THE HANDBOOK OF MANUFACTURING ENGINEERING
Second Edition

Product Design and Factory Development

EDITED BY
Richard Crowson

CRC Taylor & Francis
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Preface

Handbooks are generally considered to be concise references for specific subjects. Today's fast-paced manufacturing culture demands that such reference books provide the reader with how-to information with no frills. Some use handbooks to impart buzzwords on a particular technical subject that will allow the uninitiated to gain credibility when discussing a technical situation with more experienced practitioners.

The second edition of *The Manufacturing Engineering Handbook* was written to equip executives, manufacturing professionals, and shop personnel with enough information to function at a certain level on a variety of subjects. The level of professional skill developed by reading this handbook is determined by the reader.

This series of books is written to serve as a textbook or supplemental material for classes in engineering schools for students pursuing a manufacturing engineering bachelor's or graduate degree.

Manufacturing engineering professionals are taking the lead in a number of jobs not traditionally thought to be covered in the discipline: decision-making executives of manufacturing businesses; product design engineers; process design engineers; and positions in tooling, facility planning, and production control are now filled by engineers that first learned the trade of manufacturing engineering.

The resurrection of an undesignated apprentice in our manufacturing culture has become necessary as the technology continues to grow at a phenomenal rate. Companies can no longer afford to allow the manufacturing engineer to learn on the job. As more universities graduate engineers with bachelors to doctorate degrees in manufacturing engineering, the challenges presented by the fiercely technical world we live and work in are met by the manufacturing engineer. Therefore, the manufacturing engineer must gain as much knowledge from as many credible sources as possible. That is why this series of books was developed: to be an aid to successfully applying manufacturing engineering skills in school or on the job.

Many manufacturing engineers choose to stay in the field of manufacturing engineering due largely to the sense of accomplishment gained from creatively seeing every step of the process by which raw material is turned into a finished product. However, an increasingly large number of engineers who started as manufacturing engineers are moving into positions of supervision in the design engineering, research and development, and administrative areas. This is true because the manufacturing engineer brings the quality of knowledge that is hands-on, commonsense, and practical.

The advent of smaller and faster computer processors has made some of the systematic approaches to manufacturing affordable to the mid-sized to small manufacturer. Therefore the quality information presented by Geoffrey Boothroyd's DFMA® (Design for Manufacture and Assembly), which has historically been used by automotive and aircraft manufacturers, is becoming available to the smaller, more flexible manufacturer.

As a manufacturing engineer uses this handbook to study history and apply principles to an existing manufacturing firm, new ideas will be spawned that will allow improvements in process flow and product flow. The successful efforts of many years' experience are captured in these chapters and can be used profitably by any reader willing to think out of the box when facing challenges on a daily basis.

Human factors greatly influence productivity in the workplace, as does workplace safety. The public awareness of hazardous practices requires the manufacturing engineer to put the ergonomic and safety practices that are described in this handbook into practice.

The historic data for anthropometry is based upon the U.S. military data and statistics compiled in the 1970s and 1980s. As the culture of manufacturing expands to include the world, these data are no longer relevant. It is up to the new manufacturing engineer to seek to add to these data and generate ethnicity-specific data to assist in the design of ergonomically based products.

The cost of a product is directly impacted by injuries, product liability, and low productivity. Thus, a manufacturing engineer must strive to become expert in the mitigation of these areas.

This second edition of *The Manufacturing Engineering Handbook* is dedicated to Jack M. Walker, who was unable to participate in the editing of this book but who contributed greatly in the last few months of his life. Much written by Jack still remains unchanged in this edition because of its value in the workplace and manufacturing environment today. Jack was a wonderful and inventive man who loved to look for ways to do things that had not been thought of before.

I will always remember with joy the hours he and I spent together while he gave example after example of inventions and designs that he had authored. Most of these were incredibly simple and ingenious. Jack delighted in swimming upstream by solving problems too quickly for others. He would recount examples of being made to prove over and over again the idea he had come up with quickly. This did not discourage him, and he delighted in the fact that the proving of his ideas took many times longer than the invention of that idea. His favorite saying was that waiting for others to catch up with him was "better than a sharp stick in the eye."

His smile and the gleam in his eye let you know he had experienced a full life and had a deep understanding of the human interaction in the manufacturing engineering process. We will miss Jack, but we will all enjoy his spirit of joy at the discovery of new ways to manufacture.

RICHARD D. CROWSON
SET, CMfgT, CMfgE

Editor

Richard D. Crowson

Richard Crowson is currently a mechanical engineer at Controlled Semiconductor, Inc., in Orlando, Florida. He has worked in the field of engineering, especially in the area of lasers and in the development of semiconductor manufacturing equipment, for over 25 years. He has experience leading multidisciplinary engineering product development groups for several Fortune 500 companies as well as small and start-up companies specializing in laser integration and semiconductor equipment manufacture.

Crowson's formal engineering training includes academic undergraduate and graduate studies at major universities including the University of Alabama at Birmingham, University of Alabama in Huntsville, and Florida Institute of Technology. He presented and published technical papers at Display Works and SemiCon in San Jose, California.

He has served on numerous SEMI task forces and committees as a voting member. His past achievements include participating in writing the SEMI S2 specification, consulting for the 9th Circuit Court as an expert in laser welding, and sitting on the ANSI Z136 main committee that regulates laser safety in the United States.

Contributors

Geoffrey Boothroyd
Boothroyd Dewhurst, Inc.
Wakefield, Rhode Island

Richard D. Crowson
Consultant
Melbourne, Florida

Vijay S. Sheth
McDonnell Douglas Corporation
Titusville, Florida

Timothy L. Murphy
McDonnell Douglas Corporation
Titusville, Florida

Allen E. Plogstedt
McDonnell Douglas Aerospace East
Titusville, Florida

Marc Plogstedt
ITEC
Orlando, Florida

Paul Riedel
Certified Industrial Hygienist
Rockledge, Florida

Jeffery W. Vincoli
CSP, REP
Titusville, Florida

Jack M. Walker
Consultant
Merritt Island, Florida

William L. Walker
National High Magnetic Field Laboratory
Florida State University
Tallahassee, Florida

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1 Product Development

Jack M. Walker
and
Richard D. Crowson
with
Geoffrey Boothroyd

> The greatest durability contest in the world is trying to get a new idea into a factory.
>
> —Charles F. Kettering, CEO, General Motors
>
> but
>
> It's one heck of a lot easier to implement World Class Manufacturing principles than to go out of business.
>
> —William P. Conlin, President, Cal Comp, Inc.
>
> and
>
> You can't achieve World Class Manufacturing without first having a World Class Product Design!
>
> —Jack M. Walker

1.0 INTRODUCTION TO PRODUCT DEVELOPMENT

This chapter on product development discusses the impact of concurrent engineering on product development. In the first subchapter we discuss the need for teamwork among the various factory functions, starting with the customer's wants and his or her early involvement in the product development cycle. The role of the engineering manager, manufacturing engineer, project manager, or product engineer when guiding the product development process includes five basic steps in a systematic approach to product development. Pahl and Beitz, in their book *Engineering Design: A Systematic Approach* (1993), defined five conditions that must be satisfied when employing a systematic approach to guide the product development process. Those five steps have proven to be very crucial to the editor in creating the corporate atmosphere conducive to cooperation and concurrent engineering design in the past 30 years of product design for major corporations.

The steps are: (1) ensure the requisite motivation for the solution of the task; (2) clarify the boundary conditions; (3) dispel prejudice; (4) look for variants, i.e., a number of possible solutions that will best serve as the solution to the design problem; and (5) make decisions.

The motivation to introduce a new product is not always equally shared by each participant in the concurrent process. Some may feel the current product does not need to be changed. These feeling may stem from the insecurity change in a company brings. The uncertainty in the financial implications of the risk/reward ratio of moving into new territory that is yet unexplored may unsettle some who do not normally participate in the design process. Teams are made up of all disciplines within the company and equally share in the risks and rewards from the effort. Some team members may simply be satisfied with the status quo and do not want to learn new things. It is up to the leader of this effort to understand that the first three steps involve removing any "psychological inertia" that might deflect him or her from the objective of introducing a new innovative product to design teams. A key factor in the presentation order of these five steps is that the first three steps and about 60% of the effort are consumed in effectively communicating the product vision. The leader must present a roadmap to define what the product will be, how it will be developed, and what it will cost. The leader must also define what the product will not be, and he or she must attempt to answer any questions that may have negative connotations from those prejudiced against the product. The concurrent team is the leader's best source of information that will come from the customer and ultimately the end user. The leader must listen to team members and others and consider as many possible solutions as is practical before leading the team/company in any direction. The last step involves making decisions. These objective decisions will cause the success or failure of any product development program. Past history has shown us that products succeed for a number of reasons; unless there is cooperation in the team that develops the product, the company introducing the product to the market may simply spawn an idea others bring to profitable conclusions. The team with a vision for success is one that has agreed to rally around a winning idea. This team will succeed with a good leader at who gathers data, defines problems, and then defines solutions for those problems with the help of his or her team. This systematic approach will be discussed in more detail in later chapters dealing with machine design and product troubleshooting.

Other subchapters describe in some detail two of the commercial systems (tools) available that may be used to formalize the satisfaction of the customer and to design products that will make money for the company. These are design for assembly (DFA) and quality function deployment (QFD). The final subchapter introduces some of the rapid prototyping techniques that allow design concepts to be produced quickly to assist in product development and production start-up prior to availability of the planned "hard" tooling.

This chapter covers the first half of product development and design—the systems of determining who our real customers are and what they want, and the design of a product that meets these requirements at the lowest cost.

Chapter 2 introduces the product development of machines; the detailed design parameters for parts fabricated by machining operations, by casting and forging, and of sheet metal; and a brief introduction of the materials and processes involved in each.

Chapter 3 discusses the role of the professional manufacturing engineer in product development, debugging or troubleshooting the newly developed product, and the fundamentals of factory layout. Troubleshooting is one skill that all product development professionals must master if they are to be successful leaders. Many problems of the mechanical, electronic, and human kind follow very similar patterns. The process of understanding methods for designing solutions to problems is an important tool for all involved in the process. All of the remaining chapters in this second edition of *The Manufacturing Engineering Handbook* provide additional information that is needed in order for the manufacturing engineer to participate properly in the product design process. Both this Chapter and 2 are part of the same process, but they look at the product from different perspectives.

The entire book is a tool for use by the manufacturing engineer, engineering manager, and product development engineer, and will serve to lead the inquiring mind to other sources for additional information on various topics. This book seeks to provide enough information to give the beginning practitioner and the experienced professional useful information that will help in the execution of the product development task. Additionally, this book seeks to join others in the profession who have helped to define the role of the manufacturing engineer as he or she fills the position of design engineering manager, product development engineer, and research and development director, enriching the position with a great depth of understanding of the application of manufacturing while guiding the research and design tasks of product development.

1.0.1 World-Class Manufacturing

The world is shrinking fast. With the advent of Internet commerce, faster travel, and better communication, we have to understand manufacturing around the world and be equipped to compete in world markets. Some have termed the current century the "E-Century" after the e-commerce that is beginning to be a major factor in industry. Vast changes are taking place at a record pace. The most prominent language of the Internet is expected to be Mandarin Chinese very soon. What does the term "world-class manufacturing" mean today? Successful companies are very much involved in researching the cultures of other countries; they consider it a requirement for survival in the competitive business environment. Factors that were never part of the manufacturing world before are now very important to the successful businessman. Some of those factors include:

- Eye contact with a certain people, group, or gender, and what that means in terms of the relationship, both personal and professional
- Why should one be aware of the past history between two people or groups of people when attempting to broker a manufacturing deal?
- Is an insult if a Dutch executive with a prospective distributor of your product prepares a dossier on you?
- What economic risks are tied to the government instability of the region?

It is difficult to quantify the performance improvements required to become a world-class manufacturer. However, one significant study of several successful companies several years ago reveals the following features:

Costs to produce down 20–50%
Manufacturing lead time decreased by 50–90%
Overall cycle time decreased by 50%
Inventory down 50%+
Cost of quality reduced by 50%+ (less than 5% of sales)
Factory floor space reduced by 30–70%
Purchasing costs down 5–10% every year
A minimum of (25) inventory turns of raw material
Manufacturing cycle times with less than 25% queue time
On-time delivery 98%
Quality defects from any cause less than 200 per million

While we can be certain that no one would agree that all of the above performance improvements are required, there is a strong message here that no one can dispute. We must make a paradigm shift in the way we operate to achieve all of these "future state" conditions—and must make some major changes to achieve any one of them! There is also general agreement that world-class manufacturing cannot be achieved without first having a *world-class product design.*

The product development and design process really starts by listening to the customer (the one who ultimately pays the bill!) and understanding his or her needs (and wants). The customer's requirements should be listed, prioritized, and answered completely during the product development and design phase. The other customer we must learn to listen to is our corporation—and especially our factory. We have heard messages such as:

Use the facilities we have.
Don't spend any more capital dollars beyond those needed to support our programs.
Watch your cash requirements. (This translates to any expenditure in the chain leading to product delivery—inventory, work in process, etc.)
Do the job with fewer people.
Continuous improvement is necessary, but we also need a paradigm shift in the way we do business!
Listen to our customers.

These are all great thoughts, but it is difficult to actually run a manufacturing operation with only these high-level goals. The bottom line (dollars of profit) was the *only* focus of many companies during the 1980s and 1990s. The MBA mentality was micromanaging profits on a quarterly basis—to the detriment of the longer-term success of many companies. The top-level focus changed, and must trickle down to the working elements of the company, including the manufacturing engineering function. In the new millennium, financial uncertainty, terrorism, wars, and natural disasters constantly impact the manufacturing industry. The rush to keep the delicate balance of JIT, or just-in-time, manufacturing facilities running overshadows new innovations. A recent multiple-state power outage is expected to ripple throughout many sectors as the factories depending on electric power shut down and then restarted. This interruption caused several delays that will ripple throughout many products and ultimately affect the customer's pocket. While we must do some rather uncomfortable things to keep our companies operating in the short term, the basic change in the way companies will operate in the future is our most important focus. The trained, experienced professional in today's manufacturing world—the person responsible for getting a fantastic product idea or dream or vision out the door of the factory—is facing a tremendous challenge. He or she will find that his or her training and experience have a lot of holes in them. It has nothing to do with how bright or hard-working the person is—the *job* has changed! This manufacturing engineer will be uncomfortable trying to do all elements of the job today, and his or her management will be even more uncomfortable! Management today is facing a worldwide struggle to keep their companies afloat. Many years ago, the owner of a struggling company understood this "new, recently discovered" requirement. One of my favorite stories may illustrate this.

Henry Ford defied all his experts by insisting that the wood shipping container for the Model A battery (the battery was just coming into play as an addition to his latest model) be specified in a particular way. It must be made of a certain type of wood, be reinforced in places, and contain some rather peculiar vent holes in most of the pieces. He also insisted that this would not increase the cost of the battery from the supplier, since the quantities would be so large. (He was correct in this.) As the first Model A of the new series was coming down the line, he called all his department heads—engineers, buyers, accountants, and others—to the factory floor. The battery box was knocked down to get at the battery, and the battery was installed under the floor at the driver's feet. Henry then picked up the pieces of the box and fitted them above the battery, exactly forming the floorboards on the driver's side of the car. The holes in the boards were for the brake, starter switch, etc. The screws that held the box together were then used to bolt the floorboards down. Henry really understood the problems of total product design, cost of materials, just-in-time delivery, zero stock balance, low inventory cost, no material shortages, no waste-disposal costs, good quality, and a host of others. He was a one-man product design team and good manufacturing engineer!

In order to compete in today's marketplace, we must find new ways to increase productivity, reduce costs, shorten product cycles, improve quality, and be more responsive to customer needs. A good product design is probably the most important element to focus on.

Continuous Improvement is not a new idea. Jack Walker visited the IBM laptop computer assembly plant in Austin, Texas, in the late 1980s. He also visited the Pro Printer manufacturing plant at about this time. These were excellent examples of the concurrent engineering process required for IBM to outperform their Japanese competitors. After studying these examples of computer-integrated manufacturing (CIM), the McDonnell Douglas Missile Assembly Plant sponsored two

CIM application transfer studies with IBM's assistance: one concentrating on the production of low-cost, high-rate products, and the other on the production of high-cost, low-rate products.

Our strategy was for the studies to establish a road map for the transition to integrated manufacturing. This plan defined our existing state, what we wanted to become, projects and schedules that would be required, and the cost/benefits analyses. At that time, we had a somewhat fragmented approach to industrial automation, which included material requirements planning (MRP), manufacturing resource planning (MRPII), shop floor control, cost, process planning, bill of material, purchasing, stores, and so on. Several of these were in independent functional areas with their own hardware, software, communications, files, databases, and so on. This was the situation that we were determined to improve. Our goal was to provide a factory that would support today's changing program requirements and that would be even more productive in the future. We believe that manufacturing systems and processes that simply modernize today's operations are not adequate for tomorrow's business environment. Rather, we need greater control over product cost and quality. We need to outcompete our competition in both quality and cost—particularly when we compete oversees and find an average 17% tariff levied against U.S. products competing abroad.

Today, our company is well on the way to becoming the leading facility within the corporation in developing an architecture that ties our systems applications together and fulfills the requirements of a truly integrated set of databases. CIM has evolved into the computer-integrated enterprise (CIE), tying the various plants in the corporation together, and now into an "extended enterprise" that includes our key suppliers. The goal of supporting the complete life cycle of product systems from design concept to development, manufacturing, customer support, and eventually "disassembly" in a logical manner to perform maintenance or modifications is still the focus.

1.0.2 Cost Analysis and Constraints

Although it may appear that many of us will build different products and systems, we see a network of common elements and challenges. All products have requirements for lower costs and improved quality. All can expect competition from producers of similar products, as well as from competing different products—both U.S. and foreign. All must accommodate rapid change in both product design and manufacturing processes.

The term "low-cost" is difficult to define. If your cost is about as low as your chief competitor, whatever the product or production rate is, you are probably a low-cost producer. Benchmarking against your most successful competitors is almost a necessity. In the manufacturing business, cost is partially attributable to the direct touch-labor cost. This is modified by the direct support tasks performed by manufacturing engineering, production control, supervision, quality assurance, and liaison engineering. On some programs this may equal or exceed the touch-labor cost. Added to this is the more general overhead cost, which may double or triple the base cost. Also, since this in-house labor content may amount to a very small percentage of the overall product cost (which includes the cost paid to suppliers for material, parts, subassemblies, services, etc.), it may not be the only driving force in determining the price to the customer. Peter Drucker, in *The Practice of Management,* states that "hourly employees' wages as a factor in product cost are down from 23% to 18%, and that productivity is on the rise." General Motors' hourly employees' costs are still in the 30% range, partially due to restrictive work rules in their labor contracts. Some Japanese car manufacturers who produce in the United States pay similar wages but operate at hourly employee costs of less than 20%. The trend is toward 15%. In selecting a design approach, it is perhaps more valuable to look at total cost in calculating earnings than to look at the amount of direct labor involved. One measurement of cost and earnings is return on investment (ROI).

ROI is a relationship between bottom-line earnings, or profit, and the amount of money (assets) that must be spent (invested) to make these earnings. An example from the books of a medium-size manufacturer shows the following:

1. Accounts receivable	\$6M
2. Inventory and work in process	\$14M
3. Land	\$2M
4. Buildings and equipment (net)	\$15M
5. Total assets	\$37M

By looking closer at each item, we can improve the bottom line.

1. Submit billings sooner to reduce the amount that customers owe us.
2. Reduce the amount of raw stock and hardware in inventory. Don't get the material in-house until it is needed. Reduce work in process by reducing the cycle time in the shop, which reduces the number of units in flow. Also, complete assemblies on schedule for delivery to permit billing the customer for final payment.
3. Try not to buy any more land, since it cannot be depreciated: it stays on the books forever at its acquisition cost.
4. Evaluate the payoff of any additional buildings and capital equipment. Of course, some new buildings and equipment may be needed in order to perform contract requirements. Additional investment may also be wise if it contributes to a lower product cost by reducing direct labor, support labor, scrap, units in process, cost of parts and assemblies, etc.
5. The bottom line in investment may not be to reduce investment, but to achieve a greater return (earnings). In this simple example, we could add \$10 million in equipment and reduce accounts receivable, inventory, and work in process by \$10 million and have the same net assets. If this additional equipment investment could save \$4 million in costs, we would increase our earnings and double our ROI.

In today's real world, we need to consider one more factor. Items 1, 2, and 3 above require company money to be spent. There is a limit to borrowing, however, and a point where cash flow becomes the main driver. It is therefore essential to reduce overall costs by utilizing existing buildings and capital equipment and by doing the job with fewer people and less inventory. The sharing of facilities and equipment between products becomes very attractive to all programs. This would reduce our need for additional capital and reduce the depreciation-expense portion of our overhead. The design engineer and manufacturing engineer are certainly key members of the product development and design team, but the input from all other factory functions becomes more important as we look toward the future.

1.0.3 Project Design Teams

In an increasing number of companies across the country, both the designer and the manufacturing engineer are climbing over the wall that used to separate the two functions. In addition, a full team consisting of all the development-related functions should participate in the design of a new product or the improvement of an existing product. The team may include the following:

- Administration—senior management to empower the team
- Design engineering
- Process engineering
- Manufacturing engineering
- Manufacturing
- Quality assurance
- Marketing
- Sales
- Purchasing
- Accounting
- Production control

Profitability, and even survival, depends on working together to come up with a design that can be made easily and inexpensively into a quality product. Other appropriate team members may be representatives from:

- Distribution
- Accounting
- Human resources
- Suppliers
- Customers
- Suppliers chosen as partners in the product development process
- Shop technicians
- Assembly technicians
- Joint ventures
- A customer's accounting department who represent their company in an "open book" cost-sharing method

An excellent example of quality improvement and cost reduction is Ford Motor Company. Ford has adopted design for assembly (and design for manufacture and assembly) as one of their concurrent engineering approaches. The company acknowledges the importance of product improvement and process development before going into production. Assembly is a small part of overall product cost, about 10–15%. However, reducing this cost by a small amount results in big money saved in materials, work in process, warehousing, and floor space. Figure 1.1 shows how a small investment in good design has the greatest leverage on final product cost.

World-class manufacturers know that they cannot dedicate a single factory or production line to one model or product. The generic assembly line must have the flexibility to produce different models of similar products rapidly and entirely new products with a minimum changeover time. There are exceptions where the production quantities of a single product are sufficiently large, and the projected product life is great enough, that a production factory dedicated to a single product is the best choice.

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1.1 CONCURRENT ENGINEERING

1.1.0 Introduction to Concurrent Engineering

What is concurrent engineering? Why do we care about concurrent engineering? To remain competitive in industry, we must produce high-quality products and services

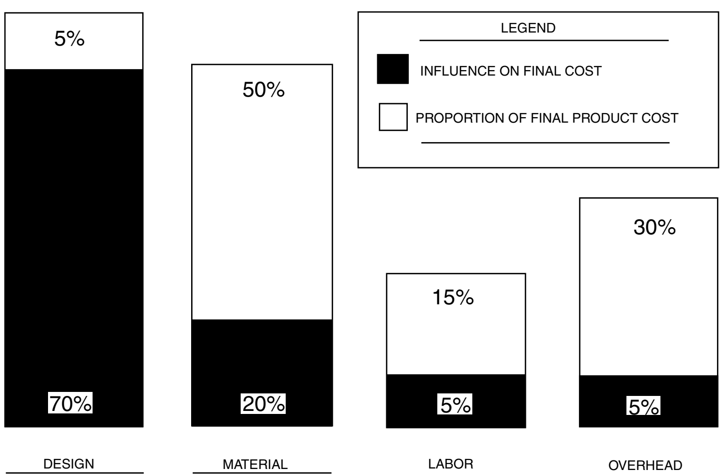

FIGURE 1.1 The cost of design in manufacturing at Ford. (Courtesy of Ford Motor Company. With permission.)

the first time. We can accomplish this by implementing concurrent engineering (CE) principles and tools in our programs. (The abbreviation "CE" in this text is not to be confused with "common European," used to denote compliance to British safety standards and engineering norms. For simplicity, it is used in this text only to mean "concurrent engineering.")

It does not matter whether we call the concept concurrent engineering, integrated product definition, or simultaneous engineering, as long as we consistently produce high-quality products on time for the best price. Agreeing on a common definition helps communication and understanding. We use the term concurrent engineering and the Department of Defense/Institute of Defense Analysis (DoD/IDA) definition because it has wide acceptance. IDA Report R-338 gives the following definition:

> Concurrent Engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule and user requirements.

Four main elements have emerged as most important in implementing CE: the voice of the customer, multidisciplinary teams, automated tools, and process management. The underlying concept is not a new one: teamwork. The secret is to involve all the right people at the right time. We must increase our understanding of product requirements by being more effective in capturing the voice of the customer. We must increase our emphasis on product producibility and supportability. This requires the involvement of all related disciplines on our CE teams. We must acquire and use the best tools to permit the efficient development of "build-to" technical data packages. Finally, we must increase our emphasis on developing production processes in parallel with development of the product.

Industry is continuing to refine and improve the elements of concurrent engineering. All of us must contribute to this process. More than that, all of us must be willing to change, and concurrent engineering requires change. Concurrent engineering must be understood to be rooted in communication, communication through the complexity of corporate and geographical cultural differences. The technical and financial issues facing the manufacturing professional today are overwhelming; when combined with the difficulty of communication, the task of competing in the world market is made much harder. Someone has said, "All of us are smarter than one of us." We must learn to think like this: everyone has something to contribute when developing a new product.

1.1.1 Why Concurrent Engineering?

Concurrent engineering is a commonsense approach to product design, development, production, and support. By collecting and understanding all requirements that the product must satisfy throughout its life cycle at the start of concept definition, we can reduce costs, avoid costly redesign and rework, and shorten the development process. We do this by capturing all customer requirements and expectations and involving all related disciplines from the start. Working as teams on all product-related processes, we can provide for a smooth transition from development to production. Experience shows that concurrent engineering results in:

Well-understood user requirements
Reduced cycle times
First-time quality producible designs
Lower costs
Shorter development spans
A smoother transition to production
A new respect for other teammates
Highly satisfied customers

It is not surprising that some CE practices, namely the voice of the customer and process management, are rarely practiced. We need to leave our comfort zones in order to implement these practices effectively. Concurrent engineering pays off in:

Product development cycle time reduced 40–60%
Manufacturing costs reduced 30–40%
Engineering change orders reduced more than 50%
Scrap and rework reduced by as much as 75%

The primary elements of CE are:

Voice of the customer
Multidisciplinary teams
Automation tools and techniques
Process management

The voice of the customer includes the needs and expectations of the customer community, including end users. Concurrent engineering can best be characterized by the conviction that listening and responding to the voice of the customer can achieve product quality. The ideal way is to capture, at the outset, all requirements and expectations in the product specifications.

The most effective way we have found to accomplish this is to conduct focus group sessions with different elements of the customer's organization. Properly staffed multidisciplinary teams provide the means to enable all requirements, including producibility and supportability, to be an integral part of product design from the outset. CE teams are broadly based, including representatives from production, customer support, subcontract management and procurement, quality assurance, business systems, new business and marketing, and suppliers. Broadly based CE teams succeed because they can foresee downstream needs and build them into our products and processes.

Not all team members are necessarily full-time. In many cases, part-time participation is all that is needed and all that can be afforded.

Automation tools and techniques provide effective and efficient means of developing products and services. Computer-based tools such as Unigraphics can be used as an electronic development fixture (EDF) during prototyping, in lieu of mockups, to verify clearances and mechanism operations before hardware is fabricated.

There are a variety of home-grown and purchased CE tools in use on programs. Their importance to CE is an increased ability to communicate and transfer data readily among team members, customers, and suppliers. With reliable information sharing, we are able to review and comment on (or import and use) product and process data more rapidly, while eliminating sources of error.

Process management is the final key to controlling and improving the organization as well as the processes used to develop, build, and support a product. This is probably the newest and least practiced element of CE. Big gains can be made by defining the program work flows and processes and then improving them. Processes define the relationships of tasks and link the organization's mission with the detailed steps needed to accomplish it. Process management is an effective way of managing in a team environment. Program-wide processes provide a means of identifying the players who need to be involved and of indicating team interrelationships. Product processes are also a part of process management, requiring the definition and development of production processes in parallel with the definition and development of the product design.

1.1.2 Concurrent Engineering throughout the Acquisition Process

Concurrent engineering practices are applicable to all programs, old or new, regardless of program type or acquisition phase. Implementing CE at the very beginning of a program makes the biggest payoff. Approximately 80% of a product's cost is determined during the concept phase, so it is very important to have manufacturing, producibility, supportability, and suppliers involved then. There are benefits of CE to be realized during the later program phases, including reducing production costs for dual-source competitions or defining product improvements.

1.1.3 The Voice of the Customer

The voice of the customer (VOC) represents the needs and expectations by which the customer or user will perceive the quality of products and services. It is the program manager's responsibility to make sure that all CE participants understand the voice of the customer and that all program requirements can be traced back to those needs and expectations.

Quality is achieved by satisfying all customer needs and expectations; technical and legal documentation will not overcome bad impressions. Meeting the minimum contractual requirements will often not be enough, especially in a highly competitive environment. Customer quality expectations invariably increase based on exposure to "best-in-class" products and services. Nevertheless, the products and services provided must be consistent with contractual requirements and within the allotted budgets. This is not an easy task; it requires continuous attention and good judgment to satisfy the customer while staying within program constraints.

Requirements definition begins at the program's inception and continues throughout the product life cycle. It is essential that the right disciplines, including suppliers, are involved at all times in order to avoid an incomplete or biased outcome. Methodologies such as QFD can be used to enable the team to analyze customer requirements and to specify the appropriate product or service.

1.1.4 Capturing the Voice of the Customer

The concurrent engineering team must maintain a careful balance between satisfying customer needs and expectations and maintaining a reasonably scoped program. Early in the product life cycle, written requirements will be sparse and general. The team will use customer needs and expectations to interpret and expand the written requirements. It is at this time that the CE team has the greatest opportunity to influence the product life-cycle cost. Studies indicate that 80% of cumulative costs are already set by the end of the concept phase. Consequently, it is vital that all available information is used to choose the best product concept based on costs and user requirements.

Later in the program, the written requirements will become more detailed. The voice of the customer will then be used primarily to help clarify ambiguous requirements. In either case, the team will have to listen unceasingly to the voice of the customer in order to capture the needed requirements. The program manager will need to provide continuous support and encouragement, especially in light of the many obstacles the team might encounter. There are many real and perceived barriers to gathering the voice of the customer:

- Restricted access to customers during competitions
- User perception of VOC as a sales tactic
- Confusion between higher quality and higher cost
- Failure to identify all users
- Lack of skills in analyzing the voice of the customer
- Rush to design
- Tradition and arrogance

1.1.5 Customer Focus Group Sessions

User focus group interview sessions can be very effective in gathering inputs from the users of a system. While there are many sources of customer needs and expectations, focus group sessions can uncover and amplify a broad range of requirements that might otherwise be overlooked. These requirements can range from the positive "We want this!" to the negative "Don't do that again!" These inputs can provide a better understanding of user needs and even a competitive edge for your program. See Figure 1.2.

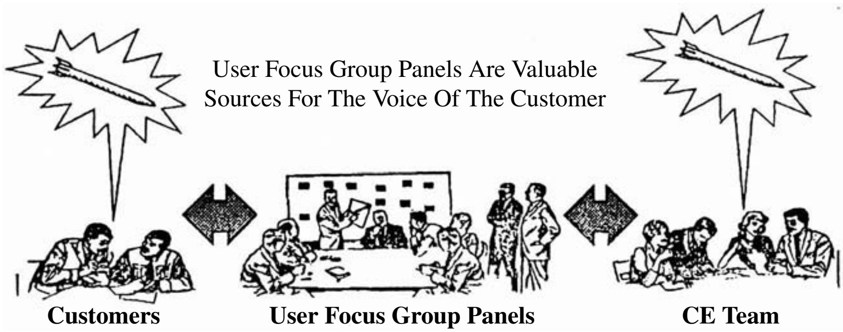

FIGURE 1.2 Translating customer requirements into requirements for the designer. (Courtesy of Technicomp, Inc., Cleveland, Ohio. With permission.)

The use of focus group sessions is especially recommended at the beginning of product conceptualization and during the support phase of a deployed system. The latter sessions identify product improvement opportunities.

A well-conducted session uses group dynamics to encourage individuals to provide inputs in a synergistic manner. A moderator leads the discussion in order to maintain focus on the critical issues and to enable each panel member to participate as much as possible. Post-It Notes (© 3M) should be used to capture, sort, and prioritize the panel members' comments using a disciplined form of brainstorming. A limited number of concurrent engineering team members attend the session as nonparticipating observers to help capture and understand the voice of the customer.

The moderator should prepare open-ended questions to stimulate and focus the session:

Why is a new product or system needed?
What do you like about the existing system?
What do you dislike about the existing system?
What makes your current job difficult?

The results of the focus group sessions can be analyzed using one of the formal process management tools or design for manufacturability tools such as DFA or QFD.

1.1.6 Communicating Cross-Culturally

When communicating to groups of people, the way the information is communicated is of extreme importance. The delivery of information sometimes makes all the difference. Good news can often be easily communicated, but be sure that bad news has more than one way of being delivered. It is sometimes necessary to think about how we obtained the information that we ourselves possess. Someone has said that how we know what we know is very important to the persons to whom we deliver the information we have. The manufacturing engineer becomes an *information broker* when leading a product development team. Behind the assertions and explanations of the product development process, the leader of the team must be prepared to explain why the decisions were made and what benefits will be reaped from those decisions. This is a natural process that must not be feared or disregarded by the leader. Each and every team member must reach a point of agreement with the leader as to the direction the team is going. Time may not permit micromanaging by the team members of the leader, but the leader must understand that if others are to follow, they must have some degree of faith that the leader knows where he himself or she herself is going.

Motivation and decisions are made by people of all cultures based upon their ways of perceiving the world, the way they think, the way they express ideas, the way they act, the way they interact, how they channel their ideas, and how they make decisions. The successful team leader will seek to understand methods of successful communication with his team, his company, and his customer base.

1.1.7 Bibliography

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1.2 QUALITY FUNCTION DEPLOYMENT

1.2.0 Introduction to Quality Function Deployment

Quality function deployment (QFD) is a methodology used by teams to develop products and supporting processes based on identifying customer needs and wants, and comparing how your product and the competition meet these customer requirements.

Quality: What the customer/user needs or expects
Function: How those needs or expectations are to be satisfied
Deployment: Making it happen throughout the organization

QFD starts with the voice of the customer. Using all practical means, the team gathers customer needs and expectations. The team has to analyze these inputs carefully to avoid getting caught up in providing what they *expect* or *believe* that the customer needs. Conceptual models, such as the Kano model shown in Figure 1.3, can be used to help each team member understand better how the customer will evaluate the quality of the product. The team can then use QFD as a planning tool to derive product and process specifications that will satisfy the voice of the customer while remaining within business and technical guidelines and constraints. The program utilizes a series of matrices, starting with the customer wants on one axis

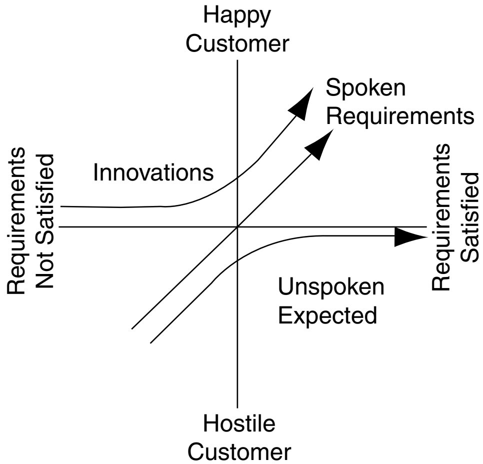

FIGURE 1.3 Kano model showing how the customer evaluates quality. (Courtesy of Technicomp, Inc., Cleveland, Ohio. With permission.)

and the company's technical interpretation of how to accomplish these customer expectations on the other axis. These elements are weighted and quantified, to permit focus on the most important issues or on the areas where the company product is most deficient.

1.2.1 Quality Function Deployment

QFD is defined as a *discipline* for product planning and development in which key customer wants and needs are deployed throughout an organization. It provides a structure for ensuring that customers' wants and needs are carefully heard, then translated directly into a company's internal technical requirements from component design through final assembly.

Strength of QFD

Helps minimize the effects of:

- Communication problems
- Differences in interpretation about product features, process requirements, or other aspects of development
- Long development cycles and frequent design changes
- Personnel changes

Provides a systematic means of evaluating how well you and your competitors meet customer needs, thus helping to identify opportunities for gaining a competitive edge (sort of mini-benchmarking)

Offers a great deal of flexibility, so it may be easily tailored to individual situations

Brings together a multifunctional group very early in the development process, when a product or service is only an idea

Helps a company focus time and effort on several key areas, which can provide a competitive edge

Applications of QFD

QFD is best applied to specific needs: areas in which significant improvements or breakthrough achievements are needed or desired. It can be used for virtually any type of product or service, including those from such areas as all types of discrete manufacturing, continuous and batch processes, software development, construction projects, and customer service activities in the airline, hotel, or other industries.

The Voice of the Customer

The first step in the QFD process is to determine what customers want and need from a company's product or service. This is best heard directly from customers themselves, and stated in their words as much as possible. This forms the basis for all design and development activities, to ensure that products or services are not developed only from the voice of the engineer, or are technology-driven.

Background of QFD

Technicomp, Inc., of Cleveland, Ohio, developed QFD. The first application as a structured discipline is generally credited to the Kobe Shipyard of Mitsubishi Heavy Industries Ltd. in 1972. It was introduced to the United States in a 1983 article in *Quality Progress,* a publication of the American Society of Quality Control (ASQC). Leaders in developing and applying QFD in Japan include Akao, Macabe, and Fukahara. U.S. companies that have utilized the Technicomp QFD program include Alcoa, Allen-Bradley, Bethlehem Steel, Boeing, Caterpillar, Chrysler, Dow Chemical, General Motors, Hexel, Lockheed, Magnavox, and others. The program consists of a series of videotapes, team member application guides, instructor guides, and other course materials.

Phases of QFD

QFD involves a series of phases (see Figure 1.4) in which customer requirements are translated into several levels of technical requirements. Phases are often documented by a series of linked matrices.

Phase 1: Product Planning. Customer requirements are translated into technical requirements or design specifications in the company's internal technical language.

Phase 2: Product Design. Technical requirements are translated into part characteristics.

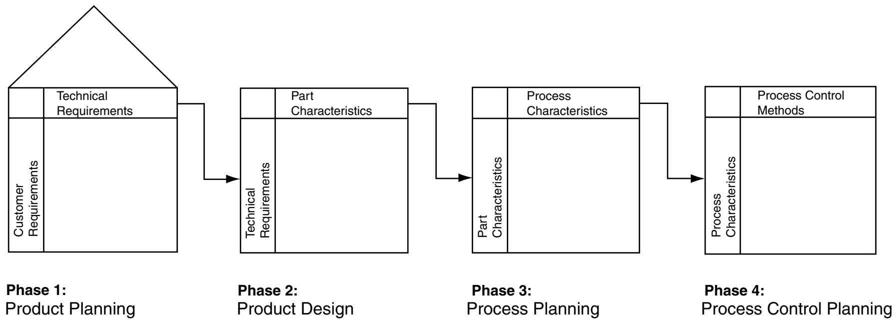

FIGURE 1.4 The four phases of quality function deployment (QFD). (Courtesy of Technicomp, Inc., Cleveland, Ohio. With permission.)

Phase 3: Process Planning. Part characteristics are translated into process characteristics.

Phase 4: Process Control Planning. Process characteristics are assigned specific control methods.

Potential Benefits

Some of the results achieved by companies that have implemented QFD include:

30–50% reduction in engineering changes
30–50% shorter design cycles
20–60% lower start-up costs
20–50% fewer warranty claims

Other results include:

Better, more systematic documentation of engineering knowledge, which can be more easily applied to future designs
Easier identification of specific competitive advantages
More competitive pricing of products or services, due to lower development and start-up costs
More satisfied customers

Requirements for Success

Management commitment to QFD is the minimum requirement; support by the entire organization is ideal. Participation on a project team is required by individuals who support QFD and represent all development-related functions, such as:

Design engineering
Process engineering

Manufacturing engineering
Manufacturing
Quality assurance
Marketing
Sales

Other appropriate members may be representatives from:

Purchasing
Distribution
Accounting
Human resources
Suppliers
Customers

1.2.2 The House of Quality

The QFD program introduces a chart in Phase 1 that is commonly called "the house of quality." The illustration shown in Figure 1.5 is a simplified example for large rolls of paper stock used in commercial printing. The following is a brief summary of the completed chart shown in Figure 1.6.

(A) *Customer requirements:* Customers' wants and needs, expressed in their own words.
(B) *Technical requirements:* Design specifications through which customers' needs may be met, expressed in the company's internal language.
(C) *Relationship matrix:* Indicates with symbols where relationships exist between customer and technical requirements, and the strength of those relationships.
(D) *Target values:* Show the quantifiable goals for each technical requirement.
(E) *Importance to customer:* Indicates which requirements are most important to customers.
(F) *Importance weighting:* Identifies which technical requirements are most important to achieve. In this chart, each weighting is calculated by multiplying the "importance to customer" rating times the value assigned to a relationship, then totaling the column.

The following are shown in Figure 1.6.

(G) *Correlation matrix:* Indicates with symbols where relationships exist between pairs of technical requirements, and the strength of those relationships.

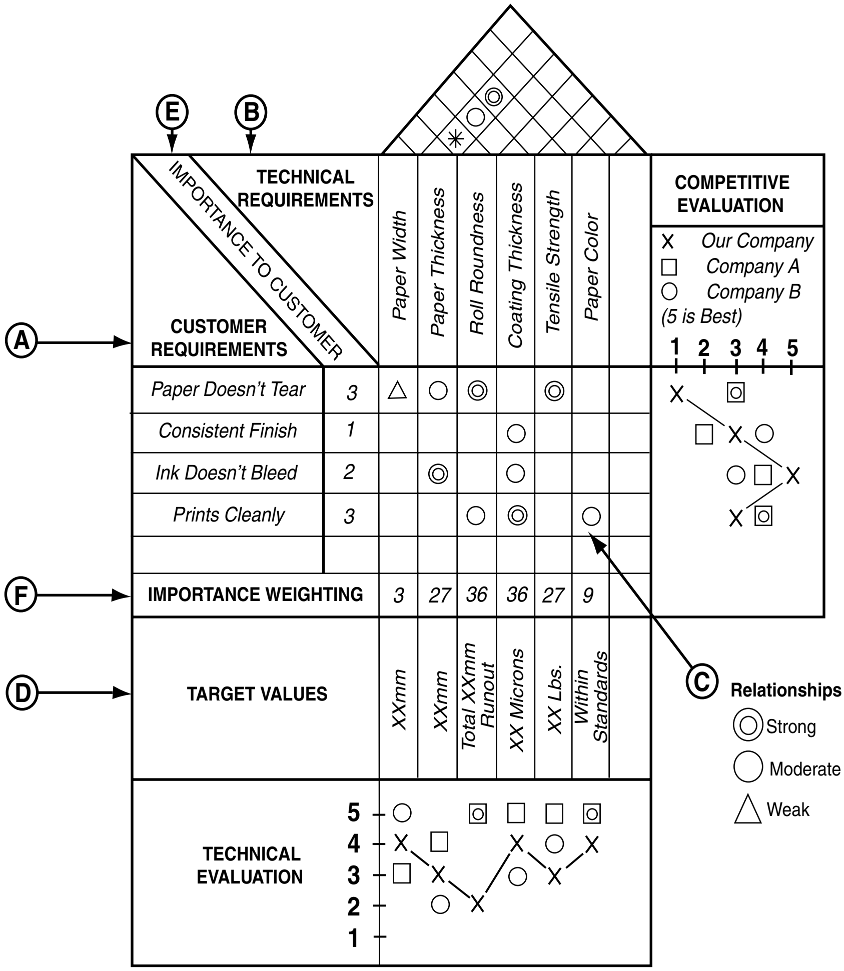

FIGURE 1.5 QFD house of quality chart for rolls of paper stock. (Courtesy of Technicomp, Inc., Cleveland, Ohio. With permission.)

(H) *Competitive evaluation:* Shows how well a company and its competitors meet customer requirements, according to customers.

(I) *Technical evaluation:* Shows how well a company and its competitors meet technical requirements.

Product Planning (Phase 1 of QFD)

Most companies begin their QFD studies with a product-planning phase. Briefly, this involves several broad activities, including collecting and organizing customer wants and needs, evaluating how well your product and competitive products meet

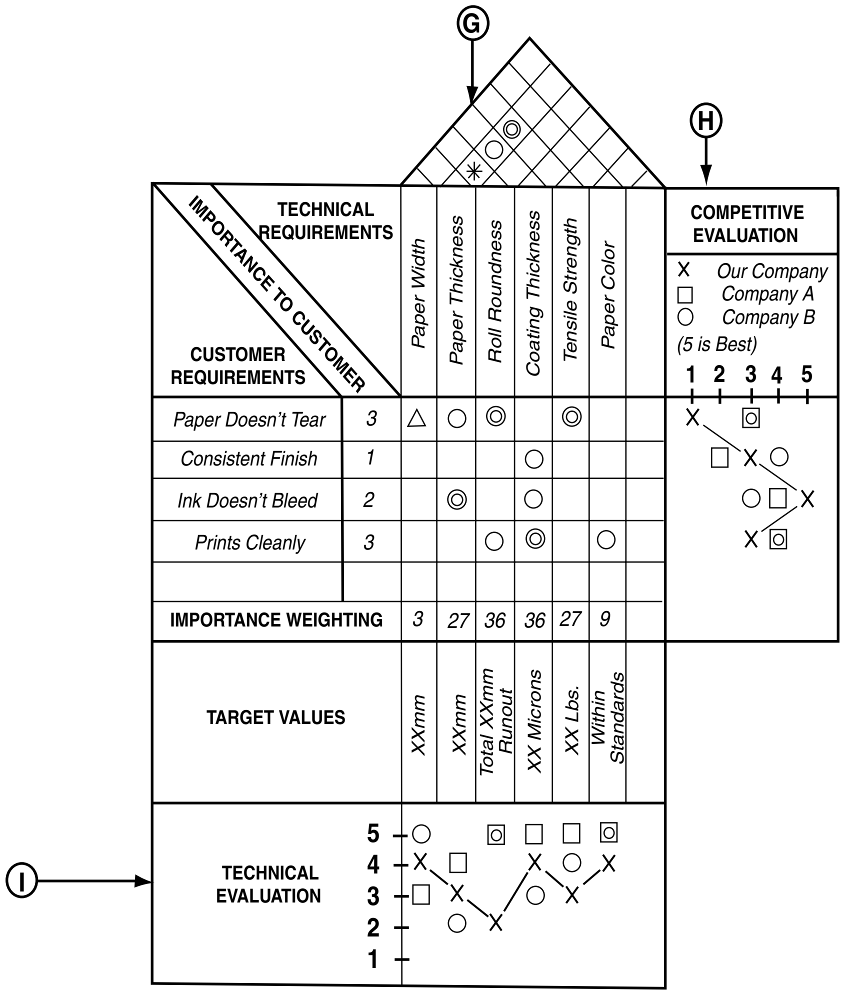

FIGURE 1.6 Completion of the house of quality chart for rolls of paper stock. (Courtesy of Technicomp, Inc., Cleveland, Ohio. With permission.)

those needs, and translating those needs into your company's specific technical language.

The House of Quality

In very simple terms, the house of quality can be thought of as a matrix of *what* and *how:*

> *What* do customers want and need from your product or service?
> (customer requirements)

How will your company achieve the *what*?
(technical requirements)

The matrix shows where relationships exist between *what* and *how,* and the strength of those relationships. Before starting a chart, the scope and goals of the study must be clearly identified. A typical chart enables you to:

Learn which requirements are most important to customers
Spot customer requirements that are not being met by technical requirements, and vice versa
Compare your product or service to the competition
Analyze potential sales points
Develop an initial product or service plan

Constructing a House of Quality

Suggested elements and a recommended sequence of construction for a house of quality are given below. Also keep in mind that the entire project team constructs the chart, unless noted otherwise. (See Figures 1.7, 1.8, and 1.9.)

(A) Customer requirements

Every chart must begin with the voice of the customer.
Identify all customer groups. Various groups will probably have some common needs, as well as some conflicting needs.
Collect accurate information from customers about their wants and needs.
Brainstorm to identify any additional customer requirements.
Use an affinity diagram to help group raw customer data into logical categories.
Transfer the list of customer requirements to the house of quality.

Do not assume that your company already knows everything about its customers. QFD teams have been astounded at the results of focused efforts to listen to the voice of the customer. Primary benefits of QFD often include clearing up misconceptions and gaining an accurate understanding of customers' demands.

(B) Degree of importance

Identify the relative priority of each customer requirement.
Use customer input as the basis for determining values, whenever possible.
Use a scale of 1 to 10, with 10 indicating very important items.

A more rigorous statistical technique also can be effective for determining degrees of importance.

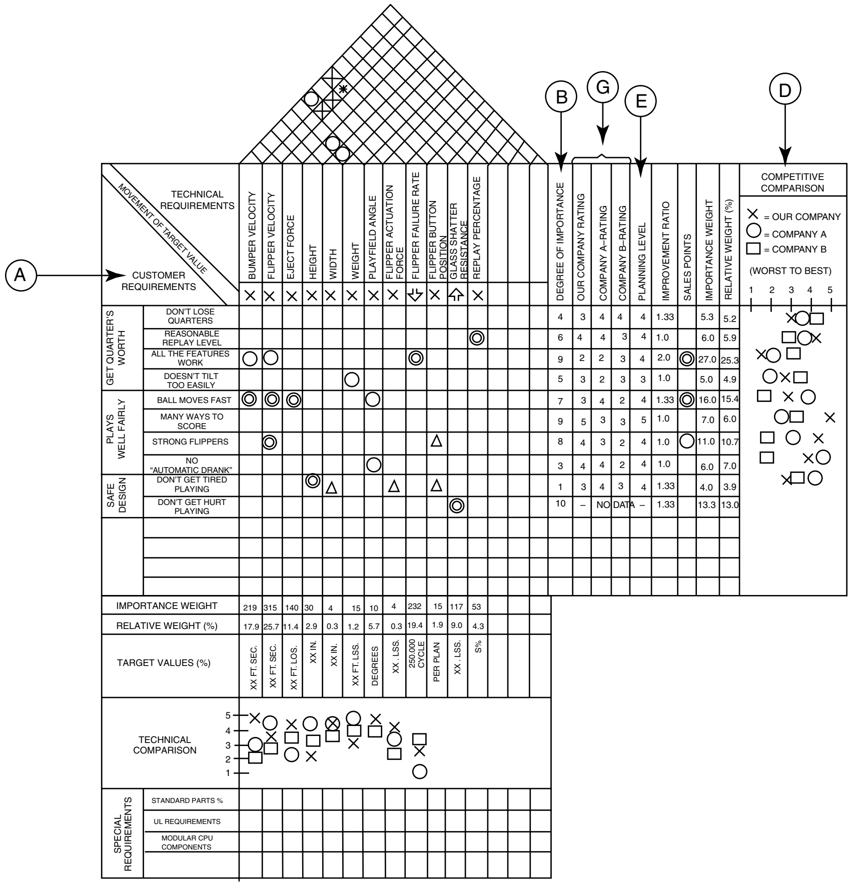

FIGURE 1.7 Construction of a house of quality: (A) customer requirements; (B) degree of importance; (C) competitive comparison; (D) competitors' ratings; (E) planned level to be achieved. (Courtesy of Technicomp, Inc., Cleveland, Ohio. With permission.)

(C) Competitive comparison

Identify how well your company and your competitors fulfill each of the customer requirements.
Use customer input as the basis for determining numeric ratings.
Use a scale of 1 to 5, with 5 being the best.

(D) Competitors' ratings

Use symbols to depict each company's rating, so that you can easily see how well, in your customers' view, your company compares to the competition.

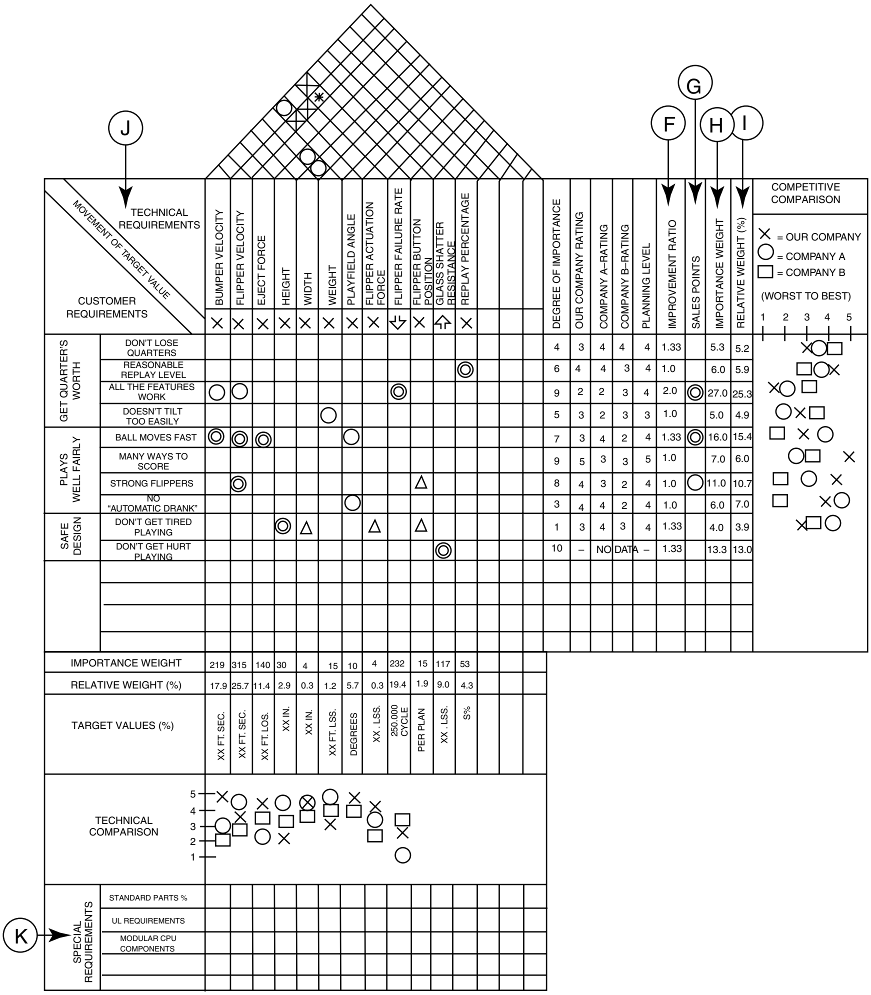

FIGURE 1.8 The house of quality (continued): (F) improvement ratio; (G) sales points; (H) importance weight of customer requirements; (I) relative weight of customer requirements; (J) technical requirements; (K) special requirements. (Courtesy of Technicomp, Inc., Cleveland, Ohio. With permission.)

(E) Planned level

Determine what level you plan to achieve for each customer requirement.

Base the rating on the competitors comparison, and use the same rating scale.

Focus on matching or surpassing the competition on items that will give your product or service a competitive edge, or that are very important to customers. (It is not necessary to outdo the competition on every item.)

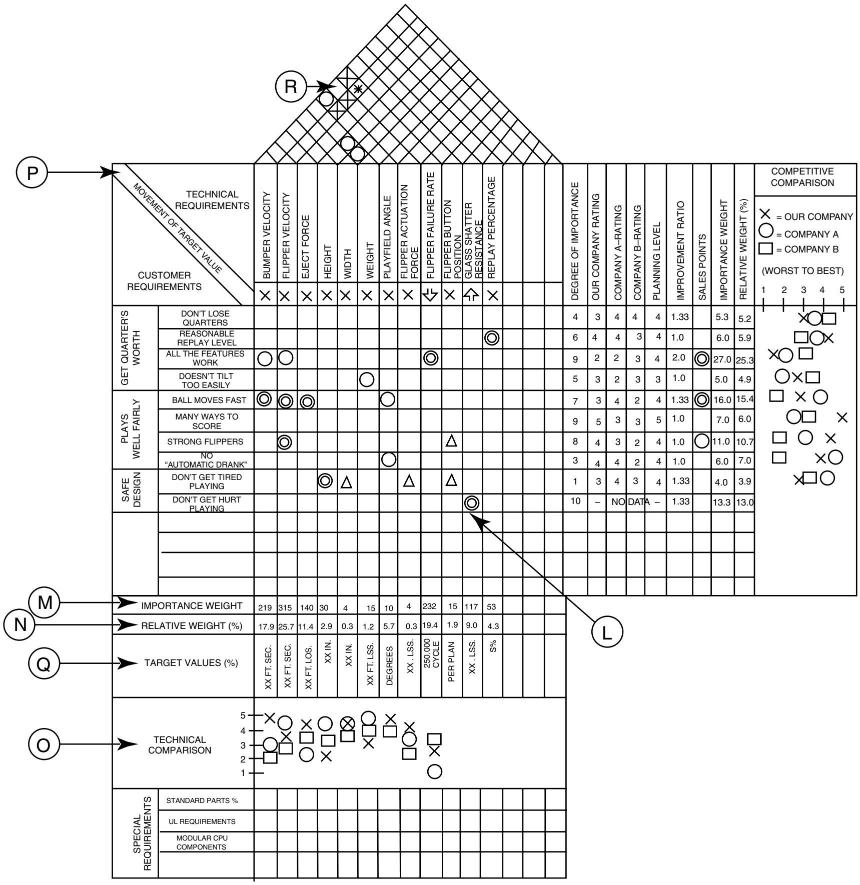

FIGURE 1.9 The house of quality (continued): (L) relationships between technical requirements and customer requirements; (M) importance weight of technical requirements; (N) relative weight of technical requirements; (O) technical comparison; (P) movement of target values; (Q) target values. (Courtesy of Technicomp, Inc., Cleveland, Ohio. With permission.)

(F) Improvement ratio

Quantify the amount of improvement planned for each customer requirement.

To calculate, divide the value of the planned level by the value of the current company rating:

improvement ratio = planned level ÷ current company rating

(G) Sales points

Identify major and minor sales points.

Limit the team to only a few points.

To indicate the importance of sales points, use symbols to which values are assigned:

⊙ = major point = 1.5
○ = minor point = 1.2

Major and minor sales points are often assigned values of 1.5 and 1.2, respectively.
Note that items with high degrees of importance are often logical sales points. Also, remember that any items that will be new and exciting to customers are likely sales points, although they probably will not have high degrees of importance.

(H) Importance weight (customer requirements)

Quantify the importance of each customer requirement to your company.
To calculate, multiply the degree of importance by the improvement ratio and by the sales point value (if applicable):

$$\text{importance weight} = \text{degree of importance} \times \text{improvement ratio} \times \text{sales point value}$$

(I) Relative weight (%) (customer requirements)

Quantify the relative importance of each customer requirement by expressing it as a percentage.
To calculate:
  Total the importance weights.
  Divide the importance weight of an item by the total.
  Multiply by 100.
Use the relative weights as a guide for selecting the key customer requirements on which to concentrate time and resources.

(J) Technical requirements

Develop this list internally, using existing data and the combined experience of team members.
Begin by collecting available data.
Brainstorm to identify any additional requirements.
Follow general guidelines while developing the technical requirements:
  Address global requirements of the product or service, not lower-level performance specifications.
  Identify performance parameters, and avoid simply restating the components of the existing product or service.
  Try not to include parts of mechanisms.

Establish definitions that are understood and agreed upon by all team members.
Use terminology that is understood internally.
Transfer the technical requirements to the house of quality chart.

(K) Special requirements

List any unusual needs or demands, such as government standards, certification requirements, or special company objectives.
Note that these items must be considered during design and development, but normally do not appear in a list of customer demands.

(L) Relationship matrix

Identify any technical requirements that bear on satisfying a customer requirement.
Evaluate each pair of requirements by asking if the technical requirement in any way affects the customer requirement.
For large charts, consider dividing the matrix into "strips," assigning them to groups of only a few team members for evaluation, and then have the full team review the combined results.
To indicate the strengths of relationships, use symbols to which values are assigned:

⊙ = strong relationship = 9
○ = moderate relationship = 3
△ = weak relationship = 1

(M) Importance weight (technical requirements)

Quantify the importance of each technical requirement.
To calculate this value, only those customer requirements that are related to a technical requirement are factored into the calculation:
Multiply the value of any relationships shown in the column of the technical requirement by the relative weight of the customer requirement.
Test the results.

(N) Relative weight (%) (technical requirements)

Quantify the relative importance of each technical requirement by expressing it as a percentage.
To calculate:
Total the importance weights.