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# A model for optimizing performance based on reliability, life-cycle costs and other measurements

BIREN PRASAD

**Keywords** heuristic-based optimization, life-cycle costs, performance measurements, concurrent engineering, product development

**Abstract.** The shorter lives of products today simply do not leave room to fix problems later, correct design errors, iterate, or redesign products many times over for lowering costs or improving quality. A well-orchestrated process, not just a program, is required to achieve corporate goals and objectives. Optimization is often a balancing act. It is the balance between the goodness of *products and services* to the *process and methodologies* that are expended to produce them. This paper describes a heuristic-based model for optimizing performance based on a set of eight distinctive indicators including reliability, life-cycle cost and other measurements. A company is considered, in this paper, to have reached a *world-class manufacturing* status if the goodness of *products and services* far outweighs the cost of *process and methodologies* expended to realize the product. In this context, productivity is measured in this paper based on 'throughput' and 'operating expenses', not just based on 'inputs and outputs'.

## 1. Introduction

Many progressive companies are interested in maintaining a competitive edge in the world marketplace and in producing high quality products. They would like to maximize the life-cycle values of a product while containing costs and environmental burdens (Bhote

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After his Ph.D., he continued his career at Association of American Railroads (Chicago) as a Senior Research Engineer, where he participated in developing methods for the composite analysis of Railroad Track Support Systems (1977–1980). He then joined Ford Motor Company, Scientific Research Laboratory, where his activities were focused upon performing research in structural optimization and developing techniques for automated design of large scale vehicle structures (1980–1982). During the latter years (1982–1985) at Ford, he was responsible for developing design sensitivity and optimization procedures on EAL (Engineering Analysis Language). His work there supported a dozen prototype designs of the automobile energy-absorbing structures for crush energy managements.

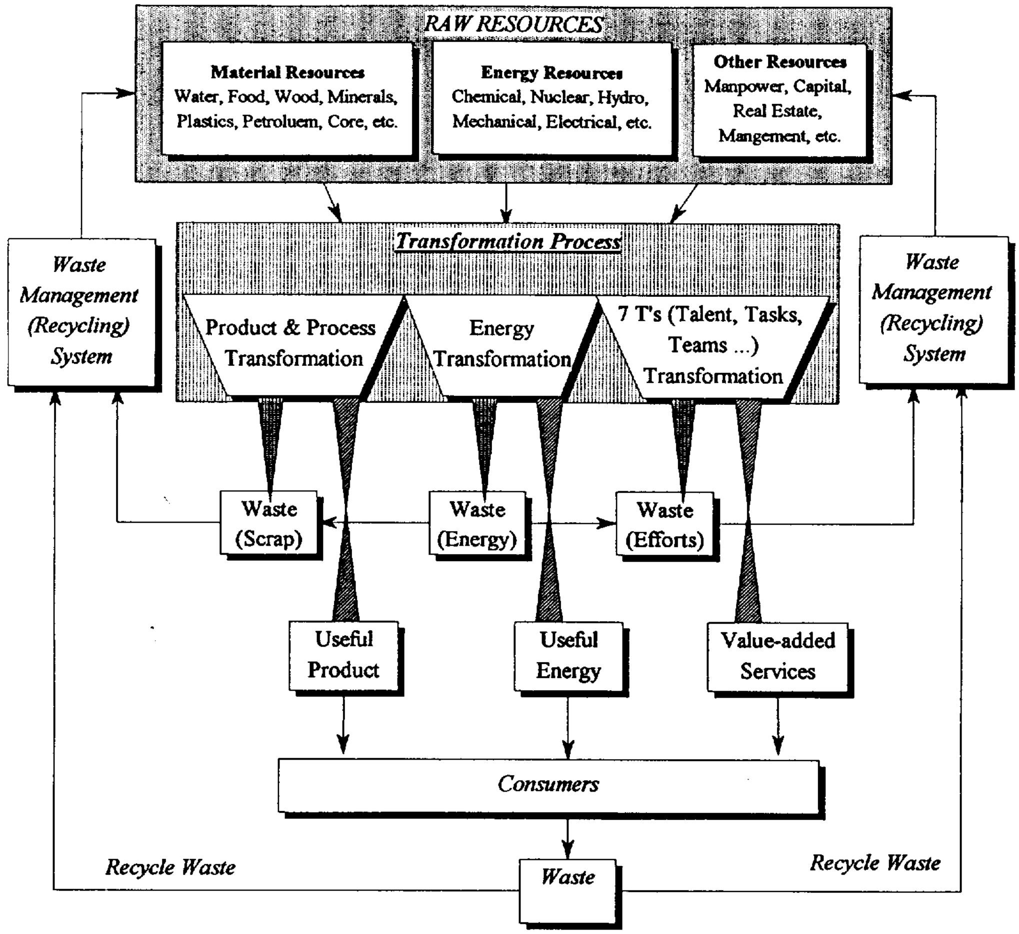



Figure 1. Scope of life-cycle management.

1997). These values include characteristics, e.g. reliability, cost, manufacturability, serviceability, recyclability and other environmental issues (Wheelwright and Clark 1992). They would like to manufacture the product at a cost much lower than their competitors. Life-cycle management (LCM) is a process often used to accomplish these goals. LCM is actually a transformation process from a set of raw resources to a useful product, energy or services that consumers want or intend to buy (figure 1). Such resources may be present as:

- Material resources (e.g. water, wood, oil, minerals, etc.);
- Energy resources (e.g. chemical, nuclear, electrical, hydraulic, etc.); or
- Other resource forms (e.g. capital, manpower, real estate, etc.).

There are three types of transformation that are commonly present during product realization (Prasad, 1996):

(1) **Product and process transformation** that produces a useful product or unexpected scrap.
(2) **Energy transformation** that produces a useful energy and some unexpected energy waste.
(3) **Seven Ts transformation** that produces a value-added service and some wasted efforts. Prasad has chosen to divide forces that influence the domain of Concurrent Engineering into a set of seven agents (called here seven Ts: talents, tasks, teams, techniques, technology, time and tools) (Prasad 1996). One of the primary team issues is the decomposition of tasks. The people's issue is the composition of teams. *Teams* are often used to cooperatively solve the problem. *Technology* issues arise due to a drive for competitiveness. Examples of popular technologies in CE are soft prototyping, visualization, product data management, design for X-ability, multimedia, electronic data interchange (EDI), etc. *Tools* mean software, hardware and networks that make CE practicable

in today's world of multinational corporations, multi-partner projects, and virtual corporations. From the *time* point of view, CE is an initiative of the product development community that has the goal of reducing the length of the product design and manufacturing cycle time by allowing teams of engineers to develop design components concurrently from their perspectives (Magrab 1997).

LCM includes not only the effective conversion of the raw resources into useful outputs, but also the management of the waste resulting from it. There are two types of waste: waste from the process of transformation and the consumers' waste that needs to be safely disposed or recycled. To date, many companies view product realization as characterized by long lead times, a multitude of engineering changes, manufacturing complications and ultimately heavy costs to satisfy the customer requirements (Magrab 1997). The number of engineering changes that occur in the best US company is 40–60% more than the best Japanese company (Wilson and Greaves 1990). This is because in most US companies, efficient decision-making processes are lacking. They either limit the process to conventional '*design review*' or '*red-team*' meetings that in turn inhibit free flow of information. Such meetings serve no purpose but to postpone the decisions from being made until after the meeting, or to centralize the decision-making authority in some committees or hierarchical tall silos or structures (Liker *et al.* 1995). For example, an engineers' choice of '*design for X-ability*' decision is often perceived as a functional service to be called upon periodically for incremental improvements in product quality, new product lead times or costs. However, the perception is clearly different in successful engineering companies, where DFX is seen as a pervasive set of engineering activities that form the life blood of the CE cooperating teams (Prasad 1994). There, decision-making steers the product design and development process. These companies determine (a) what subsystems, components, parts, materials, etc. to develop anew, (b) what can be carried over, subcontracted and (c) what can be ordered through design houses (Dika and Begley 1991). Companies define a set of consistent product objectives with respect to company and customer goals, set priorities, and allocate ample resources (Clausing 1994).

## 2. Life-cycle cost drivers

There are three main cost drivers during an entire life-cycle of a product from conception to grave: company costs, user costs and society costs (figure 2). The goal of

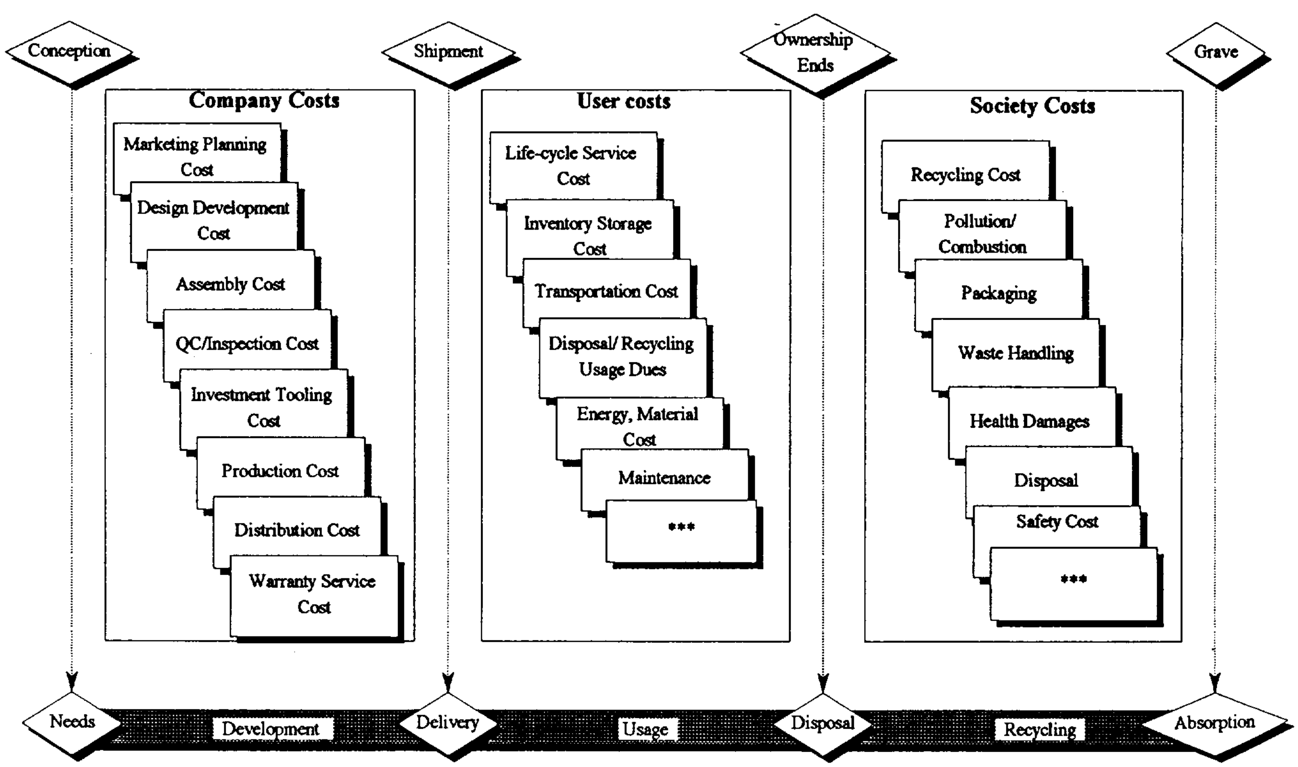



Figure 2. Life-cycle cost drivers.

the life-cycle design is to maximize values in a product, while containing its cost to manufacturer, the user and the society (Wheelwright and Clark 1992).

$$C_{drivers} = f[C_{company}, C_{users}, C_{society}] \quad (1)$$

where $C_{drivers}$ stands for cost drivers, and $C_{company}$, $C_{users}$ and $C_{society}$ represent the cost contributions associated with the company, the user and the society.

### 2.1. *Company costs*

Company costs are the costs of activities required in planning, design development, assembly, production, distribution and servicing a quality product. Company costs include all expenses that are incurred from needs to delivery until the product is shipped to the customer. Company costs are of two types: direct and indirect. Direct costs result from highly visible and documented costs of labour and material used on the factory floor. Indirect costs are everything other than labour and materials. How direct and indirect costs are collected if there are multiple product lines and/or multiple product offerings is discussed in several books (see, e.g. Fabrycky and Blanchard 1991, Ostwald 1992).

$$C_{company} \approx C_{needs\text{-}to\text{-}delivery} \quad (2)$$

### 2.2. *User costs*

User costs are the costs to the users for those activities that are performed by the user. The use period includes the time when the product is delivered or shipped, to its disposal when the ownership of the product ends. There are multitudes of different costs associated with disposal. User costs will soon begin to include the costs for recycling or disposal. These costs may vary from state to state or country to country (e.g. USA versus EU). Some EU countries do not allow landfilling of some products (e.g. German Electronic laws). In some American states, consumers are now forced to pay a disposal fee for old tyres when new tyres are purchased. Consumers may begin to pay penalties or taxes for using freon in air conditioners, refrigerators and freezers. This means a separate model would have to be developed for every location the model is to be used in. The user costs are therefore a function of expenses from delivery of a product to its disposal.

$$C_{users} \approx C_{delivery\text{-}to\text{-}disposal} \quad (3)$$

### 2.3. *Society costs*

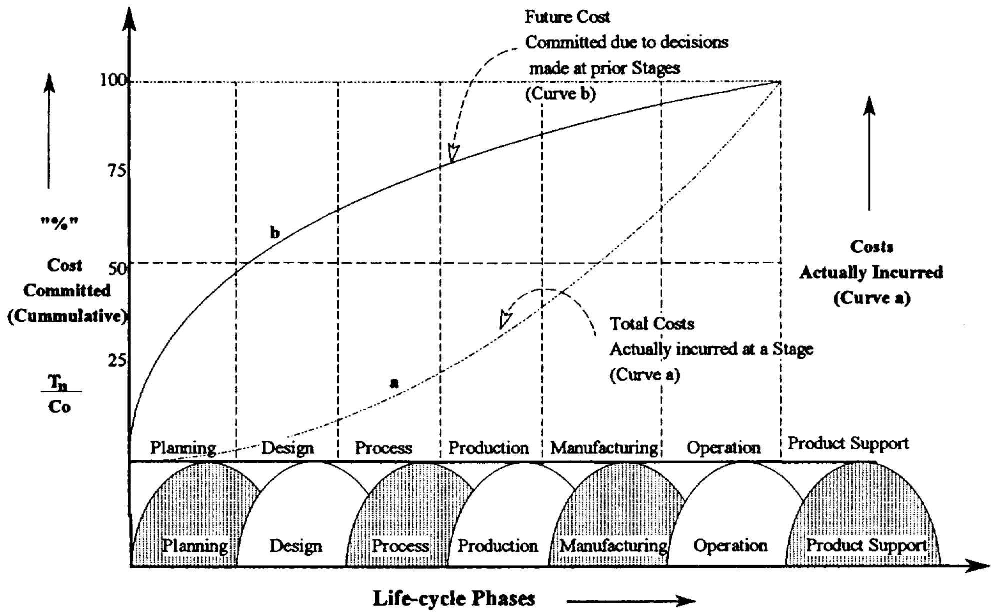
The society costs are the expenses that are inflicted on the society from the time the product is in user custody until it is disposed of or recycled safely. The ability to recycle the material, or its impact on the environment, is the major contributing cost to the society. These costs have already begun to increase, even though many of these costs are intangible. It is difficult to measure or quantify them accurately.

$$C_{society} \approx C_{disposal\text{-}to\text{-}absorption} \quad (4)$$

Some engineering and design firms do not go far enough in reducing life-cycle driver costs. Most focus on the company costs, and in a narrow sense, just concentrate on the direct costs. Very few product development teams (PDTs) attack the company's greatest cost challenge—the indirect costs. It is noteworthy that indirect company costs can be four–five times larger than the direct company costs. In spite of this, only a very small portion of any PDT considers reducing it during the design and development phase (Fabrycky and Blanchard 1991). Most PDTs believe indirect costs can only be attacked either at the management level, or during the production or manufacturing assembly phase of its life cycle (Ostwald 1992). The latter contention is certainly wrong.

## 3. Economics of reliability engineering

It has been reported (Patton 1980, Nevins and Whitney 1989) that 70–80% of the total cost of manufacturing a product is committed at the time of conceptual formulation, rising to 85–90% by the start of development before any hardware is built (figure 3). Since the actual time and expense in product development during this initial stage are low (10–30%), any changes introduced at this point cost very little but can greatly influence the subsequent costs of the production (Nevins and Whitney 1989). On the contrary, if the changes are made during the later stages, e.g. the manufacturing planning of the part, only 10–20% of the product cost is affected. Most people in many companies do not realize this fact. They start too late looking for the source of the problems, and end up spending too much time and money in 'fixing' the problems at the 'wrong' place (Liker *et al.* 1995). In reality, they only end up fixing the 'symptom' of the problems. The 'real' fix for a bad manufacturing process is not more SPC (process control), SQC (quality control) or any similar controls on the factory floor, but the discovery and elimination of the source of the problems at the initial stages, so that the




**Source:** Based on Computer-aided Manufacturing International Data and an article in Business Week, McGraw-Hill Publication, April 30, 1990, p. 110.

Figure 3. (a) Total cost actually incurred at any stage. (b) Future cost commitments at a stage due to a decision made in the prior stages.

redesigned process is insensitive to such variations (Hoffherr *et al.* 1994).

It is further said (Prasad 1996) that unknowingly making wrong decisions at the early stages, on an average over a number of tasks, turns out to be a more cost-effective way than being precise (figure 3).

For example,

Sum of costs of cancelling $N$ tasks at 25% completion point (if in doubt) + associated penalty of making an unknowingly wrong decision (to cancel them), is
$\lll$ (far far less than)
the sum of costs of cancelling those $N$ tasks at 75% point, if found that the original decision to continue at 25% point was clearly wrong (5)

where $N$ could be any number of tasks, usually more than one. The differences between the two cost scenarios are more pronounced when $N$ is large. A firm can estimate these costs in a timely and accurate fashion if previously incurred cost information is regularly captured during product development in a book of knowledge and made accessible for future use (Ostwald 1992, Magrab 1997). In general, the penalty for cancelling even a few tasks at 75% point is normally so large that it does not make sense to wait for the availability of precise information. In other words, it does not pay to make decisions late in the life-cycle process, even though most decisions at that point are likely to be the right decisions.

A similar trend occurs for the cost incurred in fixing a mistake and for the amount of control one has at any stage. A mistake committed and discovered during the planning and design phase is comparatively inexpensive to fix. However, if it is overlooked and discovered later during process engineering, such a mistake can cost manufacturers several thousand times more (Liker *et al.* 1995). By the time a mistake reaches actual manufacturing, for example it could cost a million times more to fix compared to what it would have cost if detected earlier. After a few initial stages, changes are expensive because the CAD model, prototypes, intent-definition, DFX-checks, analyses, documentation, and processing have all been completed or begun, and these must be repeated or revised.

Detection and early fixing of design can save a lot of time, which can otherwise result in material waste, additional planning time, design time, reprocessing and lost time-to-market implied by the correction process. Though the actual cost of designing a typical product is a small percentage (10–20%) of the total cost of the product, for heavy engineering products in the aerospace and defence industry, it could reach up to 40–50%. Thus, there are dual disadvantages in delaying the decision making process. First, the cost becomes high, and second at the same time the degree of control is sharply reduced.

## 4. Balancing elements for manufacturing competitiveness

Manufacturing competitiveness is a balancing act. There is no single solution—technical or non-technical—that can easily be copied or bought from Japan or other successful companies (Liker *et al.* 1995). This section elaborates this further. In figure 4, the items on the left side of the scale represent things that are 'visible to the customer'. This side is mostly made out of weights belonging to products and services. Functions and features are one of the most 'visible items' and are therefore a primary weight. This is because if a product does not have the functions or features that a customer desires, it is difficult to maintain manufacturing competitiveness (Magrab 1997). Other primary weights belonging to this side are: cost, throughput, delivery and service, and agility. There is an invisible datum line passing through the support point or fulcrum in the centre. This represents a datum level. The position of a lever-tip above this datum on either side denotes the company's weakness. In the same vane, the position of the lever-tips below the datum level indicates the strength. A desirable situation would be when the lever position is balanced. That is, weights on both sides are so placed that it deflects the beam enough, on either side, so that the tip of the lever stays below the datum (the horizontal invisible line as shown in figure 4) level.

### 4.1. *Product and services*

Products and services are what the customers see, touch and feel. The weights that determine the strengths or weaknesses on the left-hand side of the balance are:

- ***Functions and Features***: the first step is to understand market needs and/or specific customer requests. Does the product serve the customer purpose? Does it have features that are versatile, simple, easy to use and handle? The product attributes that are important to the customer must be enumerated and translated into their technical counterparts so that they can be measured by engineers (Clausing and Hauser 1988). These product attributes should include the basic product functions, which the customer assumes, will be provided. They should include the essential level of product performance required by the marketplace, or the level necessary to lead technologically if this is part of a competing strategy. They should also include those attributes that will attract and delight the customer, and will

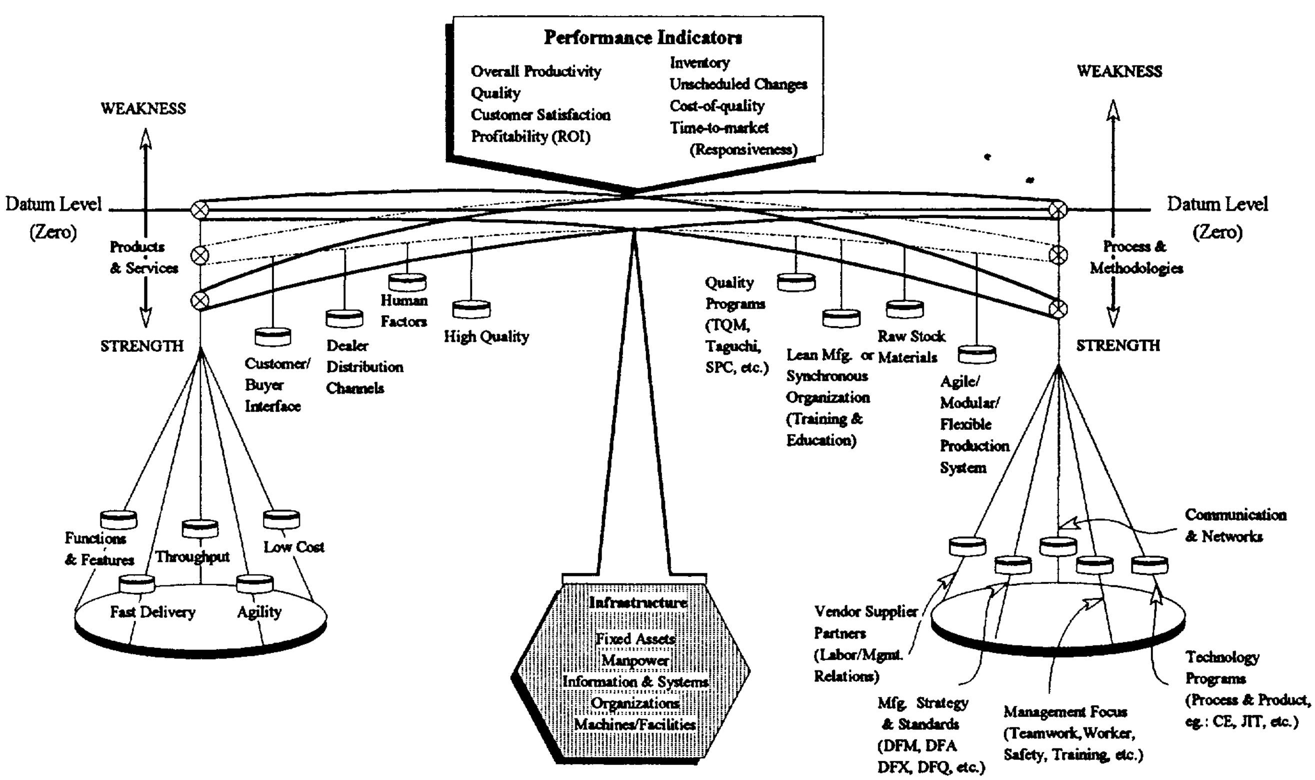



Figure 4. Balancing elements for manufacturing competitiveness.

differentiate this product from their competitors (Dika and Begley 1991). Manufacturing success requires the ability to produce top quality, often individually customized, products at highly competitive prices (Hoffherr *et al.* 1994). Often they have to be mass-produced or delivered to customers in batches as small as units of one with extremely short lead-times.

- ***High Quality***: quality is more than shiny paint—referring to an automobile for specificity. It ranges from the visual (e.g. good door fit, style, colour, etc.) and non-visual (e.g. reliability, producibility and scores of X-abilities), to customer-perceived excellence (e.g. ride and handling, performance, drive-ability, noise-vibration and harshness, door closing efforts and sound, heating and air conditioning system) performance. The myth that higher quality translates into higher costs is not always true. Many have found that overall production of higher quality products not only costs less but also reduces cost-overruns (Hoffherr *et al.* 1994). In many cases, it has been shown that higher quality products yield as much as 40% higher return on investment than lower quality products do. In today's competitive world, quality is no longer an option; it is a necessity, i.e. indirectly it is the way of doing business. It is imperative that each of the design alternatives, in consideration, meet the customer's quality requirements. Quality should not be an object when making tradeoffs. If an alternative cannot satisfy the quality target, it should be removed from further consideration. On the same token, if the product functions exceed its quality expectations at a large cost penalty, the customer will not consider it to be of great value. The product should not be over-designed in areas where the customer is insensitive (Dika and Begley 1991).
- ***Low Cost***: as quality is the price of admission into the competitive marketplace, cost is viewed as the 'ticket for survival'. Cost is influenced by many factors, and the relationship is more complex. For example, an increase in quality, and for that matter any X-ability requirement, has an adverse effect on local cost. Cost reduction cannot be achieved by keeping status-quo. Cost reduction means looking at alternate concepts, materials and process-driven designs. It means looking into fixed costs (direct labour and materials), variable costs (indirect labour and materials), and those due to waste in all forms. Complicated manufacturing systems, inventory costs, equipment (single-purpose machines), facilities and layout are some example ingredients of 'process-driven costs'. Indirect costs are often the greatest contributor to increasing the final delivery costs. Elements of indirect costs include, e.g. overhead expenses, supervision, material storage, rework, as well as hundreds of other operating expenses (Ohno 1988). Such costs can be three–four times more than the direct labour costs. Most designers focus on the direct highly visible and documented costs of labour and materials. They do not normally look at the indirect costs as elements they can possibly impact. Obviously, design by itself cannot eliminate the majority of the indirect costs. Though some indirect costs are not as 'bad', some indirect costs can be reduced or eliminated by strategic choice of tools, technology and processes at an early consideration of designs. Reducing waste and process-driven costs help in achieving higher profit margins and offers manufacturers opportunities to price their products more competitively (Ohno 1988).
- ***Fast Delivery (fast-to-market, responsiveness)***: in today's global marketplace, time is becoming a major competitive force. Quality used to take this place but not anymore (Himmelfarb 1992). Today's customer sees quality and everything else as given (taken for granted). Every automotive company wants to get its new car models on dealer's showroom floors in record time. Airlines spend billions of dollars in maintenance facilities and repairs to cut the non-flying downtime. Overnight delivery carriers are handling more and more packages with services faster than ever before. Even food chains (e.g. pizza parlours) are competing for home delivery on the basis of time rather than taste. The range for responsiveness and time-to-market is declining every time a new product is introduced. With the advent of newer and faster technologies, some day companies perhaps will be able to compress days into hours and minutes into seconds.
- ***Agility (economy of ease or flexibility)***: a prestigious study at the Iacocca Institute of Lehigh University has defined agility as the paradigm for manufacturing in the next century (Goldman and Priess 1991). Agility is defined as the ability to thrive and prosper in a competitive environment of continuous and unanticipated change, to respond quickly to rapidly changing markets and customer demands. A key element of agility is the integrated enterprise thinking. Agile enterprises are totally integrated organizations. Information flows seamlessly among manufacturing, engineering, marketing, purchasing, finance, inventory, sales and research (Dove 1993). Just as mass production in 1950 leveraged 'machine intelligence' (economy of automation), and craft manufacturing leveraged people's skills and dexterity (economy of skills),

agile manufacturing is about leveraging the 'economy of ease' with which a company can react to new opportunities. Becoming an agile virtual company does not necessarily mean downsizing. Economy of ease is taking the front seat as a competitive differentiator (Himmelfarb 1992). It is not a technological solution, if plugged in, that will enable an enterprise to respond to change. Agility is merely a concept to be used while designing products and manufacturing processes so that when markets change or when customers request change, agility in the process can come to the rescue. It allows reconfiguration of the setup with calculated penalty and change in product offerings. Agility is a part of the measure of merit that needs to be considered in product realization.

- ***Throughput***: a global enterprise requires global or integrated thinking. The former CAD measures of productivity, e.g. 'engineering CAD throughput' or number of drawings created in a week are local (thus inadequate) throughput measures. It is not a true representation for maximizing flow of work. Measures on 'number of engineering changes per unit of time', or 'ramp-up time to volume production' are closer to global measures. Such measures on work-flow provide a more accurate big picture. Throughput is the rate (per unit of time) at which the current factory process transforms the materials into finished 'usable' products (Goldratt and Cox 1986). The 'usable' means it does not include defective or scrap parts (i.e. those that cannot be converted into sales or profit dollars). Clearly, throughput is dependent upon the amount of lead-time required to finish each one of the activities. Throughput for Serial Engineering (SE) is lowest, since one starts when the other ends. Throughput for Concurrent Engineering (CE) is proportional to the degree of overlap or independence between the activities. If each of the activities is completely independent, then throughput will be proportional to the inverse of the maximum lead-time that any one of the activities will take. This is because when activities are independent all activities can be started at once.

$$\text{Throughput (for independent activities in SE)} \propto 1/(\Sigma T_i) \quad (6)$$

$$\text{Throughput (for independent activities in CE)} \propto 1/T_{\text{maximum}} \quad (7)$$

where,

$$T_{\text{minimum}} < T_i < \mathrm{T}_{\text{maximum}} \text{ for I} = 1, n \quad (8)$$

and $T_{\text{maximum}}$ = maximum lead-time activity out of all the activities $T_i$ that could be performed in parallel, $T_{\text{minimum}}$ = minimum lead-time activity out of all the activities $T_i$ that could be performed in parallel.

Besides, there are several secondary weights, e.g. human factors, dealer distribution channels, customer and/or buyer interface, that can tip the balance to one side or the other depending upon their locations on the lever (see figure 4).

### 4.2. *Process and methodologies*

Process and methodologies form the 'invisible' side of the balance (Figure 4). On this side, value is added to the raw materials or human skills. The general approach to management—the concepts used to market the product, the policy followed in making an investment, the reward system for employees, and the importance assigned to customers—are all important methodologies.

The factors that are considered influential in tilting the balance on this side of the lever below the datum line are:

- ***Raw Stock or Materials***: raw materials are defined as a variable cost of producing a unit of a product. The advantage gained due to lock on materials technology is considered part of this.
- ***Quality Programs*** [e.g. Total Quality Management (TQM) (Hoffherr *et al.* 1994), Taguchi, Statistical Process Control (SPC), Quality Circles, GM Delphi studies, Value Engineering, Six Sigma Program, etc. (Carey 1992)]. One of the principles of SPC is that inspection, once a part is produced, even if it is done on a statistical basis, is wasteful. By the time a part comes off the end of a production line and is inspected, many bad parts will have been produced. It is likely that the special cause that produced the bad part will not be easy to identify. What needs to be done is, first, to measure some key process parameters on a real-time basis. Second, identify those parameters which are sensitive to the cause of the variation, and third, address those affecting the outcome the most. Six-sigma program is named after the statistical figure of six times the standard deviation measurement. Like many earlier ones, these programs require re-engineering of the organization or modifying how it operates. Quality programs should not only be directed towards minimizing defects in production, but, also augmenting the capability of the product work-groups to monitor and correct their own operations. Augmenting includes determining the level of variability in the process, e.g. on-line factory information and performance feedback

system to monitor the flow of the product through manufacturing processes. Augmenting also includes taking necessary corrective actions to eliminate those variations. It requires bench-mark schemes, rationalized schemata for products and processes, and a company-wide strategy for implementing team communication networks. The success will depend upon the check and balances of the planned operations. For example, potential failures detected at any level need to be relayed back to team leaders. Through the chain of commands it ought to be conveyed to the design team for error-proofing the process so that it does not occur again. Such quality programs will not only create good products but will also ensure continuous improvement guaranteed over the life of the product.

- ***Lean Manufacturing or Synchronous Organizations***: lean or synchronous, often used interchangeably, is an important and crucial manufacturing strategy. There are 17 tactics that one can employ to be lean (Prasad 1996). Synchronous organization improves efficiency through such things as systematic elimination of waste, error-proofing, just-in-time inventory, work place organization and 13 others (Hartley 1992). Lean manufacturing means developing an environment that is conducive to synchronous principles. Elimination of waste includes bottlenecks of information or material movements, smooth flow of work, committee structure rationalization, etc. Good lean manufacturing programs include training and education.
- ***Agile/Modular/Flexible Production System***: internal or invisible to the customer is the ability of a manufacturer to be product flexible, modular and agile. Flexibility in manufacturing can reduce material costs, work force, inventory, idle facility or machine time, and improve material handling. While these are invisible to the customer, they do affect the overall cost, quality and timing of a product that is very visible to the customer. The tactics of a flexible production system are quite company or process-focused. They are difficult to be duplicated by the competitors, since they often are not visible. These tactics are often directed towards material or cost improvements, e.g. reduced work force through process-driven design concepts (e.g. flexible manufacturing). Such tactics also include inventory cost reduction through a combination of techniques (e.g. in-line sequencing, just-in-time delivery, defect-free supplier and improved material handling).
- ***Technology Programs***: this includes programs, e.g. just-in-time (JIT) manufacturing, virtual reality, rapid prototyping, pull system, Concurrent Engineering, relational data base systems. There is no single universal form that can fit all programs. Each of these and other automation programs must be tailored to the needs of the individual company.
- ***Manufacturing Strategy and Standards***: strategies include measures, e.g. DFM (design for manufacturability), DFA (assembly), DFQ (quality), DFC (cost), and other DFX measures. DFX stands for design for X-ability, where X-ability may symbolize any life-cycle concern, e.g. quality, cost, assembly, manufacturability, serviceability, maintainability, etc. (Prasad 1997). Kodak saved $60K in the redesign of a photocopier part by using rapid prototyping (Termini 1996). Organizations must deploy common systems, standardized tools, methods, and practices to design and develop products, tool-rooms, die design, fabrication and construction, and business support infrastructure. Polaroid deployed existing parts for 75% of its new ProCam, resulting in 35% savings in developmental costs (Hartley 1992).
  - *Use Common System*: organizations must develop technologies that use common systems to produce a variety of products, each with its own unique features and distinctions. This means that processes and technologies are not developed with a single solution in mind; they are developed to be used in a variety of applications, e.g. 3-D CAD, solid modelling, etc. Technology in itself should not be the goal of an organization. Rather, an organizational objective should be to develop technologies that have broader applications throughout the SBU for solving existing and anticipated problems.
- ***Management Focus***: companies must adopt a management style that allows more leeway to workers (empowerment), pushing decision making to the lowest appropriate levels, and greater flexibility to managers. It must reduce the reliance on corporate headquarters and begin to establish intra- and inter-corporation projects, with multi-disciplinary focus teams with a wide range of expertise. Emphasis should be on 'the process' and continuous improvement, long range thinking, and total customer-orientation in the projects that are undertaken. There should be more and more decentralization of activities and better coordination between the groups involved.
- ***Vendor/Supplier partners (including labour management relations)***: manufacturing enterprises can, and most likely will, have borders going well beyond the confines of an individual company or its subsidiaries. This postulate is supported by the success of Japanese 'Keiretsu' and is

the key to the agile manufacturing concept (Goldman and Priess 1991). The latter is manifested in many recent international developments resulting in cooperative agreements. An example of a directive is the US congressional and presidential directives in the USA and Japan to mandate transfer of technology from federal research facilities to private sectors. Other examples include CRDA (Cooperative Research & Development Agreement) and US National Science Foundation and Department of Commerce's strategic partnership initiatives.

- *Strategic Sourcing*: most companies are adopting policies to optimize outside supplier base, develop partnerships with strategic suppliers to develop mutual trust, and enter into various cooperative arrangements.

- ***Communication and Networks***: the sleuth of Electronic Mail (E-mail) and Ethernet networks [e.g. Local Area Networks (LAN), Wide Area Network (WAN) and broad band] systems, and a new generation of workstations are providing direct links between work-groups, e.g. design, analysis, manufacturing and testing, and the CE team users. Improved communication features allow data to be transferred rapidly at a higher rate of one or two orders of magnitude faster than what was feasible a few years ago. Networks, e.g. LAN, can quickly transmit huge data files almost instantaneously to a large number of interconnected users. Programs on these networks thus enable the rapid transmission of design information between work-groups and teams facilitating the CE approach. Ford boasts $2 million a year saving as a result of their wide area multinational network.
  - *Electronic Data Interchange (EDI)*: one of the biggest barriers to effective CE programs has been the lack of a common graphics exchange standard. Much of the design generated by a CAD/CAM supplied by one vendor cannot be recognized directly by another CAD/CAM system. This has been eased at least partly by the introduction of exchange standards. Initial Graphics Exchange Specifications (IGES) is the most common approach that is used currently to allow dissimilar systems to talk to each other. In this approach, the transmitting system translates data into a second language—a so-called IGES neutral file—that can be sent to different systems. Translators at the receiving end reformat the data into appropriate native forms. Today, many standards are being explored, e.g. PDES and ISO STEP standards.

  With such standards, the initial product definition data-transfer capability of IGES has been extended to include feature-based and object-oriented representations. They are currently being expanded to many application domains, e.g. sheet metal forming, finite element, numerical control, process planning, etc. As this range of functionality and application interface expands further, it will be easier for engineers, designers and manufacturing personnel to transmit data regardless of individual firmwares (brands of software and hardware systems) that may be in use.
  - *Manufacturing Automation Protocol (MAP)*: the proliferation of stand-alone manufacturing tools made it difficult, or impossible in some instances, for one machine to talk to another on the factory floor. MAP was subsequently developed by General Motors and its industry partners to facilitate and simplify communications between the growing number of machines and computers in today's automotive factories. MAP allows equipment to share data or 'talk' to each other for improved efficiency in Computer Integrated Manufacturing (CIM) factories.

Figure 5 shows three examples of how such a process and methodology will work in harmony to meet both the company and customer interests. Three process examples are 'manufacturing strategies', 'agile/modular/flexible production system' and the 'quality programs'. As shown in figure 5, the company interests are represented by one or more of the teams (multi-disciplinary, multi-functional or core competency). In the example of the manufacturing strategies case, teams are shown to take the initial step in determining the appropriate strategies, e.g. common systems, standards, DFM/DFA/DFQ/DFX, etc. which are suitable for the problem at hand. This means that they would be helpful in either enhancing the product values to the customer, or meeting the company interests (e.g. profitability). In the case of the quality programs example, the process is the reverse. The customer (in terms of VOC) provides the basic needs and wants (Clausing and Hauser 1988), which in turn are translated into appropriate methodology to be used in product design and development. The agile/modular/flexible production system, on the other hand, converts company interests into the customer interests. Many of the processes and methodologies described in this section will follow either a 'customer-to-company' or 'company-to-customer' scenario. As in the examples in figure 5, they will be leveraging the strengths of each other in protecting their interests.

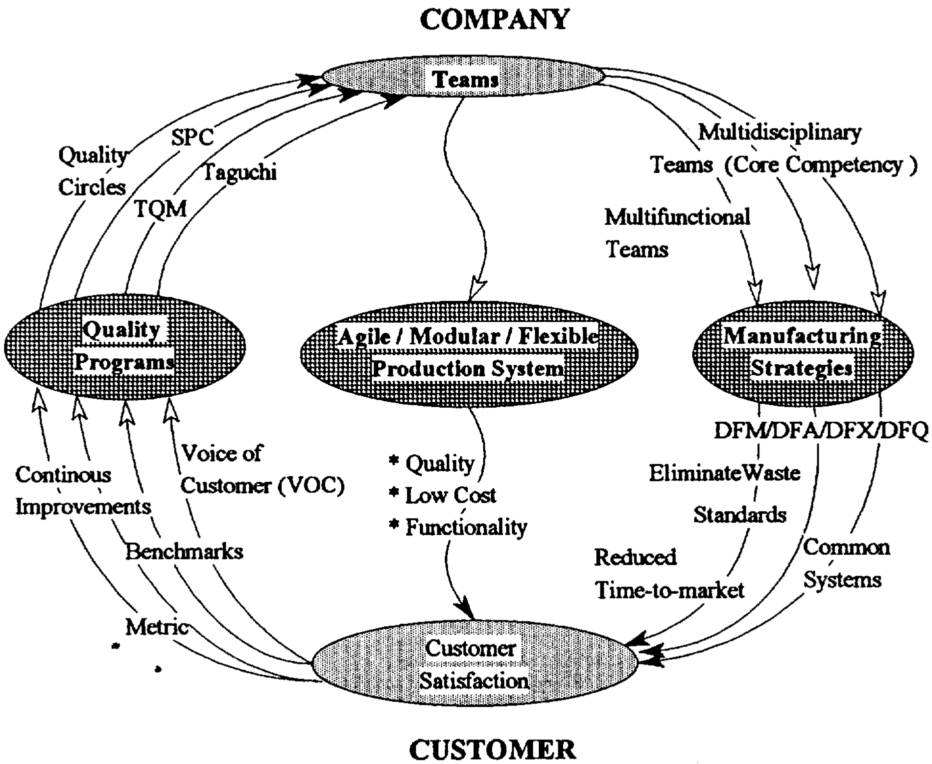



Figure 5. Examples of process and methodologies for meeting the company and customer interests.

## 5. A heuristic-based optimization model

Figure 6 shows a list of eight indicators that determine the performance of an enterprise competitiveness. Each indicator provides a measure of a company's efficiency in the world marketplace. Each indicator is shown by a directed radial line pointing away from the centre of a unit circle. A point on the unit circle represents world class level for an indicator. Such points represent a normalized or scaled value of 1.0. A point at the centre of the circle usually represents a value 100% 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 upon its distance away from the centre. The desirable state depends upon whether a performance indicator is to be maximized or minimized. The desirable state is outward of the circle (pointing away from the centre), if a performance indicator is to be maximized. The desirable state is inward of the circle (pointing towards the centre), if a performance indicator is to be minimized. For instance, a point 1 unit out from the centre may represent a level 'twice' as good or bad from the 'world-class' level. Depending upon whether the 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 indicators that need to be maximized and four that need to be minimized. They are placed alternately around this unit circle. The solid line shows the current state (figure 6). The shaded petals are formed due to the lines drawn connecting these max- and min-points, and the unit circle representing the world-class. Clearly, the shaded petals represent the net contribution from each performance indicator. In order that the current state of the process must perform better than or equal to the world class, the following must be true:

$$\text{Sum of the petal areas} \geq 0.0 \qquad (9)$$

The overall performance must show a net profit under the current conditions with or without the new product development or technology insertion. The objective is to move the four 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 intersection of the straight lines and the circles. Performance in this context represents a system's performance. 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.

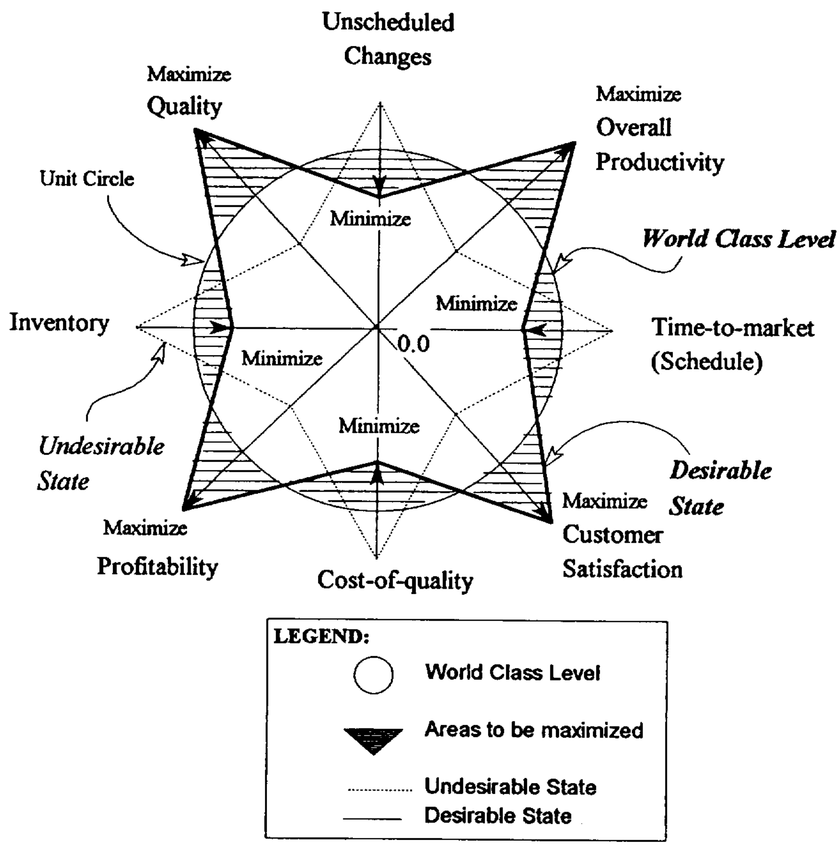



Figure 6. Performance indicators for measuring an enterprise competitiveness.

New accounting measures [e.g. Activity-Based-Costing (ABC) and Goldbratt's theory (1986)] are helpful in obtaining a system's performance.

### 5.1. *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 the whole system—both the upstream and 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 product or services completed in a given period of time. In other words, scrap or waste is not a measure of productivity.

$$\text{Productivity } (P) T/OE \qquad (10)$$

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 during this period. All outputs are not throughput, some outputs (e.g. scraps, defects, etc.) are waste. The throughput is defined as follows:

$$T = \sum_{i=1}^{N_0} [P_i * N_i * P_{v_i}] \qquad (11)$$

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 $i$, $P_{v_i}$ is the production (or throughput) value per acceptable output $i$, $N_0$ is the number of outputs (e.g. 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 is. Successful manufacturers are those who measure the difference between outputs and throughput, identify the possible source of such discrepancies and take countermeasures to prevent them at the source.

### 5.2. *Customer satisfaction*

One of the purposes of developing a 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 team's effort and time. They do not provide direct benefit to the ultimate customer. Value-added features or services are pleasant surprises to the customers.

### 5.3. *Unscheduled changes*

The success of rapid product realization depends upon 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 (e.g. during a downstream operation), it might be very costly to fix them.

### 5.4. *Inventory (I)*

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 ($\sigma$) is the standard deviation for a day's demand, and $d$ is the order ship time in days, the required inventory is:

$$\text{Inventory} = [nd + (3\sqrt{(d)}) * \sigma] \qquad (12)$$

### 5.5. *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: (i) cost to ensure quality (c-t-e-q); and (ii) cost to correct quality (c-t-c-q). They are shown in figure 7. Cost to ensure quality is the cost of doing things right (e.g. choosing the right process), the cost of doing right things (e.g. choosing right actions), and the cost of preventing mistakes (e.g. 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 (e.g. choosing the wrong process), the cost of doing wrong things (e.g. choosing the wrong actions), and the cost of inspections to discover mistakes committed earlier in the process.

Most cited product quality indicators attempt to measure the parts per million (PPM) level of conformance. This does not, however, account for criticality—e.g. a \$1 part failure may result in a \$1000 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.

$$\text{c-t-q effectiveness} = [\{\text{cost to ensure quality}\}/\{\text{cost to quality}\}]*100 \qquad (13)$$

where cost to quality is the sum of two parts.

$$\text{cost of quality} = \text{cost to correct quality} + \text{cost to ensure quality} \qquad (14)$$

$$\text{or c-t-q} = \text{c-t-c-q} + \text{c-t-e-q}$$

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

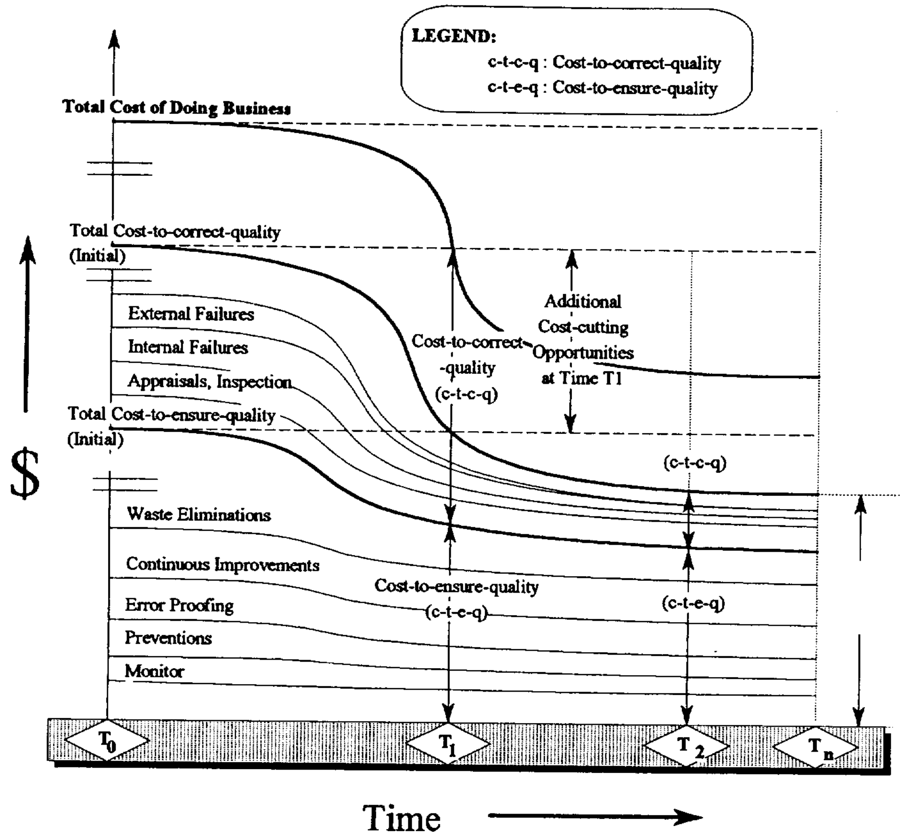



Figure 7. Cost-cutting opportunities through prevention (measurement of cost to quality).

decision-making or to track quality improvement opportunities.

### 5.6. *Profitability (ROI)*

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

$$\mathrm{ROI} = [\{G - OE\}/\{I\}] \qquad (15)$$

where gain (G) is defined as:

$$\text{Gain (G)} = \text{Net Sales} - \text{Cost of Raw Materials} \qquad (16)$$

where, net sales (or volumes) are defined as the irreversible transfer of product 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 the normal operating expenses plus direct labour and factory overhead. By grouping direct labour and factory overhead in an OE category, there is little reason for teams to overbuild their inventory. Direct labour is recognized as a fixed cost.

### 5.7. *Time-to-market*

This is a measure of the time period required to design and develop a marketable product (from concept through to rate production).

Some of these 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 performance indicators that are being used are in the areas of delivery, risk management and teamwork communication.

## 6. Concluding remarks

The paper describes a heuristic-based optimization model for maximizing a set of attributes that are favourable to improving the enterprise competitiveness and minimizing a set that is unfavourable. Eight performance indicators are considered in this paper for measuring enterprise competitiveness. Four of those attributes, which are minimized, are unscheduled changes, time-to-marker (schedule), cost of quality, and inventory. The four attributes that are maximized are quality, overall productivity, customer satisfaction and profitability. Optimization in this paper is considered a balancing act between the goodness of *products and services* to the *process and methodologies* that are expended to realize it. Examples of contributing strengths identified in this paper towards products and services' are: functions and features, low cost, agility, fast delivery (fast-to-market, responsiveness), throughput, high quality, human factors, dealer distribution channels, customer/buyer interface, etc. Examples of process and methodologies that provide contributing strengths are quality programs, lean manufacturing, agile/modular/flexible production system, vendor supplier partner, manufacturing strategy and standards, management focus, technology programs, communication and networks, etc. In this model, a company is considered to have reached a *world-class manufacturing* status only if the goodness of *products and services* far outweighs the cost of *process and methodologies* expended in providing those products and services.

## References


BHOTE, K. R., 1997, A powerful new tool kit for the 21st century. *National Productivity Review*, **16**, 29–38.

CAREY, W. R., 1992, Tools for today's engineer strategy for achieving engineering excellence: Section 1: quality function deployment. SP-913, SAE International Congress and Exposition, Detroit, Michigan, USA, 24–28 February 1992, SAE 920040.

CLAUSING, D. P., 1994, *Total Quality Development: A Step-by-step Guide to World-class Concurrent Engineering* (New York: ASME Press).

CLAUSING, D. P., and HAUSER, J. R., 1988, The house of quality. *Harvard Business Review*, **66**, 63–73.

DIKA, R. J., and BEGLEY, R. L., 1991, Concept development through teamwork—working for quality, cost, weight and investment. SAE Paper #910212. In *International Congress and Exposition*, SAE, Detroit, MI, 25 February–1 March, pp. 1–12.

DOVE, R., 1993, Agility—the key to competitiveness in the 1990s. *Automotive Industries*, Oct., A1–A15.

FABRYCKY, W. J., and BLANCHARD, B. S., 1991, *Life-cycle Cost and Economic Analysis* (Englewood, NJ: Prentice Hall).

GOLDMAN, S., and PRIESS, K., 1991, (eds) *21st Century Manufacturing Enterprise Strategy: An Industry-led View*, Volume I (Iacocca Institute: Lehigh University).

GOLDRATT, E. M., and COX, J., 1986, *The Goal: A Process of Ongoing Improvement* (Croton-on-Hudson, NY: North River Press).

HARTLEY, J. R., 1992, *Concurrent Engineering: Shortening Lead Times, Raising Quality, and Lowering Costs* (Cambridge, MA: Productivity Press).

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

HOFFHERR, G. D., MORAN, J. W., and NADLER, G., 1994, *Breakthrough Thinking in Total Quality Management* (Norcross, Georgia: Industrial Engineering and Management Press).

LIKER, J., ETTLIE, J., and CAMPBELL, J., 1995, *Engineered in Japan: Japanese Technology Management Practices* (New York: Oxford University Press).

MAGRAB, E. B., 1997, *Integrating Product and Process Design and Development—The Product Realization Process* (Boca Raton, FL: CRC Press).

NEVINS, J. L., and WHITNEY, D. E., (editors) 1989, Concurrent Design of Products and Processes, (New York: McGraw-Hill), pp. 1–24.

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

OSTWALD, P. F., 1992, *Engineering Cost Estimating*, 3rd edn (Englewood, NJ: Prentice Hall).

PATTON, J., 1980, *Maintainability and Maintenance Management* (Instrument Society of America, Research Triangle Park, N.C.).

PRASAD, B., 1994, Modern manufacturing. In M. Zaremba and B. Prasad (eds) *Modern Manufacturing: Information Control & Technology*, Chapter 1 (London: Springer), pp. 1–15.

PRASAD, B., 1996, *Concurrent Engineering Fundamentals, Volume I: Integrated Product and Process Organization* (New Jersey: Prentice Hall).

PRASAD, B., 1997, Life-cycle measures and merits for gaining manufacturing operational excellence. In *International Automotive Manufacturing Conference and Exposition*, Detroit, MI, 12–16 May, SAE Technical Paper Series #971753, SAE, Warrendale, PA.

TERMINI, M. J., 1996, *The New Manufacturing Engineer* (Dearborn, MI: Society of Manufacturing Engineers (SME)).

WILSON, P. M., and GREAVES, J. G., 1990, Forward engineering—a strategic link between design and profit. In *Mechatronic Systems Engineering*, Volume I, pp. 53–64.

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