Techniques

A method for measuring total value towards designing goods and services

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Abstract

It has not been enough to include "quality dimensions" into a product or a service and expect the outcome to be world-class. Total value signifies a set of multidimensional measures towards realizing a competitive product (goods or services) that the customers would like and are willing to pay a premium price for. A "quality dimensions" set is one of its (total value) multidimensional measures. Such multidimensional value considerations would be vital for a company in maintaining a competitive edge in today's global and rapidly changing marketplace. The first question is why a "quality dimensions" set has not been enough? The second question is what are those multidimensional sets of measures that make-up this total value content? The last question is how to determine a cumulative total value-index that accounts for these sets of measures so that an organization could use this total value-index to optimize its product realization process and thereby control its (an organization's) degree of competitiveness. The paper attempts to answer these questions.

1. Introduction

Most industrial implementations of total quality management (TQM) are based on a set of dimensions (Garvin, 1987), which are "quality-oriented", goals are "quality-focused" (Hamel and Prahalad, 1989), or efforts are "quality-driven" (Garvin, 1993). Today manufacturing sectors are much more fiercely competitive and global than ever before (Magrab, 1997). Consumers are more demanding, competition is more contentious, and ruthless, and technology is advancing (and changing) rapidly. The quality-based philosophy inherent in a TQM implementation does not exploit the non-quality dimensions present in today's complex product design, development, and delivery (PD^3) environment (Besterfield *et.al.*, 1995). The competitors are always finding better and faster ways of designing and developing products (Clark and Fujimoto, 1991). Catching up in quality-oriented programs has not been enough to be a world-class leader in manufacturing (Heim and Compton, 1992). It has only made a company on a par with its competitors in terms of inheriting some of their product's quality characteristics (Hamel and Prahalad, 1989). But relatively speaking, it gets you there a few years later. Moreover, successful competitors rarely stand still. So it is not surprising that many companies feel trapped in a seemingly endless game of catch-up-regularly surprised by the new accomplishments of their rivals (Hamel and Prahalad, 1989). What is required is a total control of one's own PD^3 process from a "total value" perspective – that is to identify and satisfy the needs and expectations of consumers better than the competition and to do so profitably faster than any other competitor (Prasad, 1996).

Today, competition has driven organizations to consider concepts such as time compression (fast-to-market) (Clark and Fujimoto, 1989), concurrent engineering (Prasad, 1996), design for X-ability (Anderson, 1990), agility, leanness, tools, and technology (such as Taguchi (1987), value engineering (Magrab, 1997), quality function deployment (QFD) (Clausing and Hauser, 1988), etc.) while designing and developing an artefact. A TQM implementation most readily addresses many aspects of "quality dimensions" (Garvin, 1987) with respect to the functions a product has to perform (Ungvari, 1991). But

The TQM Magazine
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this is one of the many sets of multidimensional measures (Wheelwright and Clark, 1992) that an organization needs to consider to become a world-class leader in manufacturing (Stalk *et al.*, 1992).

In the TQM setting, many quality tools and techniques (Hoffherr *et al.*, 1994) and strategic intents (Hamel and Prahalad, 1989) have been employed for product design and development in an effort to capture other value considerations (Stalk *et al.*, 1992) that are not quality-based (Bhote, 1997). Japanese TQC (the foundation for TQM in the USA) (Ishikawa, 1985) had also focused on one or more such aspects beyond quality such as supplier relationships (Keiretsu) (Nishiguchi, 1994), CPI (Kaizen) (Evans and Lindsay, 1995), waste reduction (Muda)(Ohno, 1988), and the learning organization (Garvin, 1993) with TQM. Though there are some side benefits of imposing such quality-based philosophies – such as on products' "cycle-time" reduction (Clark and Fujimoto, 1989), business growth, and better return on investments (Dika and Begley, 1991), the value considerations are different from those quality-based tools and techniques (Prasad, 1997). Total value signifies a set of multidimensional measures towards realizing a competitive product (goods or services) that the customers would like and are willing to pay a premium price for. Value elements are a set of multidimensional measures that are considered not only important to the customers but to the suppliers and the company. Quality dimension represents simply one of its value elements. Many organizations have experienced difficulties in accommodating other value elements that are not quality-based through a set of "quality dimensions" (Garvin, 1987) or through a deployment vehicle that is purely TQM-based (Bhote, 1997). Researchers have noted that many of the pertinent value elements (see Stalk *et al.*, 1992) required during product design and development either could not be directly imposed through TQM (Wheelwright and Clark, 1992) or could not be fully addressed through a quality-based TQM process (Hoffherr *et al.*, 1994). With a TQM process alone, it is difficult to accomplish all aspects of total value – such as X-ability, cost, leanness, timeliness, responsiveness, agility, tools and technology, concurrent engineering, and organization issues (Prasad, 1996). For instance, being Baldrige eligible is not enough (Bowles and Hammond, 1991). The quality-based criteria in Baldrige are not broad enough to keep American companies on the leading edge in coming years. Baldrige criteria do not address non-quality-based elements, for example, success-innovation, financial performance, long-term planning, growth, etc. (Bowles, and Hammond, 1991). Hoffherr *et al.* (1994) have observed a dozen cultural barriers to TQM that have impeded an organization-wide acceptance of TQM. The long-lasting competitiveness means much more than the usual idea of quality as achieving standards through six-sigma limits, zero defects, etc. Long-lasting competitiveness also means more than the usual "customer satisfaction" – anticipating what they might need in the future – to include other value considerations that are beyond "quality-based" and which address needs of the entire organization – the company, supply-chain and the internal and external customers. Besides the usual cultural barriers to TQM (Hoffherr *et al.*, 1994), there are many other challenges an organization faces today to ensure its ongoing success in the changing marketplace.

The first challenge is to energize the diverse workforce so that they buy into the concept of total value improvement (not simply based on quality improvement programs) in every aspect of the business. The second challenge is to organize the work-groups or teams so employee and supply-chain efforts are aligned with the company goals (constancy-of-purpose). One way to meet these two challenges is through cooperative teamwork (Prasad, 1996). Teamwork consists of four elements: virtual teams, technology teams, personnel teams, and logical teams (Prasad, 1996). One part of teamwork is familiarizing the work-groups with the proper use of the technical tools (Ross, 1988); the other part is employee involvement (Dika and Begley, 1991). With all sorts of empowered tools, it would not do much good if employees are not motivated (Carroll, 1997). The third challenge is to bring the right kind of talent to the right kind of tasks. We can reorganize the tasks in the best possible way but it will do little good if the right talents are not available to work on them. Furthermore employees, no matter how motivated they are, may not be able to function well until the right techniques are in place and are supported by the right set of technologies. Prasad (1996) has recognized these concurrent engineering

The TQM Magazine
Volume 10 · Number 4 · 1998 · 258–275

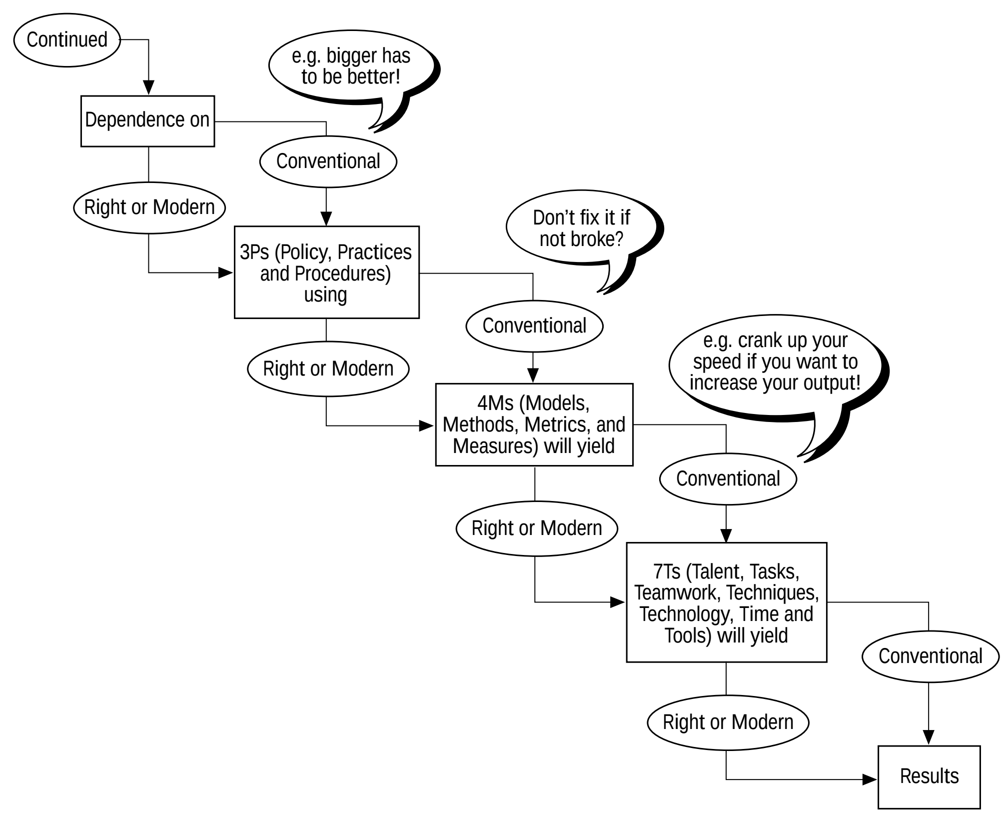
enablers as 3Ps (policies, practices, and procedures), 4Ms (money, machines, manpower, and management), and 7Ts (talents, tasks, teams, techniques, technology, time, and tools).

The mere fact of continued dependence on conventional 3Ps, conventional 4Ms, and conventional 7Ts is likely to yield conventional results (see Figure 1). The result may be an overall reduction of the enterprise's efficiency and it may affect the net profit margin. However, if the dependence is continued with right or modern 3Ps, right or modern 4Ms, and right or modern 7Ts, this will yield more likely right results (Figure 1) – meaning great products. Great products all share a set of properties (built into a product) that account for their greatness. Steven C. Wheelwright and Kim B. Clark (1992) of Harvard Business School call it product integrity. Integrity is what causes users to exclaim about the greatness of a product in words like "They got it right!", "This is the best I ever seen!", "This is cute!", etc.

Designing for value

The biggest challenge in applying concurrent engineering to a PD^3 process is defining the measures of merits (MOMs) for the realization of the total system as opposed to MOMs that are based on individual product's life-cycle concerns. As described earlier, the foundation of concurrent engineering is teaming and trading. Teaming and trading can be viewed as positive since, in concurrent engineering, a PD^3 function is no longer being performed in isolation from the other teams. They can be considered negative in that the cost or time it takes to perform a new concurrent activity together in a particular track, may increase. However, teaming has the effect of making things much easier and more cost effective elsewhere (in other life-cycle tracks of the PD^3 process). This is called shadow effect (Magrab, 1997). An example of this is in the design track itself where initial effort required to improve design contents in a concurrent engineering process may consume more time and cost than are required during a traditional process. However, this extra effort may have some positive effects in reducing labor, material, and time elsewhere (in other tracks, e.g., production, support, and procurement, etc.). If the criteria for success were based on the design lead-time alone, some concurrent engineering managers may argue

Figure 1 What makes a product great?



The TQM Magazine
Volume 10 · Number 4 · 1998 · 258–275

that concurrent engineering does not really work because design activity now costs more or takes longer to complete than the way it was traditionally performed. This is because the far-reaching effects of these early changes are normally not as severely felt during initial stages as during the downstream processing functions.

One way to handle this is to consider the cumulative effect of the incremental changes in costs over the entire product's life-cycle as true measures. It does not matter whether an individual activity (like a design activity) costs more or less, or takes more time to perform using concurrent engineering than before. It is the overall cost or time that one is mostly interested in (Margolias and O'Connell, 1990). When concurrent engineering principles are imposed on the work-groups, teams, or an entire organization in an enterprise, a great many things can change. The change usually brings pains with it – pain in learning new ways of doing things, pain in accepting new and expanded responsibilities, and pain in having to fix things when new processes and techniques do not work exactly as planned. There is often a desire to improve individual components or to assess their impact on downstream operations. Work-groups must continue to learn from these exercises and push forward to growing new frontiers. In total value management, the issue is not communication or teamwork – it is the creation of the total value content. For this reason, MOMs of product, MOMs of the process, MOMs of work-group and business process performance must be devised to permit a more rapid deployment of the most effective entities in operations, to affect a maximum return in secondary content performance while yielding a maximum cumulative return in total system content (Prasad, 1997). In order to affect the old entities in product, process, or organization (PPO), it is important to determine the differences between the old entities and the new ones. Any new modification to an old practice is based on two considerations:

(1) What effects the modification brings to the PD^3 process on its own, and
(2) How the modification affects the downstream operations.

The metrics of measurement provide a justification for each individual change, such as people, data, process, timing, or knowledge. The changed PD^3 process is not developed in a vacuum, it is often based on incremental gains or continuous improvements over the past situation, which may relate to benefits other than time or cost (Prasad, 1997). All sorts of measures are, therefore, necessary to determine its true impact.

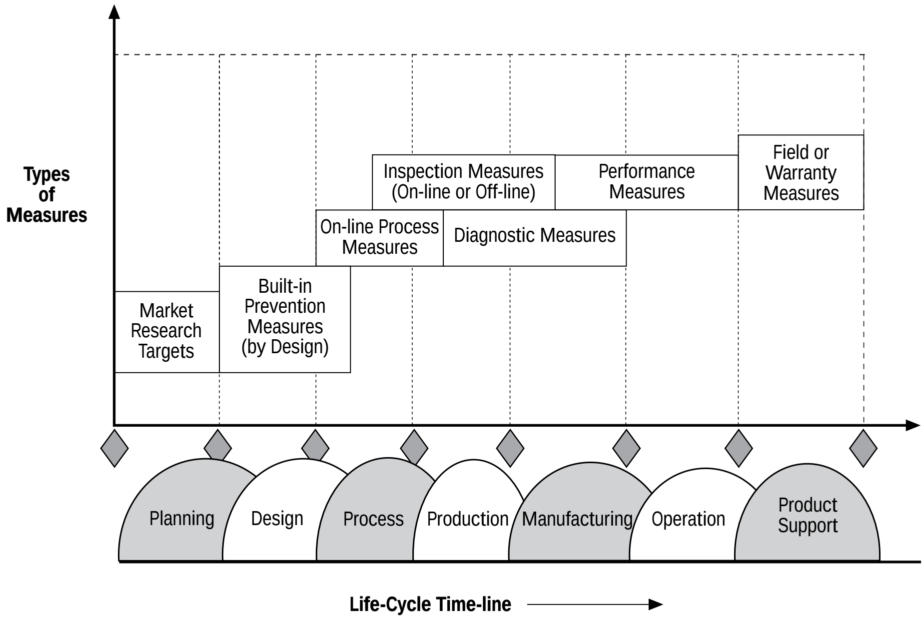
2. Establishing life-cycle measures

At the heart of any good PD^3 process there lies a concurrent engineering focus on satisfying the interests of the customers, the supply-base partners, and the company. The customer focus shows up in measures (such as market research targets, performance, field or warranty measures) that a company imposes in response to what customers desire in a product. The company focus shows up in another set of measures (such as built-in prevention measures by design, on-line process measures, inspection measures, and diagnostic measures). This assesses the company's ability to manufacture a quality product in record time and cost. Life-cycle measures generally fall into the following seven categories (Figure 2):

(1) *Market research targets.* These determine the extent to which customer satisfaction prevails in product development. This is commonly listed in the WHATs column of the QFD matrices. Examples of market research targets are strategic planning, product plans, organizational goals, meeting goals, objectives, etc.
(2) *Built-in prevention measures (by design)*. These are measures that are factored-in when the parts were initially conceived to prevent any future mishaps. Examples of built-in measures are error-proofing, design for consistency, design for insensitivity to parameter variations, and design for reliability, etc.
(3) *On-line process measures.* These are metrics that determine the cause of a process malfunction, such as deterioration of product or process area quality, machine failures, etc. Metrics are internally focused.
(4) *Diagnostic measures.* These are metrics that ascertain why a product or process is failing to perform as expected. Diagnostic measures determine which features of the structure part, or of the design prototype, are the causes of failures and are introducing out of norm behaviour. In the

The TQM Magazine
Volume 10 · Number 4 · 1998 · 258–275

Figure 2 Common life-cycle measures in product development



product area, diagnostic measures might include test results, MTBF (mean time between failures) analysis, FMEA (failure mode and effect analysis), reliability checks, quality indices, etc.

(5) *Inspection measures (on-line or off-line)*. Inspection measures are less desirable because they commonly deal with fixing a problem. They do not eliminate the cause of the problems or detect and eliminate the source of the problems. Because of these reasons, inspection measures are sparingly used in aggressive corporations.

(6) *Performance measures.* Performance measures are high level metrics that assess the overall performance of product, process, team, or the enterprise. Performance measures are generally associated with product performance in the field, or in customer use of the products compared to their competitors. These measures are customer focused and are externally based. Examples include productivity, responsiveness, cost, time-to-market, quality content, etc. A value indicator represents a combined outcome of doing two major efforts in a company: "doing things right" and "doing the right things." Doing things right is measured by the corresponding efficiency of doing 7Ts, 3Ps, 4Ms, or 7Cs. Doing the right things is measured by the corresponding effectiveness of doing 7Ts, 3Ps, 4Ms, or 7Cs. The desired result is the product of the previous two categories. The items in each of the two categories and a list of desired results is outlined in Table I.

(7) *Field or warranty measures.* These are metrics that assess the product use in the field in terms of its maintenance, upkeep, and warranty costs. Most measures are customer focused. Examples include customer-found faults, maintenance costs, customer satisfaction index, etc.

Some of the above life-cycle measures are required for an organization to become lean, while others are to become agile. Metrics for leanness do not imply agility (Goldman *et al.*, 1995). They are simply a necessary condition. Organizations need a lot of lean-capabilities to become agile. Both lean and agile are measurable, but leanness, in particular, is more observable. You can visualize a just-in-time (JIT) system by looking at a work-in-progress (WIP) inventory, floor space, or cycle time. Agility is not directly observable (in real time) because it represents flexibility or the ability to change over time. An analogy could be a distance/velocity. Leanness may be analogous to distance. When someone traverses a distance, its path can be observed. Speed or velocity cannot be observed, but is the rate of change of distance. Agility may be considered the change in rate in moving from one lean state (a distance) to another. This gives the sense of direction. Agility provides a measure of "dynamics," how fast the change can take

The TQM Magazine
Volume 10 · Number 4 · 1998 · 258–275

Table I Measuring a value indicator

Desired result	=	Doing things right	x	Doing the right things
Fewer unscheduled changes		Measured by the corresponding		Measured by the corresponding
More overall productivity		efficiency of doing the following:		effectiveness of doing the following:
Less time-to-market		Integrated product development (IPD)		Total value management
Less cost-to-quality		Integrated product and process		Concurrent function deployment (CFD)
More profitability		organization (PPO)		QFD, TQM, C4, etc.
Less inventory		7Ts		7Ts
Better quality		3Ps		3Ps
Great product		4Ms		4Ms
Increased safety		7Cs		7Cs
Increased stability				
Increased flexibility				
Increased market growth				
More customer satisfaction				

place (that is distance traversed) and "which direction to traverse." Because agility cannot be easily observed (compared to leanness), it is a difficult concept to measure and for the concurrent engineering management to grasp. Leanness, on the other hand, is easy to understand because it deals with eliminating wastes, and can be measured and observed using some lean metrics.

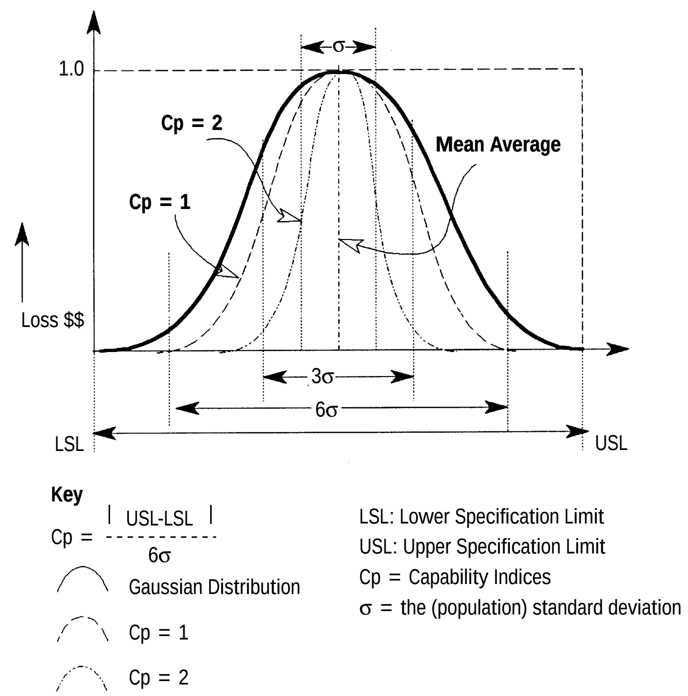
3. Identifying total value

In the evolving, highly competitive global marketplace, consistent and recurrent customer satisfaction is essential for long-term survival. Degree of competitiveness of most products – whether they are consumer goods or for the defense industry – largely depends on exceeding the customer's expectations. Customer satisfaction is achieved not through a single act, but a coordinated array of actions, each contributing a useful and interesting dimension towards an artefact's overall performance (Bhote, 1997). For example, the off-line and on-line methods of quality are a supplement to, but not a substitute for, sound engineering and manufacturing practices. Other contributors of customer satisfaction are attributed to efficiency gain and a reduction in the total resource requirements for the life-cycle support of the product (Himmelfarb, 1992). There is a difference between "what is important to a customer" and "what is considered important by a customer" for life-cycle support. For example, cost cutting may not be an important attribute to a customer *vis-à-vis* worth spending time on, but the end-cost of the product is. Design for quality is one of total value's multidimensional-measures associated with quality engineering. It is an important dimension and therefore discussed first.

Design for quality

Design for quality (DFQ) programs are commonly directed towards achieving 100 per cent prevention and 0 per cent inspection goals. DFQ means building quality control into the product (using error-proofing techniques, or statistical means such as six-sigma) when the product is first conceived and designed. Achieving six-sigma means catching defects 99.9997 per cent of the time (see Figure 3). DFQ also means minimizing

Figure 3 Gaussian distribution curves when $C_p = 1$ and $C_p = 2$



The TQM Magazine
Volume 10 · Number 4 · 1998 · 258–275

teams' dependence on some of the quality control or inspection techniques, such as the Andon method. DFQ assures that suitable quality standards are reached in meeting performance, reliability, maintainability, durability, operability, and safety, economy of manufacture and operation targets. Product quality is governed by the teams' choice of 7Ts (talent of the work force, tasks, teamwork, techniques, technology, time, and tools) (Prasad, 1996). The corresponding options in each category are quite large. The DFQ options in the technique category, for instance, may include QFD, DFMA, FMEA, Taguchi, SPC, six-sigma, etc. (Green and Reder, 1993). Quality to the customer means improved fits and clearances, no defective parts, shiny paint, reduced number of parts, improved quality comfort and superb performance. What product manufacturers do to come up with a design and build parts that perform in a quality way has very little significance. Quality assessment is a measure of product and process conformity to requirements. Merely acquiring a CAD tool or blindly designing everything on a CAD system does not assure quality. Quality must be built into the product through compliance of requirement specifications at the beginning stages of design rather than through inspection of design during later stages (Himmelfarb, 1992). The aims of quality improvement programs is to look for ways to make a product better, more reliable, and durable. The following are some typical DFQ objectives:

- The tolerance range can be increased by applying DFQ techniques to increase the design latitude. Anticipate possible quality problems during early phases of product design and prevent them from occurring by implementing error-proofing techniques that could assure correct outcomes (Clark and Fujimoto, 1991).
- The manufacturing variability can be decreased by applying DFQ to the manufacturing processes (Ross, 1988). Anticipate possible quality problems during early phases of process design and take preventive steps to assure correct assembly, and minimize variation to assure repeated performance.
- Apply lessons learned, past experiences, and team review processes to detect quality problems early (Garvin, 1993), and consciously prevent them (by design) from recurring.

The basic six-sigma metric is the capability index for bilateral limits (for example, nominal is the best). The process capability index (C_p) for DFQ is defined as the ratio of the difference between USL and LSL, and 6σ (see Figure 3):

$$\text{i.e. } C_p = \frac{(\text{USL - LSL})}{6\sigma \text{ (total range from “-3}\sigma\text{ “to “+3}\sigma\text{“)}} \quad (1)$$

where USL is upper specification limit, and
LSL is lower specification limit
C_p = Capability index.

The numerator in Equation (1) is the customer functional limit tolerance range for a design parameter chosen in a product or a process. The denominator is the measure of the manufacturing variability of the chosen parameter. Three-sigma quality is achieved when $C_p = 1$. However, it is inadequate for most products. Six-sigma quality is achieved when $C_p = 2$. A process capability index of $C_p \geq 2$ implies designs and processes that are typical of Japanese manufacturing (Liker *et al.*, 1995). Figure 3 also shows two Gaussian distribution curves in relationship to the tolerance limits, when $C_p = 1$ and when $C_p = 2$.

Prevention means hindering quality problems from happening. Prevention is a process of finding, proofing, and tracking possible error situations that may adversely affect quality or customer satisfaction, and could result in waste. There are three ways to approach prevention:

(1) Concentrate on the design of the product itself (whether it is a hard product or a service) (Magrab, 1997).
(2) Work on the production process (Liker *et al.*, 1995).
(3) Concentrate on error-proofing (EP), also referred to as fool-proofing or mistake-proofing (Juran and Gryna, 1993). Error proofing employs techniques or devices for early detection and prevention. Some major typical steps in error-proofing are:
   - identify and classify each operation or process for error-proofing needs and techniques;
   - use monitoring techniques or devices that detect errors during WIP rather than when the product or process is complete;
   - design parts that cannot be incorrectly manufactured or installed. If an error is detected, change the process, document it, and make sure (meaning

The TQM Magazine
Volume 10 · Number 4 · 1998 · 258–275

implanting EP methods) that this error will not occur again.
- find and eliminate error situations, such as minimizing waste (Japanese term – Muda), reducing overburden (Muri), controlling unevenness (Mura) and reducing possible variation. If error situations can be prevented, defects that cause problems can be eliminated (Ohno, 1988). Preventing problems from occurring has many positive effects, including increase in quality level and decrease in operating costs.

There are several commonly used computer tools and methods that can help teams focus on prevention:
- total quality management (TQM) (Besterfield *et al.*, 1995);
- quality function deployment (QFD) (Ross, 1988);
- failure mode and effect analysis (FMEA) (Freeze and Aaron, 1990);
- inventory control (just-in-time);
- ordering method for production (Kanban system ordering) (Feigenbaum, 1991);
- quality control methods and inspection (Andon system);
- delivery method for production (Pull system).

These are some of the better known tools and methods. Other frequently used methods are: (Ohno, 1988; Shingo, 1989):
- preventive maintenance;
- continuous improvements (or Kaizen concept);
- failure prevention analysis, pioneered by Kepner Tregoe;
- product mix or variety programme;
- balance of options (Katashiki system);
- balance of work flow (Heijunka system);
- fool-proofing for production (or pokayoka Jidoka concept).

Examples of DFQ benefits, experienced by NCR engineering and the manufacturing team of Cambridge, Ohio, are contained in a NCSU Videotape (SME, 1989). In the production of their 2060 terminal, aimed for the hospitality industry, the multi-functional team focused on DFQ before production. The motto "do it right the first time, and every time thereafter" paid off. Parts were reduced from 117 to 16. Vendors were reduced by 80 per cent. Communications among players improved and morale of the engineering team soared to an all time high.

Other elements of total value

Besides quality there are seven additional value elements that an organization needs to measure and control to be a world-class provider of goods and services. The following lists in each case what factors are considered important by the customers, companies, or the supply-chain partners:

Customer satisfaction

One of the purposes of developing the product is to achieve satisfied customers recurrently. Customer satisfaction means meeting the customers' needs, at the right time, and in the quantity, price, and performance they want. The cornerstone of these performance measures is the customer. Of course, if the customer does not want to buy a product, improvements in cost, weight, and investment do not really matter. At the same time, if the customer becomes disappointed with the workmanship of the product or encounters problems over its life, he or she will not buy it again. The key to understanding customer satisfaction is the recognition that there are two basic types of activity: support and value-added. While support activities are necessary for internal planning and control, they consume the team's effort and time but they do not provide direct benefit to the ultimate customer. Value-added features or services are pleasant surprises to the customers.

Overall productivity (gain or loss)

Overall productivity means cumulative gain or loss. A higher level of productivity in one specific department or discipline is not a good measure. Productivity means creating concepts that positively impact on the whole system – both the upstream and the downstream operations. The overall productivity is defined as the ratio of the throughput (T), to the operating expenses (OE). The point to note here, contrary to what is generally understood, is that productivity is not a simple ratio of the outputs to the inputs. Throughput in this context is defined as useful outputs (that customers can use) – end products or services completed in a given period of time. In other words, scrap or waste is not a measure of productivity.

$$\text{Productivity } (P) = T/\text{OE}; \qquad (2)$$

The TQM Magazine
Volume 10 · Number 4 · 1998 · 258–275

Thus, productivity entails the effective measure of how inputs (people, materials, means, etc.) are utilized in a certain period (measured in terms of operating expenses), in order to realize certain useful outputs in this period. All outputs are not throughput, some outputs (for example, scraps, defects, etc.) are waste. The throughput is defined as follows:

$$T = \sum_{i=1}^{N_o} [P_i * N_i * P_{v_i}] \qquad (3)$$

Where, P_i is the proportion of acceptable outputs (which are non-defective) of variant *i*,

N_i is the total number of outputs produced of variant *i*, and

P_{v_i} is the production (or throughput) value per acceptable output *i*.

N_o is the number of outputs (say number of assembly variants).

For convenience sake, defective outputs (or scrap assemblies) are assumed to have no production (or salvage) value, since they cannot be sold to the market as they are. Successful manufacturers are those who measure the difference between outputs and throughput, identify the possible source of such discrepancies, and take counter measures to prevent them at the source.

Unscheduled changes

The success of rapid product realization depends on the team's ability to handle unscheduled changes. Unscheduled changes occur in many ways: some are avoidable some are not. Avoidable changes are typical of products thrown over the wall before they were ready for manufacturing. Once the parts are sent back to the originating team, unscheduled changes have to be squeezed in between work. Unavoidable changes occur when circumstances change, people move, and the steps are no longer valid. Unwanted changes are caused by changes in product lines, product functionality, technology, etc. Though a number is an important measure, unscheduled changes can be very serious. For example, if errors are detected late in the process (say during a downstream operation), it might be very costly to fix them.

Inventory

Inventory includes all assets including property, plant, and equipment, but excluding value-added parts. The new definition, broadly stated, includes any item that the company could sell, not just the finished products. By including capital assets in the inventory category, teams are forced to focus on the way they are utilizing all of the investments under their control. The finished inventory is the amount the retailer must keep in stock. This amount is equal to the average demand over the order ship time plus a safety factor based on the standard deviation of demand over the order ship time:

If *n* is the average demand for one day, sigma (σ) is the standard deviation for a day's demand, and

d is the order ship time in days, the required inventory (I) is:

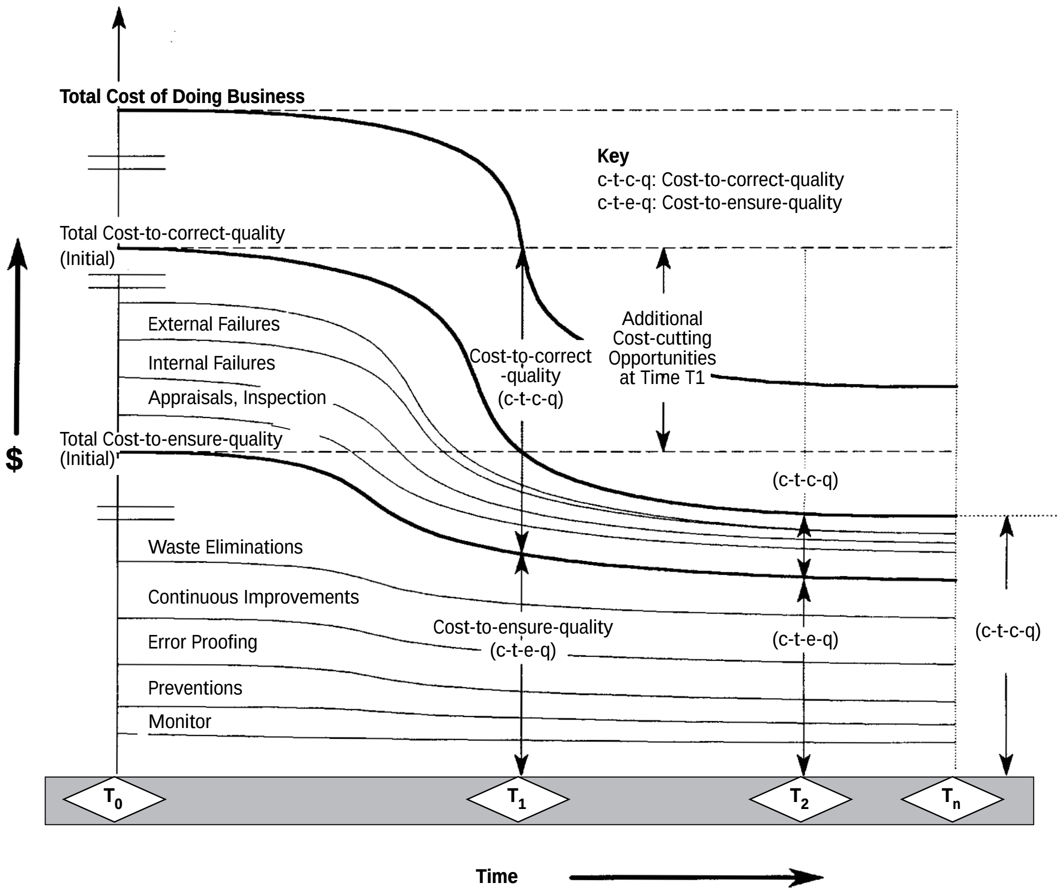
$$\text{Inventory} = [\, nd + (3\sqrt{d}) * \sigma] \qquad (4)$$

Cost of quality

Knowing how much quality costs and the way the cost is made up can provide a strong impetus for management to set off on the quality improvement trail. There are two contributory elements that affect the cost of quality: (a) cost-to-ensure-quality (*c-t-e-q*) and (b) cost-to-correct-quality (*c-t-c-q*). They are shown in Figure 4. Cost-to-ensure-quality is the cost of doing things right (for example, choosing the right process), the cost of doing right things (for example, choosing right actions), and the cost of preventing mistakes (such as anticipating problems). Prevention costs are the expenditures on activities whose objective is to prevent the occurrence of failures. They are designed to ensure or build quality during designing, implementing, and manufacturing products and services. Typical examples include the cost of training, establishing procedures, insurance, preventive or contract maintenance, planning activities and analyses of performance data, surveillance, etc. The cost-to-correct-quality is the cost incurred because of doing things wrong (for example, choosing the wrong process), the cost of doing wrong things (e.g., choosing wrong actions), and the cost of inspections to discover mistakes committed earlier. Cost-to-correct-quality falls into two categories:

(1) Appraisals are the costs associated with activities like checking, evaluating, inspecting and measuring work, supplier monitoring, appraising performance, and conducting audits on work done to assure "conformance to quality requirements." The conformance shows whether work has been performed according to the

Figure 4 Cost-cutting opportunities through prevention (measurement of cost-to-quality)



required specifications or standards. Other types of cost-to-correct-quality are internal and external failures.

(2) *Internal (or external) failures* are the costs incurred by failing to perform work right the first time. They are often associated with a product or service that does not meet the quality requirements (such as building codes) prior to transfer (or after transfer) to the customer. Costs of failures include: the disposal or correction of incorrect work; scrap or excess stock; time spent on rework; bad debts; waiting for work; and dealing with complaints from customers.

Most cited product quality indicators attempt to measure the parts per million (PPM) level of conformance. This does not, however, account for criticality – for example a $1 part failure may result in a $1,000 part failure if one part is encapsulated into another. Another measure of overall effectiveness is to track cost-of-quality (*c-t-q*), both "cost-to-correct-quality" and "cost-to-ensure-quality."

C-t-q Effectiveness = ({cost-to-ensure-quality} / {cost-to-quality}) *100 (5)

Where, cost-to-quality is the sum of two parts.

Cost-of-quality = "cost-to-correct-quality" + "cost-to-ensure-quality" (6)

or *c-t-q* = *c-t-c-q* + *c-t-e-q*

If the *c-t-q* effectiveness number is close to 100, the company is doing things more right than wrong. The effectiveness number thus provides an analytical basis for decision making or to track quality improvement opportunities.

Two common cost measures are:

(1) how much the product costs to deliver as compared to its predicted (and sometimes contracted) cost; and
(2) how this cost compares to what the customer judges its fair market value to be.

Accurate cost estimation is neither essential nor feasible during early design stages. For example, for early design improvement purposes, it may be enough to know which of the two alternatives leads to a lower cost of production than to know their actual absolute costs. It is, therefore, quite helpful to develop relative measures based on preliminary design descriptions that can predict the associated

The TQM Magazine
Volume 10 · Number 4 · 1998 · 258–275

degree of X-ability. End-cost is affected by direct and indirect costs, assembly cost, part fabrication cost, fixture cost, etc. (Figure 5). The design options (such as design configurations, material properties, manufacturing processes) also affect costs. It is unnecessary to spend a lot of time and effort to obtain an accurate cost estimate for each design option in order to suggest a design change. It is more appropriate to identify relative cost drivers to predict improvements from amongst the possible design options (see Figure 5). Early use of end-cost estimations can eliminate unwanted design changes commonly encountered in the later stages of product realization.

Profitability (ROI)

The return on investment (ROI) is defined as the ratio of gain (G) minus the operating expenses (OE) to inventory costs (I), that is:

$$\text{ROI} = (\{G\text{-OE}\}/\{I\}) \quad (7)$$

Where gain (G) is defined as

$$\text{Gain } (G) = \text{net sales} - \text{cost of raw materials} \quad (8)$$

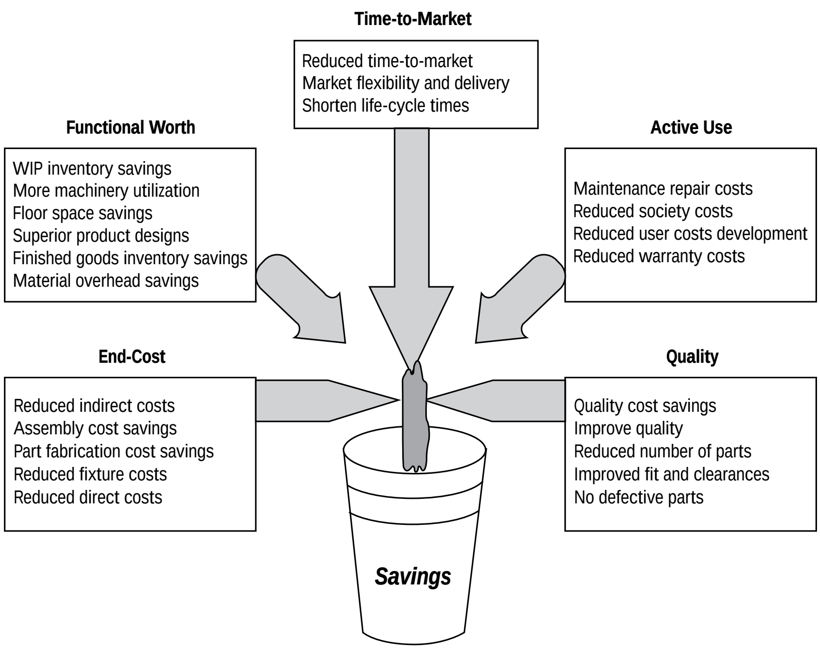
where net sales (or volumes) are defined as the irreversible transfer of products to the consumer. Such a definition of sales does not allow the transfer of goods in a consignment from a manufacturer to a dealer to be counted as a sale. OE is computed using all normal operating expenses plus direct labour and factory overheads. By grouping direct labour and factory overheads in an OE category, there is little reason for teams to over-build their inventory. Direct labour is recognized as a fixed cost.

Time-to-market

This is a measure of the time period required to design and develop a marketable product (from concept through rate production). There are many definitions of time-to-market (TTM). Some consider TTM a measure of competitiveness, others a measure of customer satisfaction – how close this comes compared to the customer's realistic desires. TTM is the length of time it takes to deliver a product in the customer's hand from the time the decision is made to launch a product.

Clearly, most of these value measures are focused directly on the customer's end-cost, delivery, and usefulness of the manufactured product. They are not concerned with the details of how a company got there. Measurements involving effectiveness of the teaming concepts or of the cross-functional department interactions on product values are not evident. Such measurements are usually in the form of the number of engineering change orders, mean time between failures, remaining time for ramp-up to part production, etc. It does not make any difference to the customers whether engineering releases the design on time or not. The intermediate PD^3 process does not produce and

Figure 5 Measures of savings associated with value engineering



The TQM Magazine
Volume 10 · Number 4 · 1998 · 258–275

capture happy customers. What most customers are interested in is getting the best-valued product at the lowest price that anybody can offer. The best-valued product ensures a continuation of the company's current share in the marketplace.

4. Designing for total value

Designing for total value (DFTV) is a powerful technique that allows concurrent teams and work-groups to determine systematically the total value of the product over its life-time in conjunction with appropriate analysis tools. FMEA is used to identify and prioritize potential problems and DFMA is used to find solutions. In conjunction with these tools, the value analysis/engineering concept (VA/VE) is employed to improve the value of a product or a service. Tools, such as activity-based costing, can help evaluate strategic planning, process redesign, or business process re-engineering (BPR) needs. Improving the total value has two meanings:

(1) *Retaining the current value at a cost lower than before*. This applies to what benefits the customers directly. For example, improving "value with respect to functionality" means developing goods or services that perform the required (or basic) functions at a lower cost, time, or manpower.
(2) *Enhancing the current value at a minimum additional cost*. This applies to values that are not associated with basic functions of the product or the system that produces it. For example, in the case of maintainability and reliability, the customer does not see a direct benefit except when it comes to frequency of product maintenance and repair.

Steps in DFTV

DFTV is based on activity charting. Activity charting is an important method for building quality into a PD^3 process (Prasad, 1996). It focuses on the total concurrent engineering process and its interfaces rather than its individual components. The steps involved in a DFTV process are:

- *Get all the facts*. A work-group or team gets information about specialty products, materials, processes, and vendors by talking to a number of company partners, and industry experts. It helps define the functions work-groups are performing or seeking.
- *Draw a process flow chart*. A process flow chart represents the work flow laid down in minute detail identifying what is planned, and how that will be done. A structured format is used to emphasize the impact of sources of variation on the process. The emphasis is on the procedure, not on the agent who is running the procedure.
- *Candidate process model or value tree*. The result of this flow charting is the development of some specifics called "candidate" process models.
- *Draw value graph – process description sheets*. The work-groups should now be able to break down the process flow into smaller tasks in the form of actions and process description sheets so as to accurately describe the associated manufacturing method.
- *Identify flow types*. This identifies the connections (sequential, parallel, alternative, join and loop) between any two activities, and timings for the completion of tasks.
- *Identify indirect expense and control parameters*. The next step is to determine indirect expenses and control parameters associated with those tasks. For example QC, SPC scheme, etc., associated with JIT manufacturing.
- *Identify process parameters*. During this step, process assumptions are identified, required machines and teams are outlined, and critical process characteristics (PtCs) are confirmed.
- *Identify new investment*. New machinery or equipment cost is also identified and estimated, and noted against the appropriate entry in the bill-of-materials.

There are many benefits that can be derived from DFTV.

Value analysis/engineering

The term "value analysis/engineering (VA/VE)" applies to a disciplined, step-by-step thinking system, with specific approaches for mind setting, problem setting, and problem solving (Fowler, 1990). It was developed to determine whether or not an artefact/system performs the way it was supposed to perform while in active use. Active use of a product implies one of the following two situations:

The TQM Magazine
Volume 10 · Number 4 · 1998 · 258–275

(1) What portion of the purchase price that is charged to the customer relates to maintaining the product in working condition.
(2) What percentage of time the product is available in such working condition for the customer's use as a function of the time it is kept in his or her possession.

"System analysis (SA)" is a process of analyzing an engineering system for its value content to the customers and the share holders, and "system engineering(SE)" is a process of improving or maximizing the total value content or its impact. The process flow chart and the associated process description sheets are used as a means of capturing the manufacturing process, just as an engineering schematic and bill-of-materials capture the design process. The main idea is to study the functional worth of each activity in a process and to analyse whether an activity is adding any value to a product system or not. The activity, which adds value is considered as useful and what does not add value to the product is considered as waste The repeated application of this analysis can lead to improving the process worth. Therefore, value engineering can be considered as a method to identify and eliminate waste. There are three types of values used in value analysis: customer-perceived value, process value, and company-perceived value:

(1) *Customer-perceived value*. This value is considered a major driver of increasing sales or market share. Customer-perceived value can be increased by providing more of the following: ease of use (functions properly), options (types of features or characteristics), aesthetics (style, colour, convenience, and look), performance (e.g., less frequent servicing or low repair history), and salvage value (exchange price or trade-in).
(2) *Process value*. This is a minimum set of value-adding tasks or activities that are needed to transform an input into a customer-usable output (perform type activities). Often such process values are design dependent and cannot be achieved without spending valuable resources (time, money, or expertise). Examples include accuracy, speed, consistency, simplicity, and suitability.
(3) *Company-perceived value*. Besides process values there are some company-perceived values that may not be relevant to the current product, but are essential for the long-term survival of the company and its competitiveness. Some examples of company-perceived value are: reusability for other products, modularity, commonality, exchangeability, and marketability (warranty, field support, etc.).

In customer-perceived value, the concurrent teams focus on two groups of customers: internal customers and external customers, and ask "what would delight them?" Delight means being best at what matters most to customers. Every step that a work-group takes during a product design affects what external customers get or perceive they get. Each design decision taken by the initiator (requester) or the supplier of functions or services indirectly affects what external customers eventually get. Such decisions can serve as a source of potential value or a point of competitive differentiation. Value engineering is a method of analysing a process, identifying the value attributes that are associated with it, and eliminating waste:

- it adds value to the functions that concurrent teams are seeking to be implanted in the product; or
- the services work-groups are performing will enable the product to have a feature that is attractive to both internal and the external customers.

Accuracy, cycle or turnaround time, consistency, timeliness, and conciseness are some of the quality attributes that are often valued by internal customers. Errors, rework, delays, high costs, and low quality services are some example measures of poor attributes for the external customers. Appropriate choice of strategies, organization, management, and design of process are often used to maximize the benefits and overcome the obvious negatives (Clark and Fujimoto, 1991). The book describes different types of strategy that one can resort to during product development. The various types of tools that are used for life-cycle management are contained in Evans and Lindsay (1995). Customers' value criteria are often reflected in a QFD requirement matrix. The customers' wants provide the basis for the value criteria, which in turn influence the process specifications. In product development, targeting the requirements of internal and external customers, organizing an integrated PD^3, selecting corporate strategies, adding value and creating the winning edge are the focus. In the improvement process, Shingo (1989) emphasizes the importance of seeking out goals. Shingo (1989) divides the pursuit of goals into three parts (Figure 6):

(1) *Focusing.* Focusing is the idea of uncovering goals that are deeper than what is immediately obvious on the surface.
(2) *Identify multiple goals.* Here the idea is not to block the various design possibilities (alternatives) before they are fully analyzed with respect to the stated goals.
(3) *Pursue goals systematically.* This refers to the idea of looking at current goals from a broader perspective that teams often tend to overlook. This could lead to spectacular improvements. An example cited by Shingo is the removal of burrs. Once a company noticed burrs occurring in a machining operation, they put their efforts in to how quickly burrs could be removed from the machined surfaces. This, however, did not eliminate the burrs problem. Since burrs were generated where tools leave the materials, burrs keep on occurring. The company then went into tracking the root cause. Once they found the root cause, the efforts for quick removal of the burrs were quickly replaced by the efforts to prevent the burrs from occurring in the first place.

When applied to product design, it is often used to identify unnecessary cost in an existing design. Value analysis, like systems analysis, is a method of identifying, analysing, and predicting the functional worth-to-cost ratio of having an activity in a process (Fowler, 1990). It evaluates whether or not an activity adds value to the work or service that is being performed. From both customers and the company's perspectives, value is defined as:

$$\text{Value} = \frac{\Sigma(\text{functions, features, or activities})}{\Sigma(\text{costs})} \qquad (9)$$

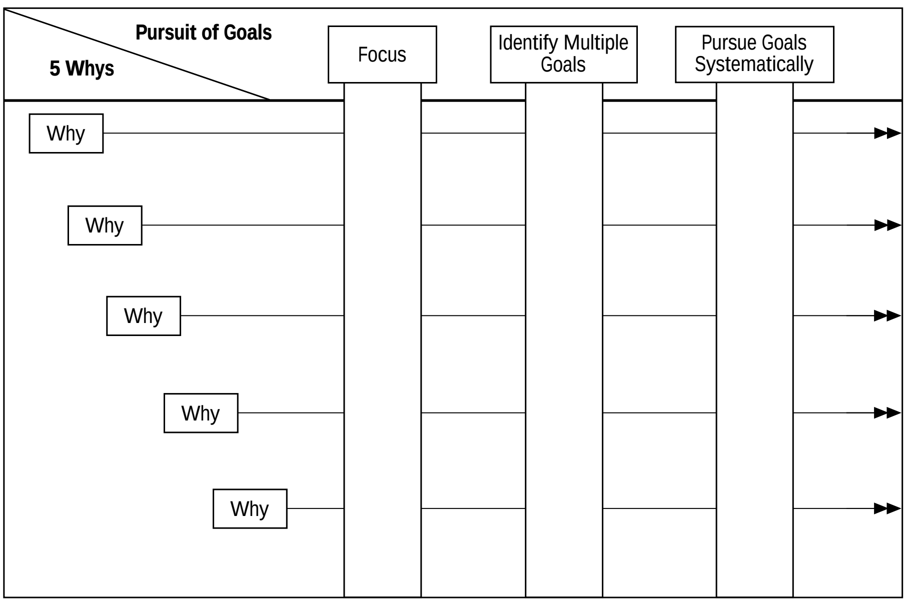
Giving the customer more value means increasing the number of customer-desired functions, features, etc., while reducing the cost of providing them. If the product has n functions or features, and F_i represents an ith function or feature that is provided at a cost of C_i, then the above equation can be expanded as:

$$\text{Value} = \frac{F_1 + F_2 + \ldots + F_n}{C_1 + C_2 + \ldots + C_n} \qquad (10)$$

Functional worth

Functional worth is a measure for defining the product's worth to the company and/or the customer. It measures the consumer utility in terms of functional-to-cost worth. Very often, functional worth is defined as the value per unit cost of the product. The savings due to functional worth are affected by WIP inventory, machine utilization, floor space, superior product design, a finished goods

Figure 6 Scientific thinking mechanism for pursuit of goals



The TQM Magazine
Volume 10 · Number 4 · 1998 · 258–275

inventory, materials overheads, etc. (see Figure 5). Benchmarking is a method for assigning values to the 3Ps (practices, procedures, and policies), and processes associated with developing a product. One of the purposes of benchmarking is to increase a product's functional worth. Benchmarking is also used to (Bhote, 1997):

- measure the subject's part performance against that of the best-in-class companies;
- determine the best-in-class features or functions; and
- establish how to achieve best-in-class performance levels.

Many use information obtained from benchmark studies for setting their own company targets. Benchmarking studies are also useful for strategic planning (to be used in QFD) (Ross, 1988), determining product or process implementation plans (Magrab, 1997), and performing VA/VE (Fowler, 1990). The other most common measure that is important to a company is through worth-to-actual time ratio.

Worth-to-actual time ratio: This is defined as the ratio of the net worth time to the amount of time actually spent on an activity to generate an output. The net worth time is the time spent only on adding values to the activities with respect to the benefits it may bring to the companies or their customers. The actual time spent on an activity will always be more than its worth, since it includes some non-value-added time. The non-valued portion will be the measure of wasted time. A corollary to this is the wasted-to-actual time ratio. This is defined as the amount of time wasted on an activity to the amount of time actually spent to generate an output.

$$\text{Worth-to-actual time ratio} = \frac{\text{Net worth time}}{\text{Actual time}} \quad (11)$$

$$\text{Wasted-to-actual time ratio} = \frac{\text{Non-valued-added time}}{\text{Actual time}} \quad (12)$$

It is related to worth-to-actual time ratio as:

$$\text{Activity's wasted-to-actual time ratio} + \text{Activity's worth-to-actual time ratio} = 1 \quad (13)$$

Depending on the activity, and whether or not time spent on an activity is value-added for the customer, company, or the process, there will always be a worth-to-actual time ratio for an activity. A temporary value for a wasted-to-actual time ratio for an activity as large as 1 can be acceptable, if it adds value to most of the other dependent activities. The cost of the product can be computed in the following manner:

$$\text{A process actual time} = \text{Tw} / \Sigma(\text{worth-to-actual ratios for all activities in a process}) \quad (14)$$

$$\text{A department actual time} = \text{Tw} / \Sigma(\text{worth-to-actual ratios for all processes in a department}) \quad (15)$$

Where

$$\text{Tw} = \sum_{i=1}^{n}[\text{Activities for net worth time}) \quad (16)$$

where n is the number of activities in a process, product, or department as the case may be.

$$\text{Cost of the Product} = \sum_{i=1}^{m}\{[(\text{activity actual time})_i * (\text{Cost factors})_i) \} \quad (17)$$

Where, m is the total number of activities inclusive of processes and the departments. An ith cost factor represents the cost per unit time spent in performing an ith activity.

The appropriateness and profitability will depend on the following questions:

- How much is the user willing to pay for the product?
- What will it cost to produce what the customers want?

The ideal profitability situation will be when in a product, most activities' worth-to-actual time ratio is closer to 1 and at the same time most activities are strong contributors to all three types of values: customer-perceived, process, and company-perceived.

5. Determining a total value-index

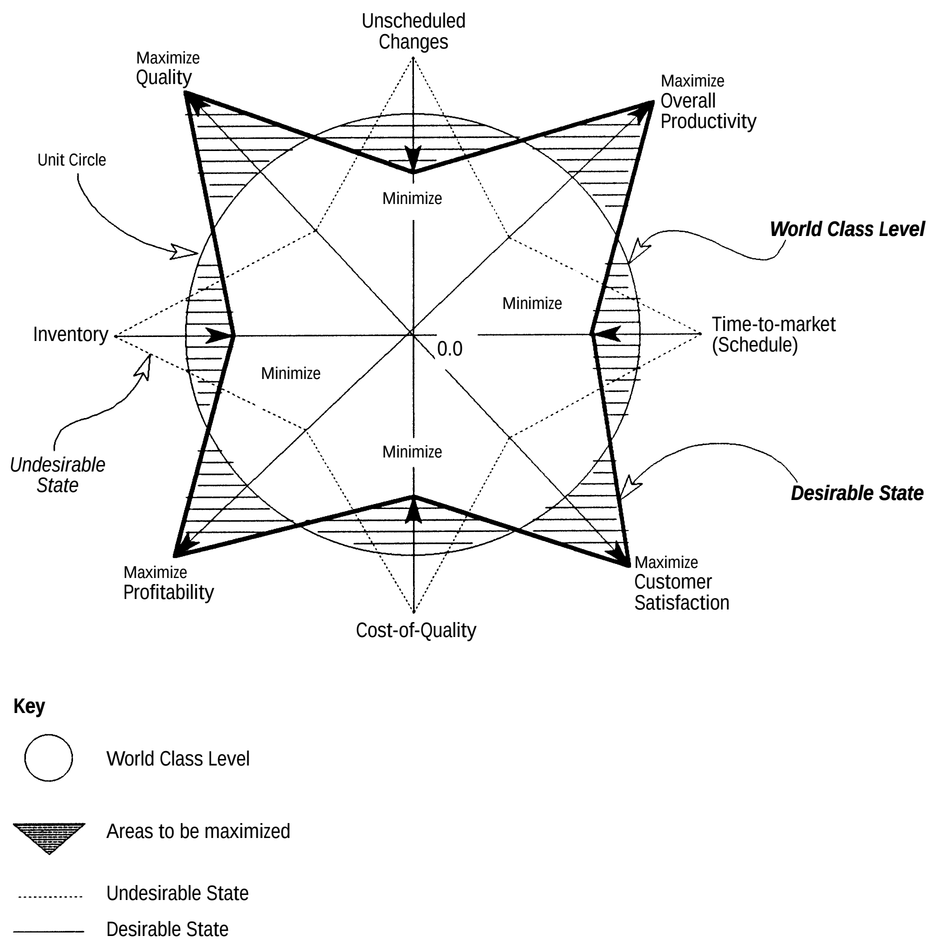
There are many ways to quantify or measure a value-index associated with the product development process. Functional worth was one such measure described earlier. In the following, a total value-index is defined, which accounts for all the aforementioned eight measures into a single (overall) cumulative measure.

Figure 7 shows a list of eight value-indicators that determine an enterprise's degree of competitiveness. Each value-indicator provides a measure of a company's efficiency or its effectiveness to compete in the world marketplace. Each value-indicator is shown by a directed radial line pointing away from the center of a unit-circle. A point on the unit circle represents a world-class level for a value-indicator. Such points represent a normalized or scaled value of 1.0. A point at the center of the circle usually represents a value 100 per cent out of range from the world-class. A point along a radial line inside the circle, thus, ranges from a value of 0 (at the centre) to 1 (on the circle). A point outside the circle ranges from 1 (on the circle) to any positive number, depending on its distance away from its centre. The desirable state depends on whether a value-indicator is to be maximized or minimized. The desirable state is outward of the circle (pointing away from the centre), if a value-indicator is to be maximized. The desirable state is inward of the circle (pointing towards the centre), if a value-indicator is to be minimized. For instance, a point 1 unit out from center may represent a level "twice" as good or bad from the "world-class" level. Depending on whether their impact on performance is to be minimized or maximized the corresponding arrow is shown pointing inside or outside the circle. It may be noted that there are four value-indicators that need to be maximized and four value-indicators that need to be minimized. They are placed alternatively around this unit circle. The solid lines shows the current state (Figure 7). The shaded petals are formed due to the lines drawn connecting the max- and min-points and the unit circle representing the "world-class." Clearly, the shaded petals represent the net contribution (impact) from each value-indicator. For the current state of the process to perform better than or equal to the world-class, the following must be true:

$$\text{Sum of the Petals Areas (gain)} \geq 0 \qquad (18)$$

The overall impact must show a net gain at the current conditions with or without the

Figure 7 Total value-index for measuring an enterprise competitiveness



new product development or technology insertion. The objective is to move the four value-indicators away from the centre and four towards the centre as much as possible. In other words, the objective is to maximize the petal areas created due to the intersection of the straight lines and the circles. Gain in this context represents the degree of system's performance in terms of competitiveness. It is important to note that performance of an organizational unit is governed largely by the system in which it is contained. It could be a worthless exercise to improve the performance of a local unit without changing the entire system, if units were interdependent. New accounting measures (such as activity-based-costing (ABC) and Goldbratt's theory) are helpful in obtaining system's performance.

Some of these value-indicators might be contradictory. For example, quality-based focus drives costs down and time up, whereas time-based focus drives costs down and quality up. Additional value-indicators that are being used are in the areas of delivery (Magrab, 1997), risk management (Prasad, 1996), and teamwork communication (Liker, Ettlie and Campbell, 1995).

6. Concluding remarks

The paper describes a set of eight value-indicators that individually measure each aspect of an enterprise's degree of competitiveness. Each value-indicator provides a measure of a company's efficiency or its effectiveness to compete in the world marketplace. The multidimensional sets of measures that make this total value content are: quality, profitability, customer satisfaction, overall productivity, unscheduled changes, inventory, cost-of-quality, and time-to-market. A set of "quality dimensions" has not been enough since it only measures one out of the eight value-indicators described above. The paper then finally derives a total value-index, which combines all the eight measures comprising its total value contents into a single cumulative measure. Since the cumulative total value-index accounts for all sets of measures, an organization could, thus, use this one index to measure the "system performance" of the entire product development process and thereby control one's (an organization's) total degree of competitiveness.

References

Anderson, D.M. (1990), *Design for Manufacturability: Optimizing Cost, Quality and Time-to-Market,* CIM Press, Lafayette, CA.

Besterfield, D.H., Besterfield-Michna, C., Besterfield, G.H. and Besterfield-Sacre, M. (1995), *Total Quality Management,* Prentice-Hall, Englewood Cliffs, NJ.

Bhote, K.R. (1997), "A powerful new tool kit for the 21st century", *National Productivity Review*, Autumn, Vol. 16 No. 4, pp. 29-38.

Bowles, J. and Hammond, J. (1991), "Being Baldrige eligible isn't enough", *New York Times,* Business Section, 22 September, p. 13.

Carroll, B. (1997), "Speaking the language of empowerment: a tale of two teams", *National Productivity Review*, Autumn, Vol. 16 No. 4, pp. 63-6.

Clark, K.B. and Fujimoto, T. (1989), "Lead time in automobile product development explaining the Japanese advantage", *Journal of Engineering and Technology Management*, Vol. 6, pp. 25-58.

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

Clausing, D.P. and Hauser, J.R. (1988), "The house of quality", *Harvard Business Review*, Vol. 66 No. 3, May-June, pp. 63-73.

Dika, R.J. and Begley, R.L. (1991), "Concept development through teamwork – working for quality, cost, weight and investment", SAE Paper No. 910212, International Congress and Exposition, SAE, 25 February - 1 March, Detroit, MI, pp. 1-12.

Evans and Lindsay (1995), *The Management and Control of Quality*, 3rd edition, August, West Wadsworth Publishing.

Feigenbaum, A.V. (1991), *Total Quality Control*, 3rd edition, revised, McGraw-Hill, New York, NY.

Fowler, T.C. (1990), *Value Analysis in Design,* Van Nostrand Reinhold, New York, NY.

Freeze, D.E. and Aaron, H.B. (1990), "Customer requirements planning process CRPII (beyond QFD)", SME, Paper No. MS90-03, Mid-America '90 Manufacturing Conference, 30 April - 3 May, Detroit, MI.

Garvin, D.A. (1987),"Competing on the eight dimensions of quality", *Harvard Business Review*, November-December, pp. 101-9.

Garvin, D.A. (1993), "Building a learning organization", *Harvard Business Review*, July-August, pp. 78-91.

Goldman. S.L., Nagel, R.N. and Preiss, K. (1995), *Agile Competitors and Virtual Organizations,* Van Nostrand Reinhold, New York, NY.

Green, N. and Reder, M. (1993), "DFM boosts US car quality", *Machine Design*, Vol. 65 No. 9, 14 May, pp. 61-4.

Hamel, G. and Prahalad, C.K. (1989), "Strategic intent", *Harvard Business Review,* May-June, pp. 63-76.

Heim, J.A. and Compton, W.D. (Eds) (1992), *Manufacturing Systems: Foundations of World-class Practice*, National Academy Press, Washington, DC.

The TQM Magazine
Volume 10 · Number 4 · 1998 · 258–275

Himmelfarb, P.A. (1992), *Survival of the Fittest: New Product Development during the '90s*, Prentice-Hall, Englewood Cliffs, NJ.

Hoffherr, G.D., Moran, J.W. and Nadler, G. (1994), *Breakthrough Thinking in Total Quality Management,* Industrial Engineering and Management Press, Institute of Industrial Engineers, Norcross, GA; Prentice-Hall, Englewood Cliffs, NJ.

Ishikawa, K. (1985), *What Is Total Quality Control? The Japanese Way,* , Trans. Lu, D.J., Prentice-Hall, Englewood Cliffs, NJ.

Juran, J.M. and Gryna, F.M. (1993), *The Quality Planning & Analysis*, 3rd edition, McGraw-Hill, New York, NY.

Liker, J., Ettlie, J. and Campbell, J. (1995), *Engineered in Japan: Japanese Technology Management Practices,* Oxford University Press, New York, NY.

Magrab, E.B. (1997), *Integrating Product and Process Design and Development – The Product Realization Process*, CRC Press LLC, Boca Raton, FL.

Margolias, D.S. and O'Connell, M.H. (1990), "Part 3 – Implementation of a concurrent engineering architecture", SME Technical Papers No. MS90-205, *Proceedings of the WESTEC '90*, 26-29 March, Dearborn, MI: Society of Manufacturing Engineers, Los Angeles, CA.

Nishiguchi, N. (1994), *Strategic Industrial Sourcing: The Japanese Advantage,* Oxford University Press, New York, NY.

Ohno, T. (1988), *Toyota Production System: Beyond Large-scale Production,* Productivity Press, Cambridge, MA.

Prasad, B. (1996), *Concurrent Engineering Fundamentals, Volume I: Integrated Product and Process Organization,* PTR Prentice-Hall, Upper Saddle River, NJ.

Prasad, B. (1997), *Concurrent Engineering Fundamentals, Volume II: Integrated Product Development*, PTR Prentice-Hall, Upper Saddle River, NJ.

Ross, P.J. (1988), "The role of Taguchi methods and design of experiments in QFD", *Quality Program*, June, pp. 41-7.

Shingo, S. (1989), *A Study of the Toyota Production System from an Industrial Engineering Viewpoint*, revised edition, Productivity Press, Cambridge, MA.

SME (1989), NCSU Videotape, *Simultaneous Engineering,* Society of Manufacturing Engineers (SME), One SME Drive, SME, Dearborn, MI.

Stalk, G. Jr, Evans P. and Shulman, L.E. (1992), "Competing on capabilities: the new rules of corporate strategy", *Harvard Business Review,* March-April. pp. 57-69.

Taguchi, G. (1987), *System of Experimental Design: Engineering Methods to Optimize Quality and Minimize Costs,* American Supplier Institute, Dearborn, MI. Also in Vols. 1 and 2, Kraus International Publications, White Plains, New York, NY.

Ungvari, S. (1991), "Total quality management and quality function deployment", *Proceedings of the 3rd Symposium on Quality Function Deployment*, Michigan, 24-25 June.

Wheelwright, S.C. and Clark, K.B. (1992), *Revolutionizing Product Development: Quantum Leaps in Speed, Efficiency, and Quality,* Free Press,Cambridge, MA.

Commentary

Worth a second read; sometimes complex but rewarding stuff from the editor of the very fine Concurrent Engineering *Journal.*