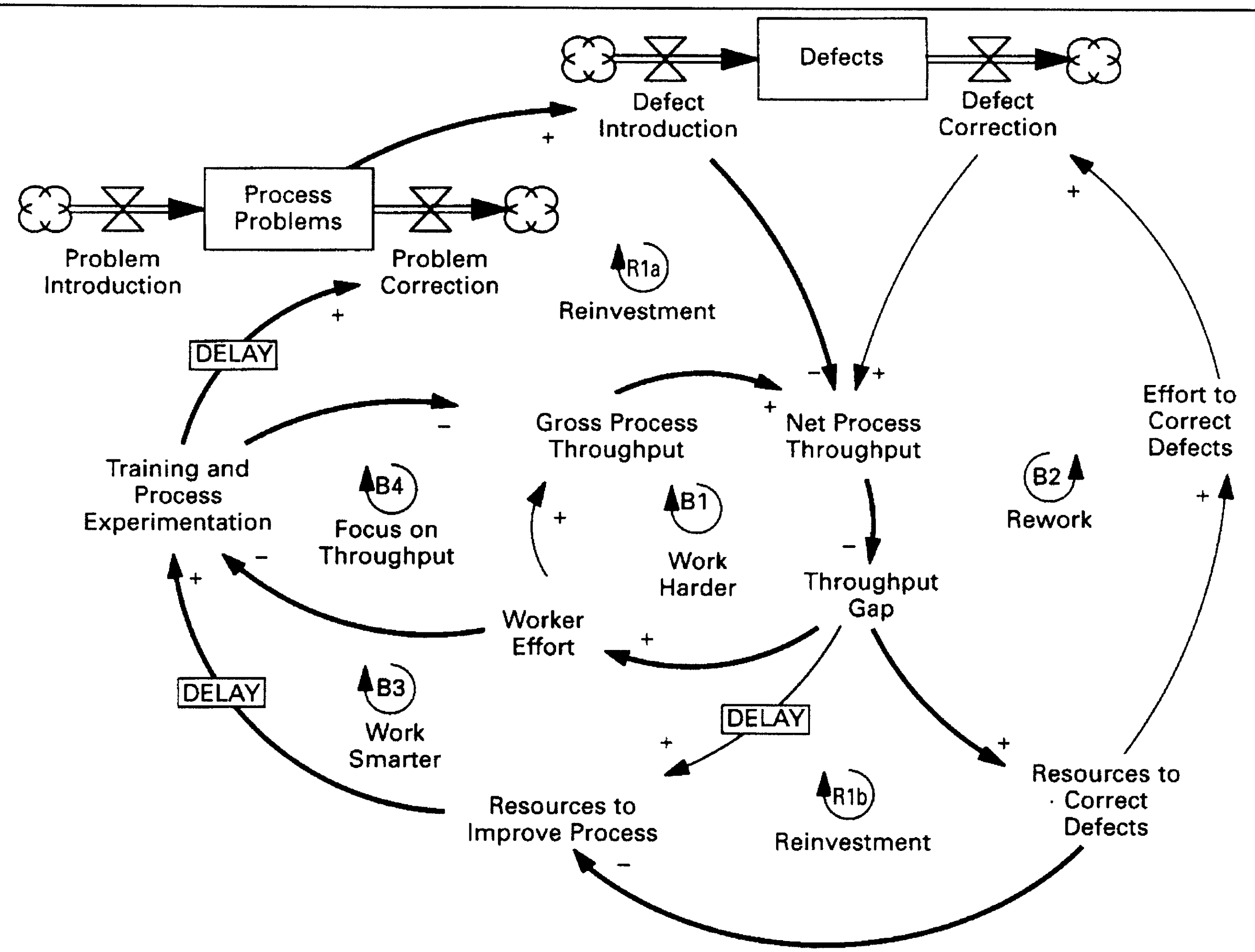

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Figure 4: Factors Influencing Product Quality

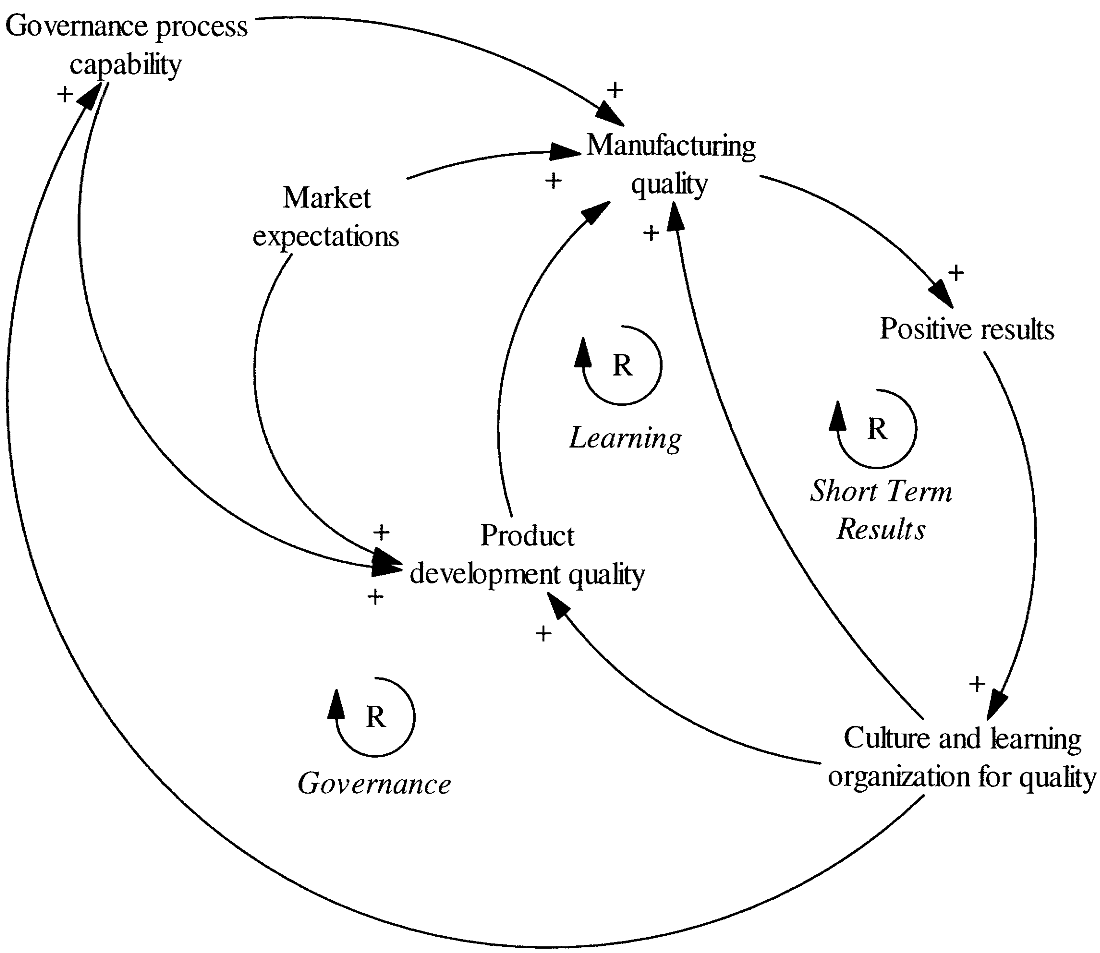

Figure 5: Influence of Standards

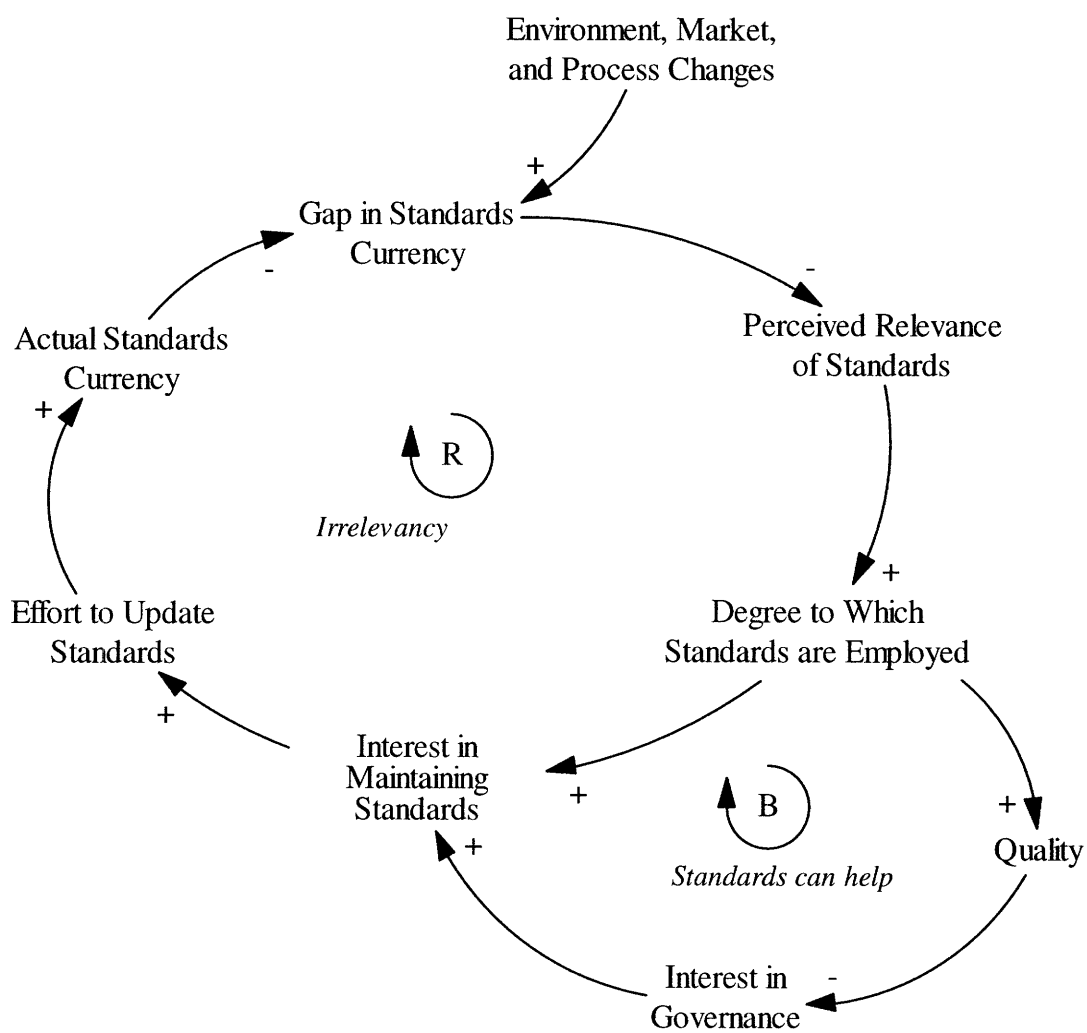

Figure 6: Influence of Various Factors on a Sample Mining Truck's Cost per Ton

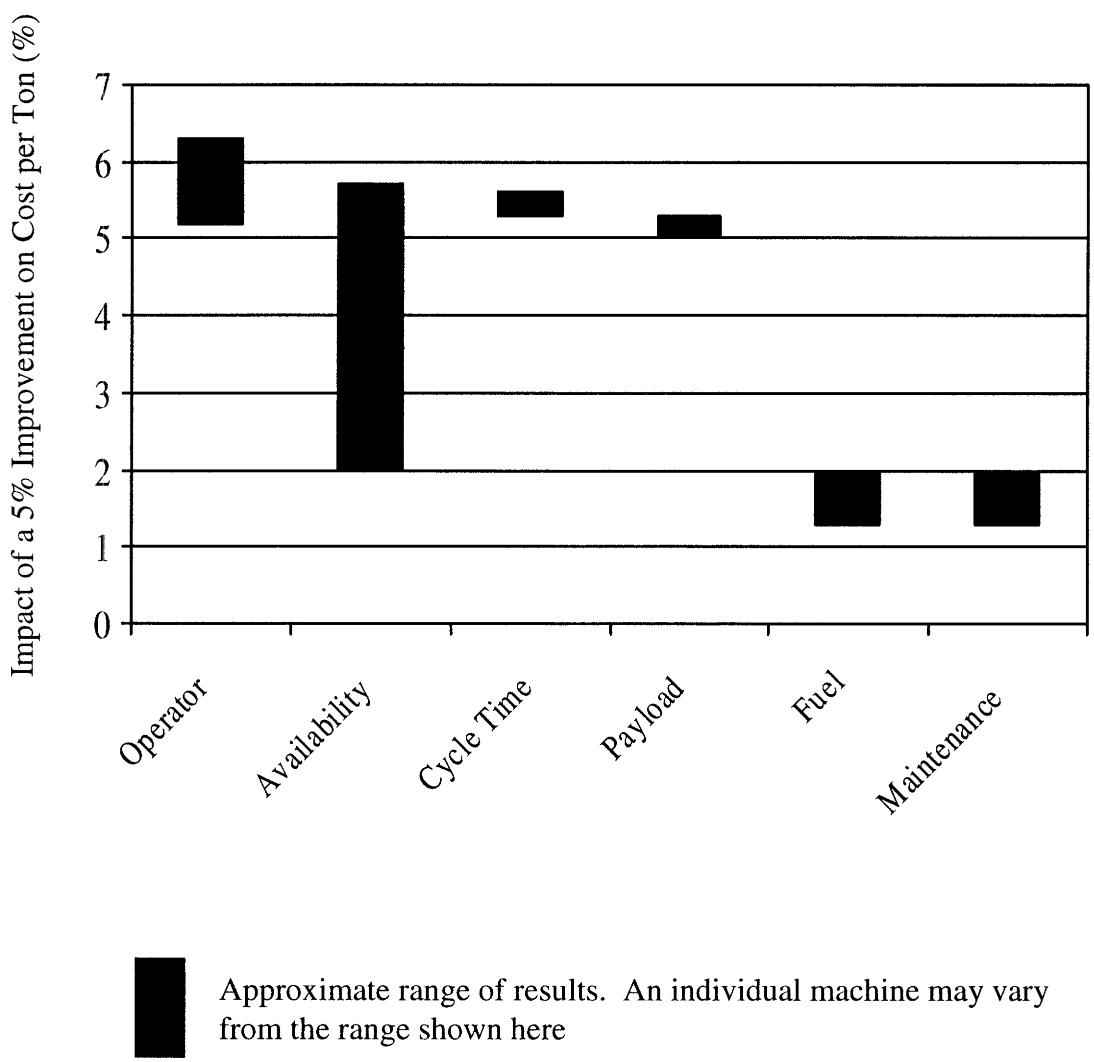

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Figure 7: Influence of Customer Relationships on Management Focus

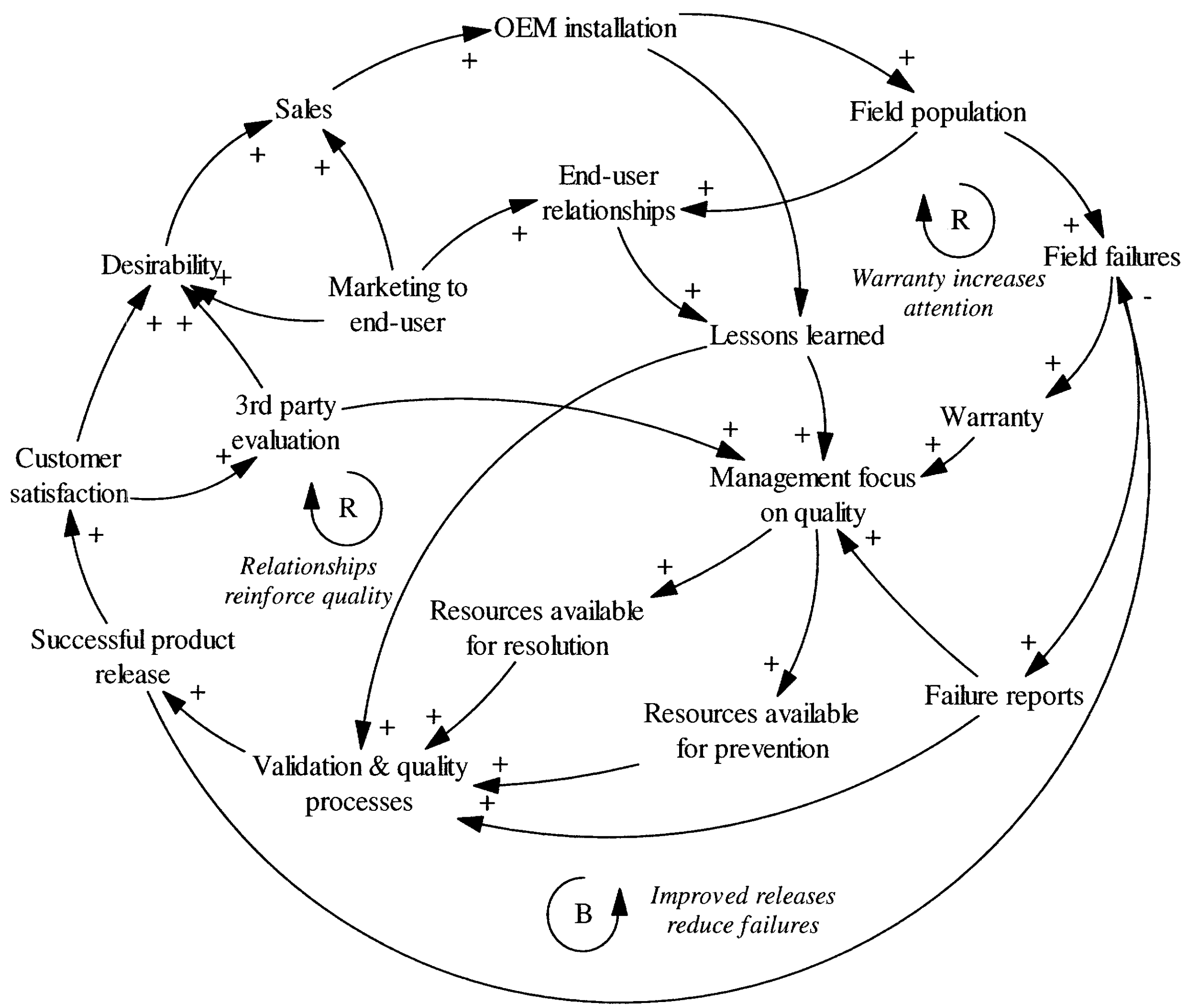
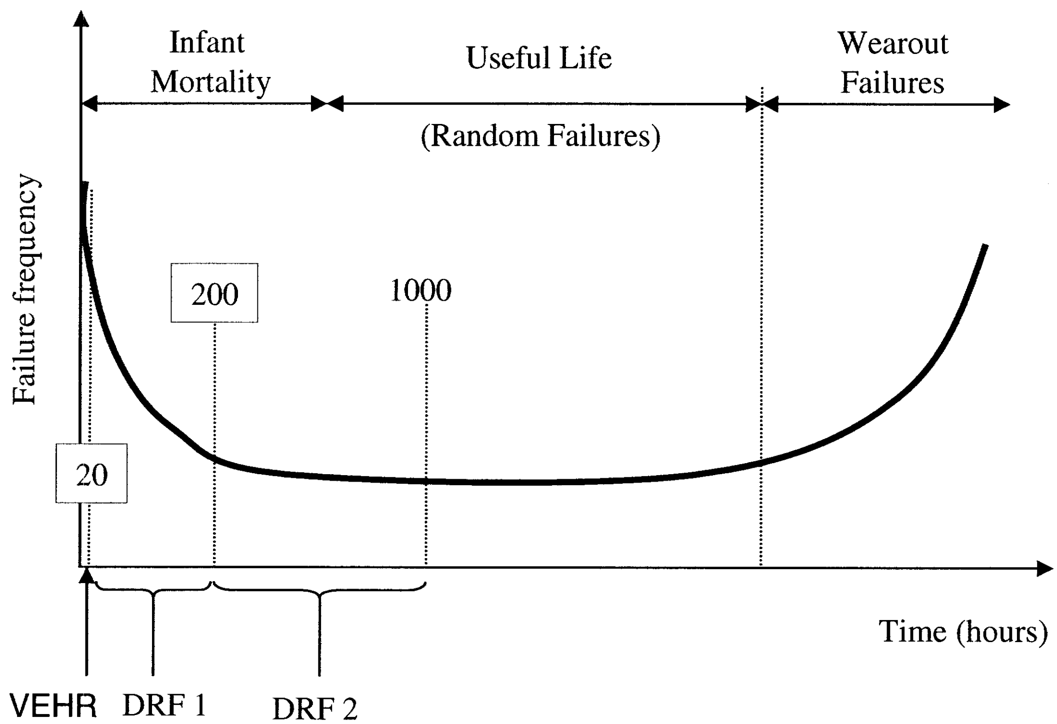


Figure 8: Reliability Bathtub Curve



Illustrative only: Not to scale

Figure 9: Reliability Comparison of Machines Manufactured in Two Plants

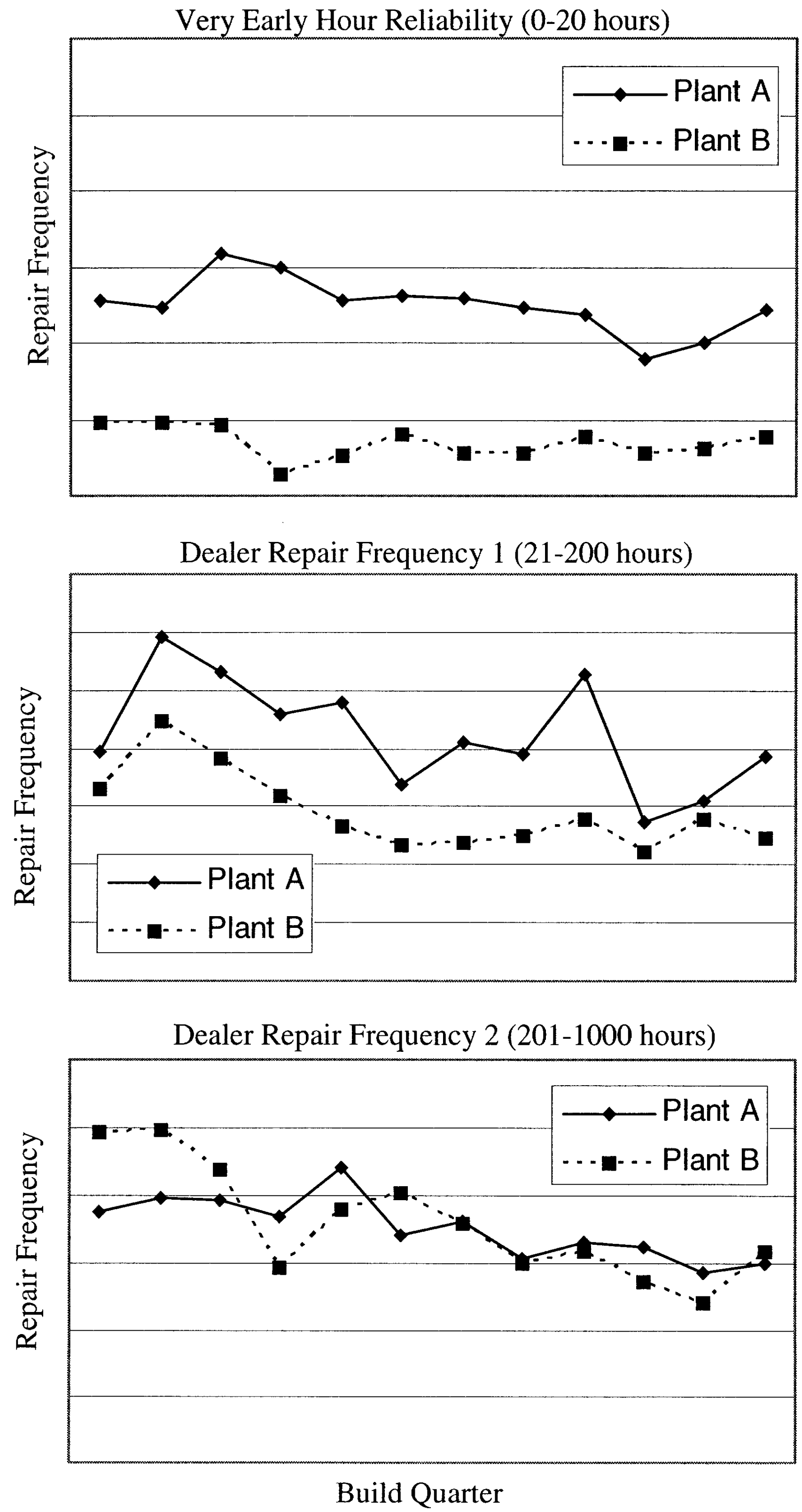


Figure 10: Engine A and Engine B Innovation

Linkages Between Core Concepts and Components	Core Concepts: Reinforced	Core Concepts: Overturned
Unchanged	Incremental Innovation Engine B Innovation: Increased rating capability Leveraged: Reinforced concepts: engine A components Unchanged architecture: engine A electronic control system	Modular Innovation
Changed	Architectural Innovation	Radical Innovation Engine A Innovation: Electronically controlled fuel system Leveraged: Overturned component: electronic fuel system Changed architecture: electronic control system

Matrix structure originated by Kim Clark and Rebecca Henderson.
MIT Sloan Courseware 15.912

Figure 11: Influence of Organizational Learning on Quality

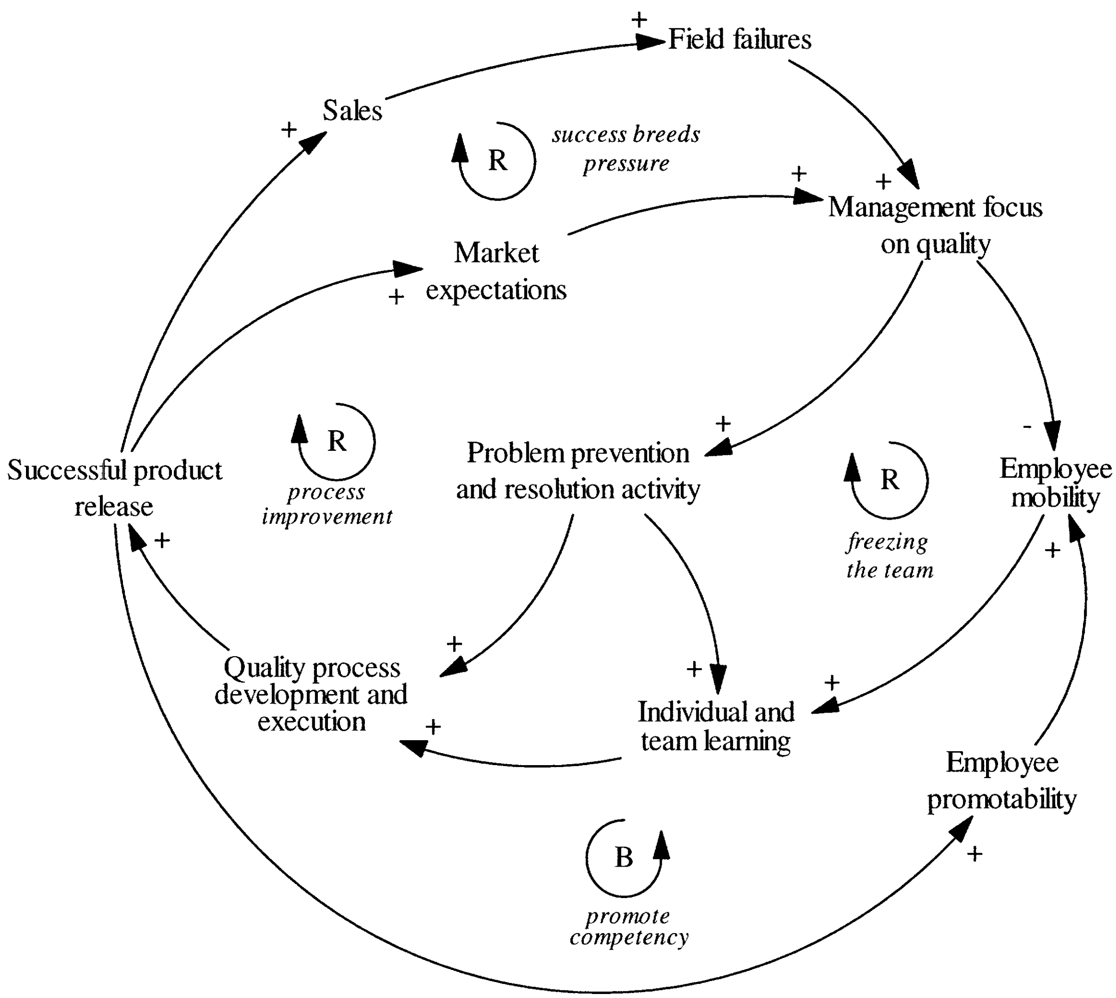


Figure 12: The Role of Bureaucracy, Trust, and Team Learning in Quality

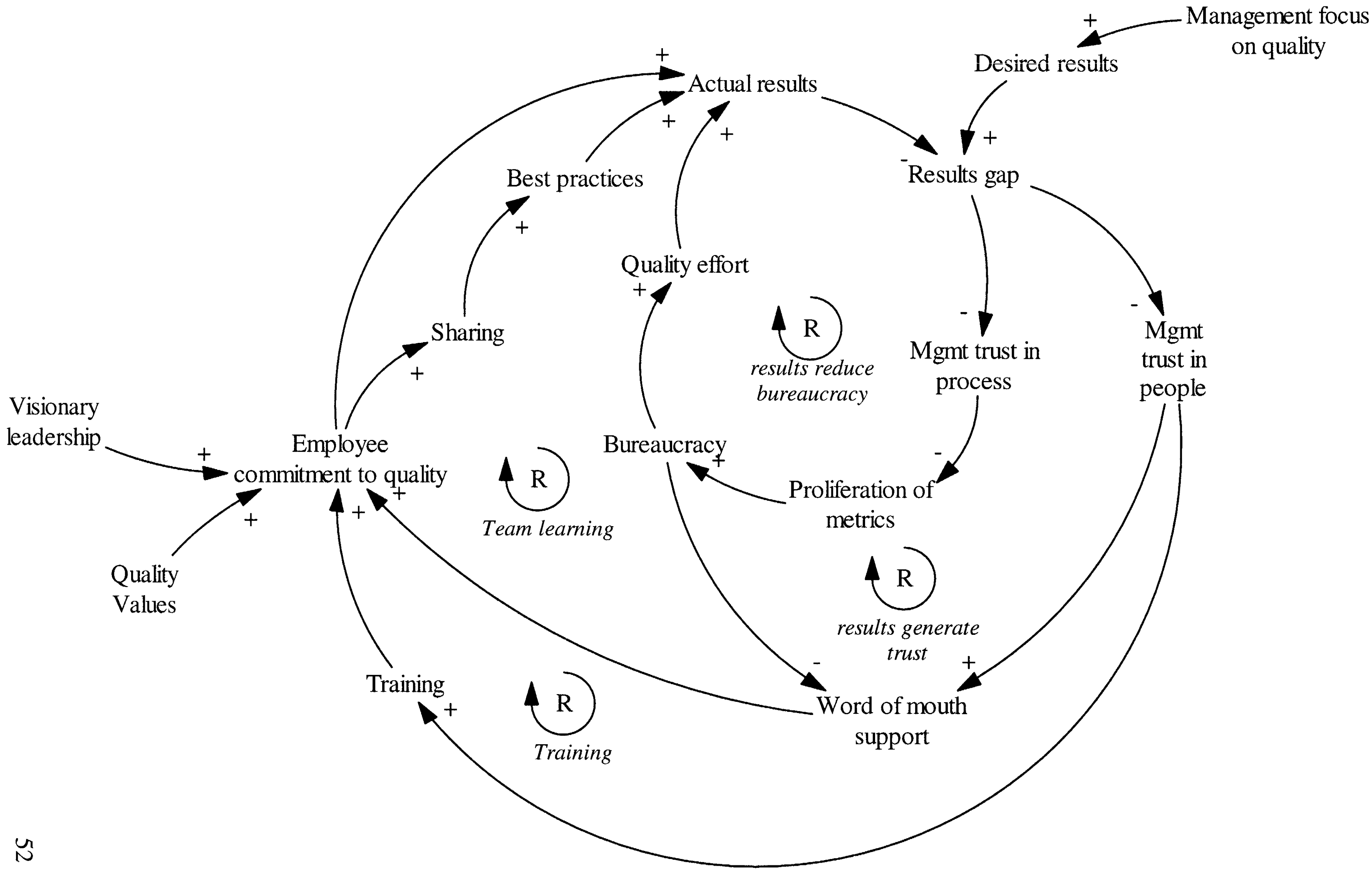
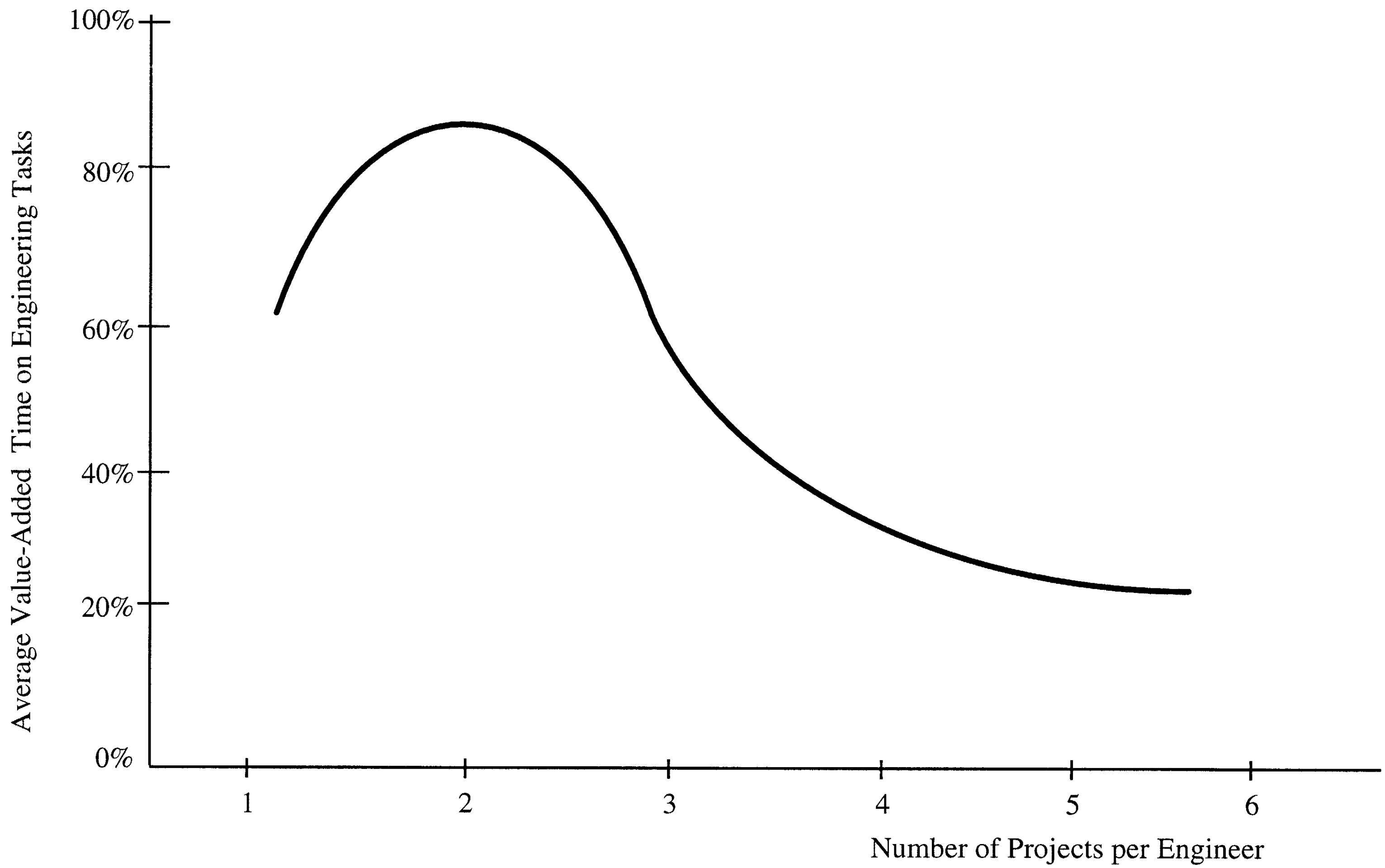


Figure 13: Project Overload Reduces Engineering Efficiency



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