Center for Quality and Productivity Improvement
UNIVERSITY OF WISCONSIN
610 Walnut Street
Madison, Wisconsin 53705

(608) 263–2520
(608) 263–1425 FAX

Report No. 69

Quality Improvement at the Design Stage
A Cyclic Incremental Approach

Søren Bisgaard

May 1991

The Center for Quality and Productivity Improvement cares about your reactions to our reports. Please direct comments (general or specific) to: Report Editor, Center for Quality and Productivity Improvement, 610 Walnut Street, Madison, WI 53705; (608) 263–2520. All comments will be forwarded to the author(s).

CQPI
UNIVERSITY OF WISCONSIN

Report No. 69

Report Series
in Quality and Productivity

Quality Improvement at the Design Stage
A Cyclic Incremental Approach

Søren Bisgaard, PhD

Center for Plasma Aided
Manufacturing, Center for Quality
and Productivity Improvement
and the Department of
Industrial Engineering

University of Wisconsin
Madison, Wisconsin

ABSTRACT

Quality control based on inspection and segregation is uneconomical and inefficient. To be effective, quality needs to be considered and planned at the product design stage. In this article we put what seems like detailed problem solving, troubleshooting and statistical experimental design work into the larger context of the design and product development process. To do this we have developed a conceptual model for the design process based on the idea of *cyclic incremental improvement.*

KEYWORDS: Cyclic incremental improvement, concurrent engineering, engineering design, experimental design, Evolutionary Operation, total quality control, total quality management

---

This work was sponsored by National Science Foundation Grant DDM-8808138 and Grant ECD–872 1545.

CQPI Report No. 69, May 1991

Quality Improvement at the Design Stage
A Cyclic Incremental Approach

Søren Bisgaard

Quality control based on inspection and segregation is uneconomical and inefficient. To be effective, quality needs to be considered and planned at the product design stage. In this article we put what seems like detailed problem solving, troubleshooting and statistical experimental design work into the larger context of the design and product development process. To do this we have developed a conceptual model for the design process based on the idea of cyclic incremental improvement.

1. INTRODUCTION

Most people associate *quality control* with mass inspection and segregation of finished products. Upon reflection, however, it is clear that an approach to quality that is based on merely separating good from bad products is expensive. In fact, at the time of final inspection, the defective products have already been made. They are as expensive to produce as the acceptable products. In addition, the necessary and costly inspection and related bureaucratic systems substantially increase manufacturing overhead. Thus, to economically manufacture quality products, quality must be *planned for and built-in during the product design phase.*

Modern quality assurance is based on a philosophy promoting continuous never-ending process improvement, prevention of defects, and removal of root causes for bad quality, in particular at the design stage. To assure quality, systems and management procedures must be developed so that quality is inherently designed into all processes and products. The remarkable fact is that this approach improves quality and simultaneously leads to overall cost reduction. In the long run, high quality costs less—not more. This seemingly counter-intuitive relationship is not just a textbook theory. Leading Japanese manufacturers as well as an increasing number of progressive American firms will testify to the benefits of this, see Garvin (1983) and Therrien (1989).

The responsibility for quality can no longer be delegated to a separate quality control department. Building in quality requires top management involvement and organization-wide planning. The Japanese call this Total Quality Control (TQC), Company Wide Quality Control, or Total Quality Management (TQM), see Ishikawa (1985), Imai (1986), Mizuno (1988). Their approach is company wide, cross functional, and includes a comprehensive management strategy. Like the strength of a chain, quality depends on the strength of *all* the individual links—the design, production, sales and service functions and all their mutual interrelationships. Therefore, Total Quality Control is an overall management philosophy that permeates every corner of the manufacturing function and every related internal service operation. Quality is everyone's responsibility, not just of the quality control department.

A key responsibility for quality must rest within product design. A poorly designed product will remain "shoddy" no matter how well the later manufacturing operations are executed. Professor Ishikawa, considered the dean of Japanese quality control until his death in 1989, repeatedly stated that "Quality must be built into each design and each process," echoing the American statistician Dr. W. Edwards Deming's point that we should "cease dependence on inspection to achieve quality," and instead "Eliminate the need for mass inspection by building quality into the products in the first place." In other words, we should move upstream and work on defect prevention and improvement as far up in the product development process as possible. Quality improvement efforts should start at the design stage.

This may sound like a logical philosophy. But how do we implement it in practice? Specifically, what is the role of quality assurance in the design function? Quality assurance in design is a vast topic; we will not be able to fully cover it in this paper, but only outline some of the aspects and applications of quality assurance techniques in the product design function. The focus will be towards the role of statistics and experimental design in the design of products. This view is based on several years of highly interactive work by the author with design and manufacturing departments of several companies.

In Sections 2, 3 and 4 we will discuss a model for the design process that we have found useful in conceptually understanding the role of statistics and quality control principles in the product design process, and in Section 5 we will provide two examples that illustrate the intimate interrelationship between design engineering and quality improvement using statistical methods. In Section 6 we provide some concluding remarks.

2. ENGINEERING DESIGN AS A CYCLIC INCREMENTAL PROCESS

To introduce the role of quality control, and particularly statistical methods, into product design, we will describe a simple conceptual model of the design and manufacturing cycle. Our discussion will be primarily about mechanical designs since this is the area where we have most experience.

Typically we imagine a linear process where design engineers create a product design starting with a new idea and clean sheet of paper (or blank CAD screen). In time, the designer produces a set of drawings and specifications which are subsequently sent to the prototype shop. A prototype is built and tested to see if the product satisfies the requirements. If so, the design is sent to the production engineers who prepare the product for manufacturing, work on developing a rational system for making it, design jigs, fixtures and the special machinery needed. Next, the product enters a trial production and production process trouble shooting phase. Finally the ramp-up to full scale production occurs.

These are the major, *logical* phases of a traditional product development process. However, these steps are rarely followed in practice.

Although we often might think of "new" designs as entirely new and following these development steps, most "new" products are, actually a new *generation* of an already existing product rather than an entirely new *species*. Creating a "new" generation of a product only requires incremental changes from a previous product design. A designer often copies and mimics previous designs, and uses analogies with already existing products as well as standard machine elements put together in new and novel ways. Seldom does a new design come from nowhere, without predecessors. For example, automotive engineers design new cars by making only marginal changes from previous models. Looking back in history, automobiles from around the turn of the century very closely resembled the wooden frames of horse carriages of the day. And, the internal combustion engine they used evolved gradually from the steam engine. In fact, many design features were the same. So without trying to downplay the importance of the work of the early auto engineers, the first automobiles were essentially a combination of two existing technologies with some additional refinements and improvements. Over time after numerous iterative cycles, we have arrived at what we now call an automobile. And clearly that design is quite different from the early models. The important point here is that the product *evolved*, and continues to evolve incrementally rather than being the creation of a revolutionary design. Thus we suggest that design engineers are more appropriately considered the midwives to the births of succeeding generations of new products rather than the Gods and creators of novel species.

To illustrate this point, consider Edison's electric light bulb design and the accompanying power distribution system which clearly was a breakthrough in terms of product development. In his product development work, Edison frankly admitted that he based the design of the electric distribution systems and their various components on analogy with the already existing gas light distribution systems, while adapting, modifying, improving, and marginally changing existing components and concepts for his use. For more details, we refer to the interesting biography by Friedel, Israel and Finn (1987) based on Edison's extensive and detailed laboratory note books.

Even more interesting is the Wright Brothers' airplane. Their first airplane design may seem like the canonical example of a truly "new" product design. However, looking more carefully into their work we discover that many features for the control of the airplane, which became the key to their success, were based on Wilbur Wright's insightful understanding of the steering and control of bicycles. This adaptation in addition to their meticulous wind tunnel experiments and accumulated experience from previous and contemporary aviators' experiments with hang gliders, were the basis for their product design. For details see Crouch (1989) and Kelly (1943).

Clearly, looking at the work of the Wright Brothers between 1899 (when their first serious interest in human flight began) and December 17, 1903, the date of the first successful take off, we must acknowledge a great leap forward in terms of product development. But their work was based on many incremental changes, inspired by building a series of prototypes and subsequent experiments followed by detailed trouble shooting and problem solving. Each iteration led to a better design. After years of meticulous experimentation with hang gliders, bicycles, wind tunnels, and finally crude prototypes of manned aircrafts they were able to fly 120 feet, then 195 feet, 190 feet, 852 feet and so on. After more work with prototypes, modifications, more troubleshooting, experimentation, problem solving, and extensive test flights, they incrementally learned better ways to design their product and improved even the smallest details. And finally, after a few more years of hard work and numerous incremental changes they developed a patentable "new" product design in 1906.

Looking at the work of early engineers, the Wright Brothers in particular, shows it is inherent in the incremental learning process that not all changes lead directly to improvements. For example, changes made over the years to automobile design did not all lead to improvements. Nevertheless, they contributed to the essential learning that comes from failure, to make better, safer, more fuel efficient, and comfortable automobiles.

We are suggesting, then, that product design is usually an incremental learning process based to a large degree on experimentation, problem solving, and detailed trouble shooting. Admittedly our examples are historic, but we believe they still are representative for much of today's product development work. We also admit that it might sound more systematic and scientific to think of a design theory based on starting out with a clean sheet of drafting paper and a bright idea, followed by linear deductive logic. But our experience, working with and studying the work of design engineers, has led us to believe most design work is better thought of as a learning, problem solving, and trouble shooting process.

3. LEARNING MODELS: AN ANALOGY WITH BIOLOGICAL EVOLUTION AND CORRECTIVE FEEDBACK

As indicated we have found that most product designs evolve, rather than originate from a sudden stroke of genius (or a revolution). In fact, we think the design process has much in common with the biological evolution of species originally expounded by Charles Darwin (1859). This process has been explained in a particularly lucid way by Box (1957) in connection with his concept of Evolutionary Operation (EVOP) which is a method for optimizing production processes. According to Darwin, living species advance because of two mechanisms: (*i*) Variability, and (*ii*) Natural Selection of favorable variants. To explain these mechanisms, Box uses a simple example of the possible evolution of lobsters and a diagram reproduced in Figure 1. In particular Box (1957) explains:

> It is supposed that a particular mutation produces a type of lobsters with "length of claws" and "pressure attainable between claws" corresponding to the point *P* on the diagram and that in a given environment the contours of "percentage surviving long enough to reproduce" are like those shown in the figure. The dots around *P* indicate offspring produced by the initial type of lobster. Since those in the direction of the arrow have the greatest chance of survival, over a period of time the scatter of points representing succeeding generations of lobsters will automatically move up the survival surface. This automatic process of natural selection ensures, without any special effort on the part of the lobsters, that optimum-type lobsters exist. It also ensures that if the environment alters so that the survival surface changes, the lobsters will change correspondingly to the new point of maximum survival.

We find that man-made products evolve much the same way. Designers and manufacturers continuously try new variations. The prototype lab tests and the market-place ensure "survival of the fittest." Moreover, like lobsters adapt to a changing environment, so do products evolve, guided by the forces of changing customer expectations of quality, performance, and cost, as well as changes in the competitive environment.

In his explanation of EVOP, Box (1957) suggests that in order to take advantage of the process of evolution in the industrial context, "what we have to do is to imitate this [naturally occurring] process." In the specific context of product development, this means that we need to deliberately mimic the two essential features of biological evolution, namely (*i*) variation, and (*ii*) selection of the most favorable variant.

In the process of product development, we can consider the discovery or invention of entirely new concepts or products as analogous to genetic mutations. For the sake of the discussion a typical example of mutation might be the invention of the transistor. On the other hand, this year's model of an automobile, a new airplane model, or a larger microchip, are more appropriately considered to be generated by incremental variation and natural selection, much like succeeding generations of lobsters.

Another important model that helps explain the inner workings of the design process is the cyclic learning process/corrective feedback model known in the quality control literature as the Plan, Do, Check, Act (PDCA) cycle. The EVOP model explains on a relatively macroscopic level how product designs evolve and improve through a never ending sequence of iterations or cycles. The PDCA cycle, on the other hand, is the detailed mechanism that drives each cycle in the process of product variation.

The PDCA cycle idea originated with Dr. Walter Shewhart of Bell Laboratories in the 1930s, in connection with the development of specifications and quality inspection, see Shewhart (1939). Dr. Deming then extended the idea and explained it in the early 1950s to Japanese managers and engineers. Today this cycle, also known as the Deming Cycle, is considered a general purpose tool for problem solving and one of the most fundamental concepts in Japanese quality literature.

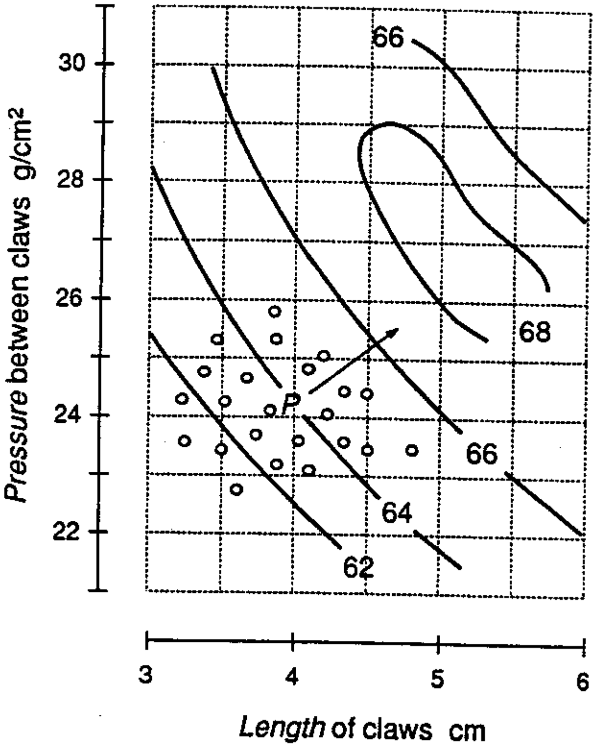

Figure 1. *Evolution of a species of lobster. Contours show the percentage surviving long enough to reproduce in a given environment.*

The PDCA cycle (shown in Figure 2) begins with gathering data and data analysis of the current situation. Based on this analysis, a plan is formulated, and the finished plan implemented. After implementation, planned improvements are checked to see if they led to real improvements. Then either the plan becomes the current standard, or is suitably modified, leading to another PDCA cycle.

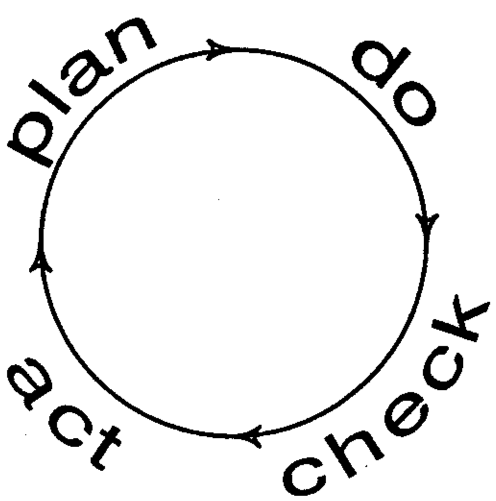

Figure 2. *The Plan–Do–Check–Act (PDCA) cycle, by Dr. W. Edwards Deming.*

We will now combine these two models, the EVOP idea and the PDCA cycle, to explain the product development process.

4. PRODUCT DEVELOPMENT AS A CYCLIC INCREMENTAL IMPROVEMENT PROCESS

Figure 3 shows the common linearly depicted product development process wrapped around as a continuously rotating PDCA cycle; thus making it explicit that product developement is a continuous never-ending process, and not a project that ends when the product is introduced into the market. For each turn of the PDCA cycle, a new generation (offspring) of product designs is generated, and depending on its survival in the market place, it is selected as the standard or base (parent) for the next generation. Figure

3 shows only one large macroscopic PDCA cycle, but in reality many small PDCA cycles orbit around each individual step in the product development process like small moons around planets.

Although many steps in our product development model are the same as in standard textbook models, see Vincent (1989), it is important to note a few differences. In particular we want to emphasize the importance of (*i*) establishing systems for learning, corrective feedback, and preventive feedforward, (*ii*) the forming of cross functional product development teams that stays with the product from the beginning to after the market introduction, and (*iii*) the use of customer feedback, benchmarking, customer surveys, and experiments to feed information about customer satisfaction with the product back into the design process. Note also the specific phase of product optimization and robustification.

We consider customer input of primary importance. It is their needs and expectations regarding quality, performance, delivery, and cost that will ultimately decide whether a product is "fit", and hence "survive" as a success. However, feedback from customers using the product is not enough. Even before the first draft of a product design, we should "listen to the voice of the customer" or, even better, "establish a dialogue with customers" to solicit ideas about product design and potential improvements. It may seem trivial, but extraordinary arrogance toward customer needs and expectations is often displayed by management and design engineers (see Halberstam, 1986). In a global competitive environment, customers quickly learn that they need not put up with products that break, malfunction, or cause damage and losses. Only companies that strive to satisfy, and possibly exceed the constantly moving target of their customers rising expectations will stay in business.

The new technique Quality Function Deployment (QFD) maps out the relationship between customer requirements and expectations, and product functions and specifications. In this article, we will not discuss this technique further but refer the reader to Hauser and Clausing (1988). QFD is currently being tried by many companies and some strongly advocate it as a tool for "listening to the voice of the customer". This and other tools and methods such as market surveys, customer use of early prototypes, customer interviews, feedback from service departments, repair data, and information from insurance companies can help "establishing a dialogue with the customers" about ways to improve the products.

In Figure 3 we show the product development process as a sequences of blocks, which may imply that each step must be finished before the next can begin. However, we support the ideas of *Simultaneous Engineering* expounded by Hayes, Wheelwright and Clark (1988) and *Concurrent Engineering* as described by Winner, et al. (1988). The driving force behind these concepts is the desire to reduce total product development cycle time. One way to achieve this is to overlap the product development phases. For example, once the specifications of parts of a larger design have been agreed upon, these specifications can be carried forward to the prototype shop or sometimes to the production engineers who can start designing the dies, jigs, and fixtures before the whole design is complete. Of course, the specific design detail must be frozen. And, this implies that the early design reviews must be based on solid facts, data, and carefully executed experiments and capability studies. Another important prerequisite for this is the use of cross functional (concurrent) teams consisting of design engineers, as well as production engineers, marketing people, sales, quality control, and service function personnel who work together throughout all product development phases and even after market introduction. Thus we don't regard the

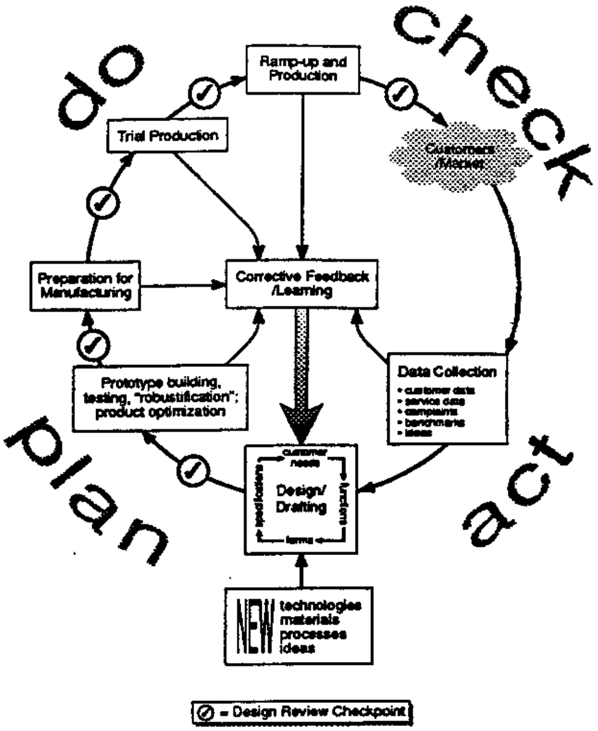

Figure 3. *The continuous process of cyclic incremental improvement of product designs as a PDCA cycle.*

ideas in this paper as alternatives to the Concurrent Engineering proposal by the Institute for Defense Analysis (see Winner et al.,1988), but rather this paper is a further discussion and an attempt to clarify the connection between that proposal's heavy emphasis on experimental design techniques, Taguchi Methods, and statistics in the reported case studies, and the main report's emphasis on product development time reduction.

5. EXAMPLES OF USING STATISTICS IN PRODUCT DESIGN

In the previous sections we have discussed the product development process as an incremental cyclical learning and problem solving process. In this section we will provide a few examples of how this process works in practice, particularly showing where statistical methods helped increase the rate of learning, and systematized the problem solving process.

EXAMPLE 1: INCREMENTAL IMPROVEMENTS OF BALL BEARING DESIGNS

The Swedish Ball Bearing company, SKF, is the world's largest manufacturer of rolling bearings and has a worldwide reputation for their high quality products. They have been in business for more than 80 years and are producing a mature product. Nevertheless they constantly seek to remain ahead of their competitors. Most of their quality efforts are concentrated on maintaining a high degree of consistency (low variability) in their production. This work is guided by the use of statistical process control (SPC),which incidentally, often leads to discovering ways to reduce the variability and thereby the manufacturing quality.

Another SKF effort, however, is geared towards improving the design of ball bearings. Although ball bearings are standard machine elements sold as a commodity, there is currently a trend towards specializing the ball bearing designs to specific customer needs—such as automotive applications, electric fans, or washing machines. For one application, SKF engineers and statisticians recently conducted an eight run, two-level factorial experiment varying three design specifications to see which would produce the longest lasting bearing for that application. The factors which were varied were the inner ring heat treatment, the ratio of the ball to the outer ring raceway radii (also call the osculation), and the design of the cage that locates the balls in the raceway. For each of these factors, two different levels were chosen: the standard and an alternative specification.

The factor osculation was particularly interesting. Prior to the experiment, one could argue that a large ratio between raceway and ball radii would make a small contact area and hence less friction, less heat, and therefore, less wear and a longer lasting bearing. Another contrary argument suggested that if the contact area is larger (achieved by making the radii ratio closer to one) the bearing can transfer more load and therefore last longer. These are typical examples of the kinds of arguments based on logical deductions that often take place among design engineers. In some instances, existing theory can help resolve the issue. In others, a statistically designed experiment can provide a quick, reliable, and efficient answer.

In this instance, the SKF engineers discovered something entirely unexpected. In six out of the eight experimental trials the results from an accelerated life test were between 16 to 25 hours. Two other tests showed the observed life was in the range 85 to 128 hours. Of course, this unexpected result led to several replications of the experiment, and it was discovered that these tests were not flukes. Rather this was an unexpected two-factor *interaction effect* between the outer ring osculation and the heat treatment specification previously unknown to SKF's engineers and research staff. It would be interesting if this interaction could be justified theoretically, and hence lead to a new and better understanding of the fundamental theory of ball bearing design, ultimately leading to even better ball bearings in the future. In any case the real power of experimental design is when it is used in conjunction with theory in an iterative inductive–deductive learning process, as explained by Box, Hunter and Hunter (1978).

Another interesting discovery from this experiment was that the cage design had little effect. Thus SKF was free to choose the more economical design. We can imagine engineers arguing endlessly in meetings about which design was better. With a well planned experiment these issues can be resolved quickly and engineers can move on to other problems, thereby reducing overall product development time.

The SKF example is remarkable because the design of ball bearings is so mature. On the other hand, it is typical of the power of incremental design improvements. Based on this success, the SKF statistician and his staff have conducted several other successful experiments for improving the ball bearing designs to meet or possibly exceed special requirements from particular customer groups. For more on this experiment and SKF, see Hellstrand (1989). Another example of using experimental design techniques for developing a prototype design for a complex manufacturing machine is described in Bisgaard (1989).

EXAMPLE 2: CUSTOMER-DRIVEN INCREMENTAL QUALITY IMPROVEMENT OF CAMERAS

The following case illustrates an advanced level of quality product development using statistics. This case study is originally due to the internationally recognized quality management expert Professor Kano of the Science University of Tokyo and Japanese Union of Scientist and Engineers (JUSE), and partially described in Kano (1987). During the early 1970s, the camera industry reached a product development plateau. Most cameras focussed through the lens or used an interlocking distance device, and had a built-in light meter often coupled directly to either the aperture or shutter speed. From a technical point of view the cameras were perfect. If the amateur photographer ended up with bad pictures, the operator, not the camera, was to blame. However, the Konica company formed a small group of design engineers, manufacturing engineers, and marketing people to consider the future development of cameras. In an initial meeting, the group decided that Konica was not in the business of manufacturing cameras, but rather to satisfy ordinary consumers' desire for high quality pictures of everyday events. As a consequence, the Konica group visited several photo development laboratories to see samples of developed films and prints. Often customers had many poorly taken pictures. A formal statistical study of the defective pictures was then conducted over time and a Pareto diagram (like Figure 4) was made to classify the defects into categories. From this Pareto diagram, we see that the most common cause for defective pictures is under-exposure and the second most frequent problem is out-of-focus. Other causes were much less frequent. Initially, this shocked the Konica engineers, because of the wide dissemination of strap-on flashes and interlocking distance measure devices. Still the statistical results became the clue to further product developments.

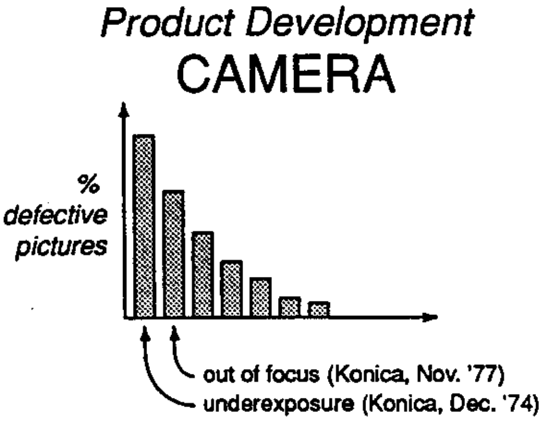

Figure 4. *A Pareto Diagram of causes for defective photographs.*

The Konica group subsequently interviewed select groups of customers. Most often the customers explained that they were happy with their camera, and blamed themselves for the poor quality pictures. A common explanation for under-exposure was that photographers forgot their flash at home, but still wanted to take pictures of indoor family gatherings. This "dialogue with the customers" led to the development of a miniature built-in flash. This new camera, the Piccari C35EF, introduced in 1974, was an instant success, and other manufactures quickly started copying the idea.

The Konica group, however, was already busy working on the next product model. As indicated in Figure 4, the second biggest reason for defective pictures was out-of-focus. The Konica engineers discovered that an American company in the projector business had developed an auto-focus system. Konica obtained rights to use this system, miniaturized it, and built it into their new line of cameras. This camera, the Juspin C35AF was released in 1977 and was also an instant success which was quickly copied by competitors.

Next followed a renewed study of the quality of pictures taken with these new cameras. This time the Pareto chart showed that often customers would discover an entire roll of film was blank due to defective film loading. Unfortunately Konica lost the leadership in product development. It was instead another company that developed a new camera with the previous features and added automatic loading and winding to reduce this problem.

Here we see a sequence of quality-driven product improvements made by a cyclic incremental approach, which ultimately reshaped an entire industry. The incremental improvements were driven by clearly defining customers' ultimate, but not necessarily conscious, quality expectations—namely good pictures, not just a camera with high quality lenses. We call this approach "establishing a dialogue with the customer", aimed at soliciting ideas for product innovations and quality improvements. The more commonly used phrase "listening to the voice of the customer", might convey the unfortunate connotation of one-way communication from customers to the manufactures assuming that customers explicitly know what they want.

This case story also clearly shows the role of scientific inquiry as a means of identifying the root cause of a problem. In this case, the statistical method used, a Pareto analysis, is technically very simple. It was, nevertheless, a statistics-driven scientific approach. In other situations, more complicated statistical tools might be necessary. However, we should keep in mind that the complexity of the statistical tools needed is incidental to the situation and clearly irrelevant in judging the quality of the solution.

6. CONCLUSION

These case studies support the thesis that quality improvement is essential at the design stage. Traditional end inspection for quality will not do. Progressive companies are now increasingly turning their attention to upstream improvement in the design of products and processes. This requires a scientific approach and close cooperation between design and manufacturing engineers, as well as quality engineers and statisticians. Thus it is not overly ambitious to claim that modern quality improvement represents a shift from traditional quality control. And this paradigm shift has a tremendous impact on the way design engineers work, see Woodruff, et al. (1990).

In this article we have suggested that the work of design engineers as being mostly sitting at their drafting board designing new products based on a linear deductive thinking process is not representative of how engineers really work. In reality, most design engineers work like Edison and the Wright Brothers. They are involved in incrementally changing and improving previous generations of designs which involves much problem solving, trouble shooting, and prototype testing. For this mode of operation to be more efficient, statistical methods of experimental design can be very helpful and facilitate a reduction in overall product development cycle time—the goal of Concurrent Engineering and other recent efforts.

ACKNOWLEDGEMENT

This work was sponsored by National Science Foundation Grant DDM-8808138 and Grant ECD-872 1545.

REFERENCES

Bisgaard, S. (1989), "The Quality Detective: A Case Study." *Philosophical Transactions of the Royal Society of London*, A 327, pp 499–511.

Box, G. E. P. (1957), "Evolutionary Operation: A Method for Increasing Industrial Productivity." *Applied Statistics*, Vol. 6, 81–119.

Box, G. and Bisgaard, S. (1987), "The Scientific Context of Quality Improvement." *Quality Progress*, June , pp. 54–62.

Box, G. E. P., Hunter, W. G. and Hunter, J. S. (1978), *Statistics for Experimenters*. New York: John Wiley and Sons.

Buffa, E. S. (1977), *Modern Production Management*. New York: John Wiley and Sons.

Crouch, T. (1989), *The Bishop's Boys: A Life of Wilbur and Orville Wright*. New York: W. W. Norton.

Darwin, C (1859), *The Origin of Species*. New edition, 1963 available through Washington Square Press, Inc. New York, NY.

Deming, W. E. (1986), *Out of the Crisis*. Cambridge: Massachusetts Institute of Technology, Center for Advanced Engineering Study.

Dertouzos, M. L., Lester, R. K. and Solow, R. M. (1989), *Made in America: Regaining the Productive Edge*. Cambridge, Massachusetts: The MIT Press.

Friedel, R., Israel, P. and Finn, B. (1987), *Edison's Electric Light*. New Brunswick, New York: Rutgers University Press.

Garvin, D. A. (1983), "Quality on the Line." *Harvard Business Review*, September–October, pp.65–75.

Gomory, R. E. (1990), "From the 'Ladder of Science' to the Product Development Cycle." *Harvard Business Review*, November–December, pp. 99–105.

Halberstam, D. (1986), *The Reckoning*. New York: William Morrow and Company.

Hauser, J. R. and Clausing, D. (1988), The House of Quality." *Harvard Business Review*, May–June, pp.63–73.

Hayes, R. H., Wheelwright, S. C. and Clark, K. B. (1988), *Dynamic Manufacturing*, The Free Press.

Hellstrand, C. (1989), "The Necessity of Modern Quality Improvement and Some Experiences With its Implementation in the Manufacture of Rolling Bearings", *Philosophical Transactions of the Royal Society of London*, A 327, pp 51–56.

Imai, M. (1986), *Kaizen: The Key to Japan's Competitive Success*. New York: Random House.

Ishikawa, K. (1985), *What is Total Quality Control? The Japanese Way*. Englewood Cliffs, N.J.: Prentice–Hall.

Juran, J. M. (1988), *Juran on Planning for Quality*, New York: The Free Press.

Juran, J. M. and Gryna, F. M. (1970), *Quality Planning and Analysis*. New York: McGraw–Hill.

Kano, N (1987), "TQC As Total Quality Creation", *Preceeding of ICQC' 87*, pp.143–148, Tokyo.

Kelly, F. C. (1943), *The Wright Brothers: A Biography Authorized by Orville Wright*. Republished 1989 by Dover Publications, New York.

Lloyd, D. K., and Lipow, M. (1977), *Reliability: Management, Methods, and Mathematics*. Second Edition, published by the authors, Redondo Beach, California.

Mizuno, S. (1988), *Company Wide Total Quality Control*. Tokyo: Asian Productivity Organization.

Schmitt, R. W. (1988),"Design-Centered Innovation," in *Design Theory '88*. Edited by Newsome, S. L., Spillers, W. R. and Fingers, S., New York: Springer Verlag.

Shewhart, W. A. (1939), *Statistical Method from the Viewpoint of Quality Control*. Originally published by Graduate School of the Department of Agriculture, Washington D. C. Reissued by Dover Publications with foreword by W. E. Deming, 1986.

Shigley, J. E., and Mischke, C. R. (1986), *Standard Handbook of Machine Design*. New York: McGraw–Hill.

Taguchi, G. (1987), *System of Experimental Design*, White Planes New York: Unipub.

Therrien, L. (1989), "The Rival Japan Respects: Motorola's Secret, Strong R&D, Built-in Quality and Zealous Service," *Business Week*, No. 3133, November 13, pp. 108–118.

Vincent, G. (1989), *Managing New Product Development*. New York: Van Nostrand Reinhold,

Vodosic, J. P. (1969), *Elements of Engineering Design*. New York: The Ronald Press Company.

Winner, R. I., Pennell, J. P., Bertrand, H. E., and Slusarczuk, M. M. G. (1988), *The Role of Concurrent Engineering in Weapons Systems Acquisition*. Washington D. C.: Institute for Defense Analysis, IDA Report R–338.

Woodruff, D., Miller, K. L., Armstrong, L., and Peterson, T. (1990), "A New Era for Auto Quality", *Business Week*, No. 3184, Cover Story, pp.84–96, October 22.

Young, J. A. (1988), "Technology and Competitiveness: A Key to the Economic Future of the United States", *Science*, Vol. 241, p. 313..