The Design Process: A Detailed Look
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⇒ *Introduction*

Most designs today will be a synergistic combination of mechanical elements, electronics, controls, and computers, all well-integrated from the very beginning of the design process. Good design methods can make the difference between a marginally-useful, error-prone, expensive conglomeration of circuits, motors, and mechanical components and a highly-reliable, cost-effective, high-performance integrated system. Knowing how to design well will improve the systems and devices you create. At the same time, your knowledge of sensors, actuators, electronics, controls, mechanical systems, etc., will improve your design skills, both by giving you more design alternatives and by allowing you to communicate more easily with all the engineers on your multidisciplinary design team.

Society relies on design because design meets the needs of the members of society and the needs of society as a whole. Design is not a random activity. The successful designer merges the following during design activities:

- *Focus and Motivation – The Right Mindset*
  Technical expertise without the right motivation and without a vision will not lead to successful designs. Focus on the need; become an expert in the problem and solve the right problem. View problems as opportunities to excel! Don't ask the customer what they think they need, ask what the problem is! Don't overlook the big picture; look at the problem and its surroundings; test the limits (big, small, fast, slow) as you explore the problem; never stop asking "Why?" Find inspiration from outstanding examples – products, people, companies, methods. Embrace the design attitude: be willing to take risks, try different things, extend yourself, and learn from failure. Identify multiple solutions to the problem; it is highly unlikely that the first solution identified will be the best solution.
- *Process and Procedure*
  The successful designer or design team follows a process, a procedure, from the problem definition to the problem solution. This process is not a rigidly-adhered-to set of rules, but rather a guide to keep the designer or design team on track towards the final destination – the problem solution. This formal plan is essential in breaking the project down into tasks, in assigning responsibility and authority, and in measuring progress. Consider whether radical product innovation or incremental improvement is best. Believe in iteration in the design process and strive for constant improvement.
- *Documentation*
  The steps which lead to the problem solution must be documented so they can be continually reviewed, as design is an iterative process. Good documentation will show others how the design solution was obtained. State all the assumptions made during the process and why they are necessary. Assumptions should be challenged since they are often constraining and limit opportunities in solving the problem.

This section describes some of the primary concepts of modern engineering design. It is only a summary and by consulting the references you can learn more about the concepts discussed. The design process is described in generally chronological order. Some design concepts, such as *Concurrent Engineering*, are general ideas that affect the whole design process. After describing the general steps, an overview of some of these modern design concepts including two powerful design tools, *Quality Function Deployment (QFD)* and *Parameter Design*, are given.

Generally, a good design process includes the following steps:

Need Definition
Concept Generation
Detail Design
Manufacturing

⇒ *Need Definition*

Need or opportunity recognition is the first step in the design process and the activities and results of this step determine the course of action of the remaining steps. View problems as opportunities! Poor need and opportunity recognition lead to a failure of the design process, even if the succeeding steps are technically successful.

Products fill the needs of the consumer; if they don't, no one buys them. That part of a company which determines the needs is often referred to as the *marketing* department. If the need can be precisely identified, the product can be designed to meet exactly that need, and consumers will buy it. It is important to identify the problem the consumer faces and understand it completely, and not let the consumer prescribe a solution by stating what he/she thinks is required. The statement "Tell me what the problem is, not what you think you need" exemplifies the approach needed when working with the customer. In many cases, the problem is stated in terms of the symptoms or consequences of the problem. Explore all that is known and unknown about the problem and translate it into fundamental needs. Needs often are a consequence of applying a value system to the situation. Sometimes this value system is externally imposed (such as specifications or regulations), sometimes it comes from an understanding of the customer, and other times it comes from a critical review and a vision of the ideal.

Under concurrent engineering, the *engineering* and *manufacturing* departments are involved in the need definition process, as well as *upper management*. If the product is a technical machine or tool, engineering often has insights that marketing could miss about what is exactly necessary or useful or feasible. Manufacturing can sometimes trim extra fluff from the need statement that might make it less expensive to create. Ultimately, marketing presents the need (or opportunity) to upper management, who gives it to engineering to implement.

The need is defined as a set of attributes that the product must fulfill for the consumer (e.g., a car must not only move people from place to place, but be fuel efficient, meet government regulations, have trunk space, look good, etc.). The attributes are often weighted by their importance to total customer satisfaction. This list of weighted attributes can be used in the design tool called *Quality Function Deployment (QFD)* to make sure the product is addressing the needs of the consumer. QFD is described in more detail later, and comes into play in several parts of the design process.

At this stage, the question of whether a product has electronics, controls, computers, actuators, sensors, etc., has not been considered. Exactly how much integration will be used is determined in the conceptual and detail design stages.

⇒ *Concept Generation*

Once the need is identified, it is the job of *engineering* to design a product to meet the need. *Marketing* stays involved to keep engineering focused on the need, and *manufacturing* makes sure the design is manufacturable.

1. Problem Statement

The first step is to define a *problem statement* describing the need. This problem statement should only be in terms of the need, and not refer to any particular solution. Think about the opportunity or problem and all dimensions of it. This leaves the door open to unusual solutions that may work better than the standard ways of doing things. The problem should be written or sketched out by the engineer in his/her own words. This should be done in the design notebook so that this beginning part of the design activity is readily accessible during the subsequent activities. The form of this restatement of the problem can be an outline list, a mindmap, or a short narrative. Restatement does not mean repeating the words of the formal problem statement. The approaches used by the designer to restate the problem should be varied and several should be used on the same problem. Several approaches are:

a) *Less Specific* – Make your statement less specific than the formal statement when a solution-specific reference is made.
b) *More Specific* – Make your statement more specific than the formal statement by translating some of the adjectives in the statement to terms that can form the basis of a specification.
c) *Solution Words* – When writing the opportunity or problem statement, avoid solution-biased words in the description. Use verbs to describe the problem as much as possible. Use nouns that are not specific to an existing technology.
d) *Iteration* – Improve your definition of the problem several times by replacing one statement with a new one which better defines the problem. Often this process moves from the specific to the general, especially when a solution–based problem statement is involved.
e) *New Presentation* – While the word 'statement' implies text, a very useful way to understand a problem or opportunity is to draw a sketch of the system which incorporates or contains the problem. Most problems exist within some system and areas of solution involve many elements of the system. Some approaches to take for looking at the system of a problem include: a flow approach where some entity that moves between parts of the system is modeled; a logic approach where the value of some entity in a system affects the value of

another; or a mathematical model which portrays the relationship between elements of the system.

f) *Related Statements* – In many cases, the number of words and the areas of a problem described will be large. Understanding how the descriptive terms fit together is important to understanding the problem. Use a table showing the relationships (positive correlation, negative correlation, additive relationship, conflicting relationship, redundant relationship) between different aspects of the problem.

Problems are not easily understood. Most design problems are ill-defined at the beginning. The goals are vague with many constraints and criteria that are unknown; the problem is often not internally consistent; the formulation of the problem is often solution–dependent; proposed solutions often set boundaries around the problem and establish criteria and constraints; and multiple solutions are possible with wide divergence of the solution concepts. Hard work is necessary to gain the understanding of an ill-defined opportunity or problem that can lead to outstanding and exceptional design solutions.

2. Clarify Goals and Objectives

The goal in this step is a statement which summarizes the essence of the opportunity or problem and a list of hierarchical objectives. Objectives are quantifiable performance expectations of the design and serve to clarify the meaning of the goal. Identify the measurable characteristics for the design, place measures on these, and develop objectives that set threshold levels against which a design will be measured. Often these thresholds arise from technical and customer considerations. One way to look for objectives is to ask “What is meant by that?” This question is best answered using a hierarchical question and answer process moving from the less specific to the more specific. Tools for organizing this process are the objective tree and the objective list.

The objective tree is a graphical a graphical tool for organizing and developing hierarchical objectives. At the top of the tree the goal is placed. Under the goal, we split off several objectives which are more specific statements for the goal. Below these, we state even more specific objectives. The bottom level of the tree states objectives which are easily measured on a quantitative scale. Usually these are physical dimensions and a target level is set for the measure. This target becomes the design target. Associated with each target is a favorable direction of variance. In some cases falling below the target is favorable, while in other cases exceeding the target is more favored.

The objective list is a different form for showing and developing the hierarchical structure. Instead of a graphical picture, the objective list is an indented text list much like an outline form taught in writing composition. Successive indents lead to increasing levels of specificity and quantitative measures.

While both forms can be used to develop the set of objectives, the real contribution to design is the organization that they lend to the design process. Another process for coming up with the set

of objectives is one of the free-form-thinking methods such as mindmapping. The free-form list created by these methods is then transcribed to the structure of the list or tree.
Once the list is created, another tool for looking at the objectives is a relationship matrix. Using a matrix structure, the objectives are listed both as row and column headings. Focusing on the upper diagonal portion only, look at the intersection of two objectives and identify the relationship between the two. Objectives can be positively correlated meaning that the design features that address one objective are likely to impact positively on the other. Objectives can also be negatively correlated meaning that the objectives appear to conflict with each other. Objectives can also be independent with little or no relationship between them. The degree of relationship can also be recorded using high, medium, or low levels. One perspective on whether a design is innovative or not is how the design challenges the assumptions about the relationship between the design objectives, more specifically, how the design challenges negatively-correlated objectives.

3. Establish Basic Functions

All features have functions, that is, things that they do. Even the simplest artifacts have many functions. Design decisions are organized around the functions that an artifact is to achieve, the things that it is to do. Since decisions are made from choosing from alternatives, the alternatives arise from analysis of the functions necessary. In some cases, the choice of an alternative leads to the identification of new sets of functions that must be satisfied for the artifact to operate.

There are two methods for identifying the functions or tasks required to achieve a given outcome. The function-tree approach follows the same model as the objective tree with greater specificity as the levels move down the tree. How is a function stated? Since functions are things that are done, the use of verbs is natural. It is important to note that many features have multiple functions, which are usually by design. By using a feature or a form to satisfy more than one function, the design is simplified with fewer discrete parts and often less things that can go wrong.

The block-diagram approach to defining functions focuses attention on the transformation of inputs into outputs. The system is defined as residing in a box with inputs entering the box on the left and outputs exiting on the right. The macro view of the system starts with a black box where the conversion steps or actions on the primary inputs and primary outputs are not defined. The next level diagram is drawn by considering three types of inputs/outputs: energy, material, and information. The box is considered transparent and the main functions of the system are defined within the box. The next step is to break down the overall function into a set of sub-functions where the linkage between these sub-functions is the flow of energy, material, or information. Each sub-function should be stated in terms of a verb followed by a noun or nouns. At this stage, the sub-functions may reflect a bias towards a particular solution. This is normal during the development of a list of functions as long as the designer recognizes this bias and revisits the sub-functions later trying to remove it. The end result of a diagram approach to defining function is a set of blocks with functions worded on each box and connecting arrows between sub-functions showing flows of inputs. One convention in the diagram approach is to show secondary (and perhaps undesired) outputs as arrows exiting the bottom side of the box. This convention draws attention to items that should be minimized as part of the system design.

Mastery of function analysis comes from practice and learning from the mistakes made. Mistakes are identifies by trying to use the results you come up with. In many cases, the mistakes are mistakes of omission, forgetting that some information, material, or energy flow needs to be included. Function analysis is not a step that is once completed and then never repeated during the design process. Function analysis is an ongoing activity.

4. Set Requirements

Requirements are measures of performance that the design must meet. Requirements cover the look and feel of the design, the operation of the design, and the customer actions when using the design. Requirements can be thought of as falling into three areas:

<u>Product Characteristics</u>: product performance, features, quality, reliability, size, weight, purchase cost, operating cost, and ergonomics

<u>Product Life</u>: life span, obsolescence life, lives for replacement and renewable parts, warranty period, and storage or shelf life

<u>Customer Use</u>: installation procedures, documentation, start-up procedures, maintenance, and disposal

Sources of requirements include the objectives, regulations, certification standards, state of the art, current market practice, ergonomic data, and design decisions. Requirements generally have numerical values associated with them. Requirements that come from design decisions are used to guide the parallel design of components of complicated systems.

5. Generate Alternatives

The natural tendency in problem solving is to pick the first solution that comes to mind and run with it. The disadvantage of this approach is that you may either run off a cliff or into a worse problem than you started with. A better strategy is to select the most attractive path from many ideas or concepts.

Concepts or alternatives that meet the need should be generated. Functions provide the basis for generating alternatives. Alternatives considered should cover a broad range of possibilities rather than small variations of the same approach. Often an innovation at a function level leads to an innovation at the full concept level as it opens up new horizons of problem understanding and new avenues for pursuing solutions. Ideas should be generated for each step in the function diagram. *Creativity* is the key. Here's how to be creative in 4 easy steps:

Step 1: Preparation
Learn as much as you can about the problem, the possible solution technologies, related technologies, possible methods, the state of the art, etc. The more you know to start with, the more useful your contribution to the solution will be. As a designer with a multidisciplinary knowledge, you will know about technologies and methods that a standard engineer may not know about, and be better prepared to have ideas involving multidisciplinary, integrated solutions. Because the state-of-the-art review is so important in the design process, a separate section follows this section to discuss it in more detail.

Step 2: Incubation
Take a break. Think about something else for a while. Sleep on it. Play golf (but not too much, because it is addicting). Work on a totally different project. Give it rest for a day or so, if possible, and let it germinate deep in your mind.

Step 3: Illumination
Get an idea. This can happen spontaneously, when you are not thinking about the project at all, or in a more deliberate attempt to get ideas. There are several methods for generating ideas (including brainstorming) in this step that can help you turn your preparation and incubation into a really good idea. The more preparation you did in step 1, the better your idea will be.

Step 4: Implementation
Make it happen! Take your idea and implement it, and do it the best way you can. Sweat the details and do it right. Your idea is worthless until it is implemented, and if it is implemented poorly it will fail as a profitable product whether the basic idea was good or not. This is the step that makes or breaks the idea, and sometimes the engineer doing the design.

One of the classic ways to get an idea (in step 3 above) is called *brainstorming*. The design team gets together and begins describing solutions that they have come up with on their own. The team members build on each other's solutions, getting new ideas and modifying old ones, until a large number of diverse concepts results. An important rule during brainstorming is that the concepts are not judged or criticized during the process. Negative criticism will only shut down the creativity of someone who might otherwise have made an important contribution later on.

Another method of creative thought is called *mind mapping*. Starting at a central focus idea (such as the problem to be solved, or the function being studied from the function diagram), ideas are written down as fast as they come. These ideas lead to other ideas, which spawn ideas of their own. The unconventional structure of the mind map often allows ideas to come to the surface that might not appear in a more conventionally structured approach.

6. Evaluate and Select Alternatives

Once a whole bunch of concepts have been generated, one (sometimes two) promising alternative must be selected as the solution to the problem. Here is where the disciplined analysis and judgment that was relaxed during concept generation comes into play. One common method uses the following steps:

> *Step 1: Feasibility Judgment*
> This is a "gut reaction" decision based on past experience to weed the undoable concepts from the doable ones. It includes the decision of whether the company wants to get involved in the kind of product or technology that the concept requires. The question to ask here is: "Can we make the concept possibly work?" If so, then -
>
> *Step 2: Technology Readiness Assessment*
> This analyzes the level of technology required to make the concept work. It also includes whether a working proof-of-concept prototype can be made, whether all the ways the concept can fail are known, and whether the product can be safe enough to use. The question to ask here is: "Is the concept possible with current technology?" If so, then -
>
> *Step 3: Go/No Go Screening*
> The concept is judged by whether it actually meets the specified need. If it is possible and doable with current technology, but does not meet the need, the concept is scrapped. Sometimes the concept can be "patched" to meet the aspects of the need that it otherwise neglects. The question to ask here is: "Will the concept meet the need?" If so, then -
>
> *Step 4: Decision Matrix*
> All the concepts that have survived to this step are doable by the company, possible with current technology and meet the need. It only remains to chose the one that best meets the need.

One of the classic decision matrix methods is the *Pugh Matrix*. In this method, one of the possible concepts is chosen as a *standard* (or *datum*), and, for each attribute of the need, all of the other concepts are compared to the standard as to whether they are better (+), worse (-), or no different (0) at meeting that attribute of the need.

For example, in the matrix below, Printer Concept *B* prints more quickly than Printer Concept *A*, while Printer Concept *C* prints slower than A. The best concept is usually the one with the most +'s and fewest -'s. Often, however, the strengths of one concept can be transferred over to cover the weaknesses of another concept. A new set of hybrid concepts is generated, and the Pugh matrix is used again to judge which concept best meets the need. This method is repeated until the design group has the best idea it can come up with.

The table below is a Pugh matrix showing how well each of several hypothetical printer concepts meets the need attributes. The concepts are judged relative to Printer Concept *A*.

	Printer A	**Printer B**	**Printer C**
Low Cost	S	0	+
Fast Printing Speed	T	+	-
Clear Printing	A	-	0
Low Power Consumption	N	+	+
Use Standard Paper	D	+	0
	A		
Total +	R	3	2
Total -	D	1	1

⇒ *State-of-the-Art Review*

Research is an important part of a designer's job. In fact, a recent study of some of the most innovative companies by the National Research Council listed *keeping abreast of the state of the art* as one of the primary components of good design practice. The *State-of-the-Art Review* is that body of information that must be gathered in order to become expert in the area of the problem. It is the foundation for the entire design process. If it is done well the chances of achieving an outstanding design are increased greatly. It is important to note that the *State-of-the-Art Review* will be continuously updated throughout the design process as you gain experience by collaborating with customers and others who are experts in specific areas. Areas of study should include:

Historical Perspective:
It is important to consider information from the earliest known references to the problem area. This can help prevent efforts that merely serve to 'reinvent the wheel'. It is also possible that information may have been determined in the past which could now be utilized because of inadequate technology at that time. New technology might now be available to make it possible to incorporate the 'old' information into an outstanding design.

Trends in the Field:
We want our designs to meet future needs and be as long-lasting as possible. Therefore, we must anticipate future needs. One way to do this is to look at past and present trends and try to determine future trends.

New Technology:
It is the responsibility of engineers to solve problems by applying existing technology, especially the latest technology. We must search for ways to produce designs that achieve breakthroughs in quality, performance, and cost. You must investigate all new technologies that could possibly be applied to the problem.

Marketing:
Who is the customer? Where can I find them? Do I have the names of potential customers that I can approach during the design process? What does the customer want

in the way of: cost, reliability, safety, performance, etc.? What is the potential market for the product? What would be the likely production volume? What service requirements are there? Who will perform the service? How is the product likely to be used? In what environment will it be used?

Design:
What are the competing products on the market? What are the results of reverse engineering one of the competitors' products? What technologies are being used? What engineering disciplines will be involved (mechanics, electronics, mechanisms, thermodynamics, etc.)? What materials are being used? Is there an opportunity to use new materials? Who are potential vendors for the design? What research journals would have information pertaining to this area? What articles on this topic have been published in the past 5 years? What periodicals are likely to have articles related to this design? What are the pertinent articles in the past 5 years?

Manufacturing:
What manufacturing methods are being used in producing the parts on the competing products? What are the limitations of these manufacturing methods? Are there any new manufacturing methods that could be used? How are the competing products assembled? What is the assembly sequence? Where can I find data on manufacturing costs? What fastening methods are used for the parts? Are there any assembly problems? Who are potential vendors for the manufacturing? What research journals would have information pertaining to manufacturing-related topics? What articles on the manufacturing methods we expect to employ have been published in the past 5 years? What periodicals are likely to have articles related to this design? Have there been any pertinent articles in the past 5 years?

⇒ ***Detail Design***

After the concept is decided upon, the concept is turned into a set of specifications that manufacturing can use to produce the final product. While any design that adheres to the concept will meet the need, there are design methods that can be used to help make a high-performance, low-cost, quality product that people will want to buy.

Taguchi's *parameter design* concepts move quality control from the manufacturing stage to the detail-design stage. Often, if design variables are set carefully, the quality of the product can be improved without resorting to higher-precision tooling on the assembly line. Parameter design is discussed in more detail later.

Knowledge of *design for manufacture / design for assembly (DFM/DFA)* concepts can speed the development cycle by reducing rework time, and make the manufacturing and assembly processes faster and more reliable. Designing your parts to be easy to fabricate and assemble will save redesign time later. Communication should also remain open with the manufacturing department to make sure that the design is manufacturable with the available tooling, and to give manufacturing time to set up and test any new processes that may be required. *Design for test (DFT)* principles can shorten the time it takes to test the product during manufacturing or troubleshoot the system at the site. *Design for Safety, the Environment, and Recycling* principles must be applied by every responsible engineer at every stage of the design process.

Keeping *product structure (modularity)* in mind during the detail design phase will allow you to re-use existing proven designs and methods in parts of your new product, saving engineering and manufacturing the time and effort needed to develop them. Using *Quality Function Deployment (QFD)* will help you judge how important the different engineering characteristics are with respect to the need being met, as well as how important each physical part of the product is. Important parts can be designed carefully, while unimportant parts can be done cheaply or left off altogether. QFD is discussed later.

⇒ ***Manufacture***

The result of detail design is a prototype device and detailed specifications, from which manufacturing will make into a usable product. If the principles of *concurrent engineering* were followed, manufacturing will have been involved in the whole design process from the very beginning, making sure that the design can be manufactured as specified and offering suggestions on how to design the product so that it can be built more quickly and cost-effectively. If manufacturing has been closely involved, the prototype should translate smoothly into the final product.

The process isn't always as linear as it looks in theory. Often a design concept will not work out, or the customer's needs may change, or any number of things could go wrong that would send the product backward in the design process. *Concurrent Engineering* tries to eliminate such backward progress by constant communication between all parts of the company that are involved with the product.

⇒ ***Concurrent Engineering***

In the past, the standard product design process would go something like this: marketing would come up with a product need and pass it to the engineers, the engineers would design something to meet the need and pass it to the manufacturers, who would manufacture it. This is known as the "over-the-wall" method (each department passes their idea "over the wall" to the next department) and is the obvious, most direct method of design. Unfortunately, it has several major weaknesses.

When marketing passes a need to engineering, the engineers often interpret it differently than marketing intended, because the two departments do not use the same terms or idioms for the same ideas. It may be more difficult to meet the need than marketing thought, or there may be a simpler way to meet a similar need which would satisfy marketing's requirements. When engineering passes the finished design to manufacturing, manufacturing may have to alter the design substantially in order to manufacture it cost-effectively, without knowing which features are critical to the design and which are incidental. Finally, when the manufactured product doesn't work right, the design gets passed back "over the walls" to engineering or to marketing to try to figure out how to get it to work correctly or whether the product is actually fulfilling the need. The departments are not focused on a common goal, and the project has to be redone several times, resulting in a poor quality product and a long development time.

A multidisciplinary product has the further disadvantage of a communication gap inside the engineering department, between the software, computer, controls, electrical, and mechanical engineers, for example. Lack of communication and understanding can lead to problems in several areas, such as electrical noise, power requirements, chip selection, cable routing and even case size. Studying multidisciplinary engineering will enable you to communicate more effectively among the different disciplines involved in the design and better understand the issues involved in software, computers, controls, electronics, and mechanical design.

The primary feature of concurrent engineering is the *simultaneous involvement of all departments*. An interdisciplinary team, including marketing, engineering, and manufacturing people, follows the product from need identification to the final assembly line. The whole team participates and communicates in each step, so that the engineers are clear on what the actual need is, marketing knows what alternatives there are, and manufacturing can make sure the design is manufacturable before it reaches the final specification stage. The key is constant communication (to clear up misunderstandings) and constant awareness of the state of the project (so that problems can be spotted as early as possible). Here we discuss the marketing, engineering and manufacturing departments only, but representatives of other departments such as testing, quality control, sales, and management are also included in the design team to ensure that their requirements for the product are met.

The main effects are a *drastic reduction in development time*, as rework is practically eliminated, and everyone is up to speed on the project from the very beginning; and a *higher level of quality*, since errors due to interdepartmental ignorance are caught early.

Concurrent engineering also encompasses such ideas as:

> *Corporate Restructuring:*
> Instead of dividing the company by tasks (marketing, engineering, manufacturing), the company is divided by project so that different divisions, each with their own branches of marketing, engineering, and manufacturing, are working on different products. Sometimes the company personnel are classified both by task and by project in a matrix-type organization.
>
> *Aggressive Goals:*
> The Cannon Personal Copier was the result of a design goal that many in the industry thought was too difficult to make reliable and did not have enough of a market. Shooting for a copier that was small enough and cheap enough for one person to buy while being reliable enough not to need an immense staff of service people is the kind of aggressive

goal that concurrent engineering excels at meeting - and that opens huge new markets for exploitation.

Design for Manufacturing and Assembly:
The design engineers are trained in the various manufacturing methods so they can design parts that are easier and quicker to make and less likely to fail. Products are also designed to reduce the complexity of assembly. Where possible, part count is reduced and the parts are designed so that they fit together only the correct way.

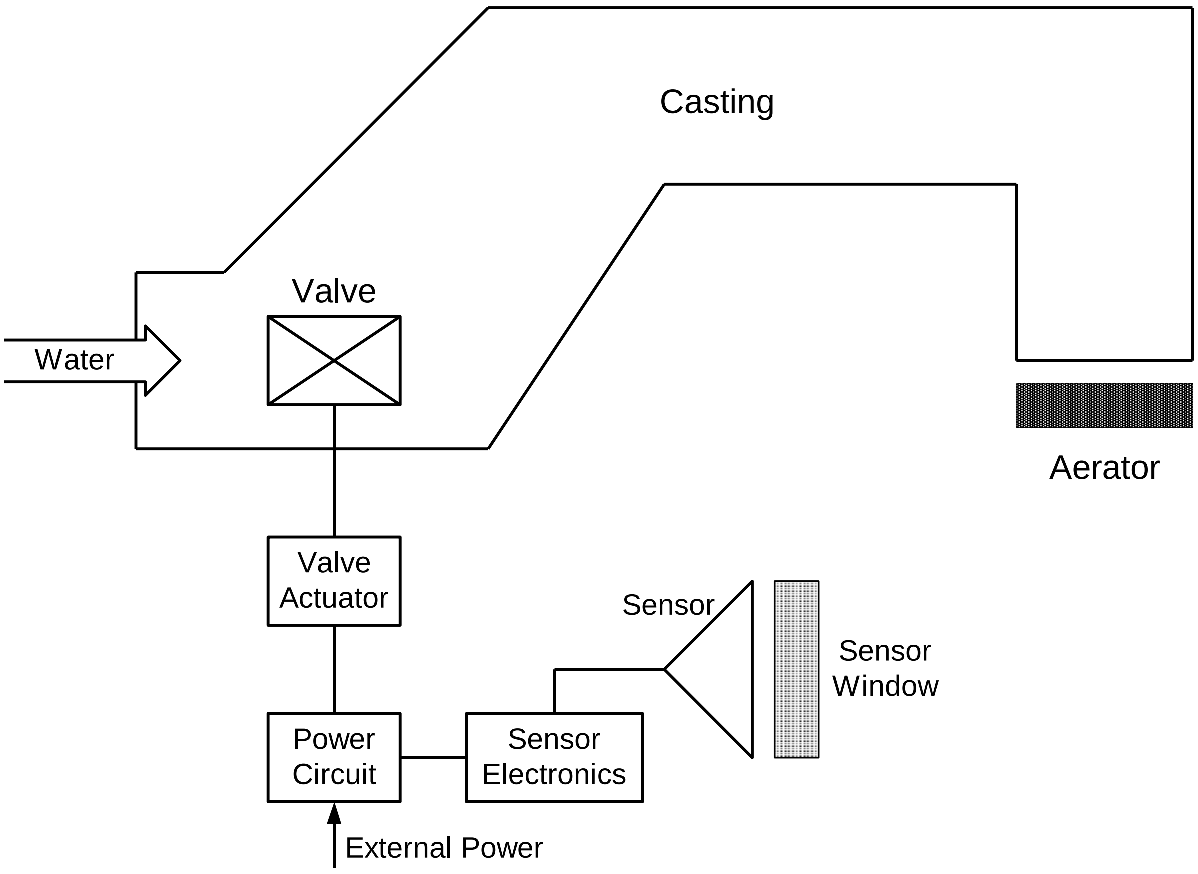
Prototyping on the Main Production Lines:
Communication between engineering and manufacturing allows the prototypes to be run on the main production lines and not on a specialized prototyping facility, where special skills and equipment are available. If the prototype functions correctly and can be manufactured on the main lines, it will not need to be redesigned for mass production.

Close Involvement with Suppliers and Customers:
Concurrent engineering requires improved communication not only among departments but also with suppliers, to make sure the parts supplied are exactly what is required, and with customers, to make sure the finished product is exactly what they want. The customers and suppliers are involved in the design process early, so that their ongoing evaluations and suggestions can be taken into account.

Often the term concurrent engineering also refers to all improved, modern design practices in general, including QFD, parameter design, and product structuring. Used together, these design methods work to maximize the quality and minimize the development time of a given product.

⇒ ***Quality Function Deployment***

People make the decision to buy a product based on the *perceived quality* of the product - whether they feel the product will meet their needs. QFD helps make sure that the product is focused on meeting the needs that the consumer wants met. As a simple example, we will analyze an automatic faucet design using QFD. The figure below shows an automatic faucet where the water turns on when the sensor detects that something is under the spout.



Schematic Diagram of an Automatic Faucet

The needs met by the product are listed as *customer attributes*. They are ranked by relative importance (1 - least important, 5 - most important). If competitors make a similar product (e.g., products A and B), and/or the company is trying to improve its own product (e.g., product C), the competing products are rated or *benchmarked* by how well they meet the customer attributes. In our example, some of the customer attributes are shown in the table below.

Customer Attributes	**Importance**	**Competitors**		
		A	**B**	**C**
Functionality				
Compatible with current plumbing	5	4	5	5
Detects hands only under faucet	4	3	2	1
Sensor works when window is wet	4	4	2	3
Rinses soap off quickly	3	4	2	2
Efficiency				
Reduces water usage	4	1	4	2
Low cost	2	4	2	3
Low electric power usage	3	2	2	5
Maintenance				
Easy to maintain	4	2	3	2
Long expected life	3	3	5	2
Easy to fix	2	2	1	4

Among other things, one thing we see is that "Detects hands only under faucet" is a fairly important attribute. Faucet *A* does a medium job of detection, and faucet *B* is less accurate. Our old product, product *C*, has a very inaccurate detector. Given the relative importance of proper detection, an improved sensor system should be a major goal of our new design.

The needs are met by the *engineering characteristics* of the product. While the customer attributes are more vague and non-quantified, engineering characteristics should be qualities that can be quantified. In our example, some engineering characteristics are:

Flow: pressure drop, water exit velocity, water flow rate, valve actuator strength

Sensor: range, sensitivity to window impairment, lag between sensor and valve

Miscellaneous: electric power consumption, plumbing interface, access to interior systems

A matrix is used to compare the engineering characteristics to the customer attributes, to see which characteristics are important. By focusing engineering effort on the important characteristics, the product can be improved in ways that are important to the customer. Each engineering characteristic has a "strong relation" (S), "medium relation" (M), "weak relation" (W) or "no relation" (blank space) to each customer attribute. The figure below shows a QFD matrix relating the engineering characteristics of an automatic faucet with the need (customer attributes) for it.

QFD Matrix

Engineering Characteristics

Customer Attributes	**Importance**	**Flow**	Pressure Drop	Water Exit Velocity	Water Flow Rate	Valve Actuator Strength	**Sensor**	Range	Sensitivity to Window Impairment	Sensor-Valve Lag	**Miscellaneous**	Electric Power Consumption	Plumbing Interface	Access to Interior Systems
Functionality														
Compatible with current plumbing	5												**S**	
Detects hands only under faucet	4							**S**	**M**	**W**				
Sensor works when window is wet	4							**W**	**S**					**W**
Rinses soap off quickly	3		**M**	**S**	**S**					**M**				
Efficiency														
Reduces water usage	4		**W**	**M**	**S**			**M**	**W**	**W**				
Low electric power usage	3					**M**								
Low cost	2		**W**	**W**	**W**	**M**		**W**	**W**			**M**	**M**	**M**
Maintenance														
Easy routine maintenance	4								**S**				**M**	**M**
Long expected life	3		**M**		**M**	**W**						**W**		
Easy to fix	2												**M**	**S**
Importance of Each Characteristic			**24**	**41**	**72**	**18**		**54**	**90**	**17**		**36**	**69**	**40**

From the chart, it can be seen that water exit velocity is very important for the "rinses soap off quickly" attribute, somewhat important for the "reduces water usage" attribute and marginally important for keeping the cost down. (The ratings given in this chart are simply the author's opinion - other analysts may come up with different ratings.)

The total importance of each engineering characteristic is calculated by multiplying the importance of the customer attributes by the strength of the characteristic's relationship to those attributes. Strong relationships use a weight of 9, medium relationships have a weight of 3, and weak relationships have a weight of 1 (other weighting schemes may be used). For example, the total importance of water flow rate (the third column) is 3 x 9 (rinses soap) + 4 x 9 (reduces water use) + 2 x 1 (cost) + 3 x 3 (long life) = 72. The most important characteristic is sensitivity to window impairment (90), because the sensor must work correctly even if the window is wet, and maintenance costs can be kept down if the window doesn't need to be wiped off by the maintenance crew. Water flow rate (72) and the plumbing interface (69) are also relatively important characteristics. The least important are valve-actuator strength (18) and sensor-valve actuation lag (17).

The QFD chart will show areas of opportunity for improving the design, such as unimportant engineering characteristics that can be optimized for cost control, important engineering characteristics that should receive special attention, benchmarks that none of the competitors excel in (and we can use as a selling point), and high benchmark ratings of competitors that can be copied.

Along with determining which engineering characteristics are important, the QFD matrix can also be used to determine which specific parts of the product are important. The figure below shows a QFD matrix that determines the importance of each part of the faucet by relating the parts with the engineering characteristics that they influence.

QFD Matrix

Parts

Engineering Characteristics	**Importance**	**Plumbing**	Casting	Valve	Valve Actuator	Aerator	**Sensor System**	Sensor	Sensor Window	Sensor Electronics	**Power Circuit**
Flow											
Pressure Drop	24		**S**	**M**		**S**					
Water Exit Velocity	41		**M**	**M**		**S**		**S**	**M**	**W**	
Water Flow Rate	72		**S**	**M**		**S**		**W**	**S**		
Valve Actuator Strength	18			**M**	**S**						**M**
Sensor											
Range	54							**S**	**M**		
Sensitivity to Window Impairment	90							**M**	**S**	**W**	
Sensor-Valve Lag	17			**S**	**S**			**W**		**W**	**W**
Miscellaneous											
Electric Power Consumption	36			**W**	**S**			**W**		**W**	**M**
Plumbing Interface	69		**S**	**W**							
Access to Interior Systems	40		**M**	**M**	**W**					**M**	
Importance of Each Part			**1728**	**843**	**639**	**1233**		**809**	**972**	**263**	**111**
Cost of Each Part ($)			**3.00**	**1.20**	**3.00**	**0.25**		**0.75**	**0.50**	**1.25**	**1.00**

Again, each part has either a strong (S), medium (M), or weak (W) relationship (or no relationship – blank space) to each engineering characteristic. Multiplying the importance of each characteristic by the strength of the relationship and summing the values for each part gives the relative importance of each part. From the figure, it is seen that the most important part of the faucet is the casting (1728), with the aerator next (1233), both because they relate strongly to the flow of water through the faucet. These parts should be carefully designed and optimized. The least important parts are the electric power circuit (111) and the sensor electronics (263), because in this case the functionality of the faucet depends mostly on water flow and range accuracy, neither of which are much affected by the power circuit or the sensor electronics. Optimizing these sub-systems are much less critical to the success of the product.

The part importances are compared with the expected cost of each part. If the important parts do not cost more than the unimportant parts, it could indicate an opportunity to improve the design. In the example above, the aerator is very important but is the cheapest part in the faucet. Spending more money on a more sophisticated aerator design might improve the end quality enough to more than justify the increased cost. On the other hand, the power circuit is more expensive than the sensor or sensor window, which are 7 or 8 times more important to the design. Cutting the cost of the power circuit may result in a cheaper product with almost no loss in quality.

The QFD matrix is, of course, only as accurate as the data it is given. If the importance of the customer attributes are miscalculated, the product will be less likely to meet the real customer demands. If the strong, medium and weak relationships are misjudged, or all customer attributes are not accounted for, the design may do worse than expected. In the faucet example, customer attributes relating to safety have been ignored. Safety considerations may make the power circuitry much more important than the analysis shows.

QFD matrices for real products usually have many, many more customer attributes and engineering attributes than the faucet example. Other information is usually also included, such as how the engineering characteristics interact with each other and quantified target goals for the engineering characteristics.

Since it requires a fairly complete list of parts and engineering characteristics, QFD is best suited for improving a prototype or an existing design. In a class design project, QFD will be useful as a means for defining the goals of the project (in the customer attributes), making sure the goals are addressed, and evaluating how well you are meeting those goals.

⇒ *Design for Robustness: Parameter Design*

Genichi Taguchi has developed an innovative design method which analyzes quality during the design process instead of only after the design has been finished. Taguchi divides quality design into three stages: *system design* - concept generation and development, *parameter design* - optimization of design variables, and *tolerance design* - improving the precision of the manufacturing machines. The cost of improving product quality increases as the design progresses through the three stages. In the past, companies tended to focus on tolerance design when a higher quality product was called for. Often the design process goes straight from system design - a working prototype - to tolerance design. Taguchi discovered that while tolerance design made marginal improvements in quality at higher cost, parameter design at the product development stage could make a better quality product without changing the manufacturing process at all or adding substantially to product cost.

Quality is maximized by optimizing certain *quality indicators* of the product. A quality indicator for a nail might be making it exactly the right length (a "nominal is best" case), while for a car it might be the lowest possible pollution emission ("smallest is best") or highest possible gas mileage ("largest is best"). The level of a given quality indicator is determined not only by the precision of the manufacturing process (optimized in tolerance design) but also by the various controllable design variables (optimized in parameter design). In the case of the nail, length may be affected by material choice, tempering and surface finish. Instead of making the nail-point-cutting machine more precise, careful selection of materials, tempering, and surface finish could have the same effect, possibly for less money than the improved nail-cutting machine would cost.

The factors that affect a given quality indicator are divided into *controllable factors* and *non-controllable factors* (or *noise*). Controllable factors are those which the designer can set (in the faucet example, the valve type and the calibration of the sensor are controllable factors). Noise factors are those which either cannot be controlled by the designer (such as the size of the user's hands) or are chosen not to be controlled by the designer due to the expense incurred if they were controlled. For example, the pressure in the water pipes can be controlled, but this would add unwieldy cost to the design. It is better to make a faucet that works well under a range of pressure conditions. Several experiments are done on prototypes of the product, varying the controllable and noise factors in a systematic way. The final design will use the set of controllable factors that both optimizes the quality indicator and minimizes the quality indicator's susceptibility to the noise factors. Sensitivity of the quality indicator to variations in the noise factors is measured by the signal-to-noise (S/N) ratio.

To demonstrate the parameter design optimization process, we will use the faucet, described in the QFD section. The quality indicator will be "water delivery accuracy" (which means that when a hand is positioned below the spout, water will flow onto the hand). This involves both accurate sensing of the position of the hand and accurate water flow to the sensed position.

For controllable factors we will use (A) sensor calibration (the sensitivity of the sensor to the presence of a hand), (B) stream focus (whether a tight stream or a wide spray), and (C) stream angle.

For noise factors we will use (N1) user hand size, (N2) water pressure at the site of the faucet, and (N3) sensor window obstruction (by water droplets, dirt, etc.). In actual operation, these factors are not controlled, but they must be controlled during the tests so that the design that is least susceptible to noise may be found. The goal of the parameter design optimization is to select controllable factors A, B, and C so that (1) water delivery accuracy is optimized and (2) the effect of N1,N2 and N3 on water delivery accuracy is minimized.

A set of experiments is done on prototypes of the faucet. In each experiment, the values of controllable factors A, B, and C are chosen in different combinations and the accuracy of the resulting faucet is tested under different combinations of N1, N2 and N3. The combinations are determined by the use of orthogonal arrays, which produce a balanced experiment from which the effect of each factor on the quality indicator may be viewed separately from all other factors. By using orthogonal arrays to dictate the factor combinations to be tested, it is not necessary to test *all* the possible combinations of factors to determine the optimal design. The use of orthogonal arrays allows the designer to get the most information from the fewest possible number of experiments.

In our example, we will use two different values for each controllable and noise factor as follows:

Factor	**Level 1**	**Level 2**
A. Sensor Calibration	Near	Far
B. Stream Focus	Tight Stream	Spray
C. Stream Angle	Vertical	30° from vertical
N1. Hand Size	Large Adult	Small Child
N2. Water Pressure	High	Low
N3. Window Obstruction	Clean	Dirty

Four experiments are performed at each of four noise-factor combinations for a total of 16 tests.

The figure below shows the experimental results of parameter design optimization for the automatic water faucet.

							⇩		
				N1	1	2	2	1	
				N2	1	2	1	2	
Experiment	**A**	**B**	**C**	**N3**	1	1	2	2	**S/N**
1	1	1	1		***0.3***	***0.7***	***1.1***	***0.7***	***2.4***
⇨ **2**	1	2	2		***0.5***	***0.7***	***0.9***	***0.9***	***2.3***
3	2	1	2		***0.6***	***1.0***	***1.2***	***1.1***	***0.0***
4	2	2	1		***0.5***	***0.6***	***0.8***	***0.5***	***4.3***

The sixteen numbers inside the grid are the accuracy of the faucet at each set of controllable factors and noise factors, in inches from a nominal point on the palm of the user's hand. The accuracy value where the two block arrows intersect is the experimental result of the nearcalibrated (A = 1), spray focus (B = 2), 30 degree (C = 2) faucet under the noise conditions of a child's hand (N1 = 2), high water pressure (N2 = 1) and a dirty sensor window (N3 = 2).

The four accuracy values for each set of controllable factors are used to determine the *signal-to-noise ratio* for that design using the following equation:

$$\frac{S}{N} \text{ ratio } = -10 \log \frac{y_1^2 + y_2^2 + y_3^2 + y_4^2}{4}$$

The best design in terms of accuracy and insensitivity to noise will have the highest signal-to-noise ratio. This particular formula is used for "smallest value is best" quality indicators. For "largest is best" or "nominal is best", other signal-to-noise ratios are used.

Experiment 4 appears to have the best S/N ratio. However, as discussed above, not all of the combinations of controllable factors have been tested. But because of the way the experiments were selected (using an *orthogonal array*) we can expect to be able to find the best value of each controllable factor independent of the other controllable factors, and thus come up with the best total design.

In the *response table* below, the S/N ratios for each experiment at a given controllable factor level are averaged and compared:

	Controllable Factor		
Level	**A**	**B**	**C**
1	2.35	1.20	3.35
2	2.15	3.30	1.15

In the first column, the average S/N ratio of all the experiments where factor A is set to level 1 (that is, experiments 1 and 2) is compared to the average S/N ratio of all the experiments where factor A is set to level 2 (experiments 3 and 4). The chart shows that the best S/N ratios occur when A is set to level 1, B is level 2, and C is level 1 - a case which wasn't used in our experiments!

As the last step, the final design is tested by running a 5th experiment (called the confirmation experiment) to make sure that it produces a higher signal-to-noise ratio than all the other cases we tested.

Typical parameter design analyses usually have several more controllable factors and noise factors, resulting in many more tests. Also, each factor can have more than two levels. Testing many factors at two levels is useful to determine those factors that most influence the quality indicator. Using three levels instead of two can allow the designer to interpolate to an optimum value of the controllable factor which isn't necessarily any of the levels used in the experiment.

Careful use of orthogonal arrays in the control and noise factor levels will keep down the number of tests without a significant loss of accuracy.

⇒ ***Product Structuring***

One of the keys of selling to everybody is to give everybody exactly what they want, no more and no less. Ideally, each customer should be able to order the product with exactly the features they want, in the color and style they want. In *product structuring*, or modularity, the product is designed as a number of modules. A given module in the product can be replaced by another module that has a different appearance, performance or functionality, while the rest of the product remains the same. The result is a new (but related) product, on which most of the development work has already been done.

Consider an upright vacuum cleaner. Replace the motor with a more powerful one, and you have a high-end product for people who wouldn't buy an "ordinary" vacuum cleaner. Use a cheaper casing, and sell it for less to those on tighter budgets. Paint it a nice neutral color and use more durable components, and you can sell it to hotels and other institutions as an industrial-use vacuum.

On the other hand, a given module can be used across product lines - the motors used in the vacuum cleaner, can, with proper design, be used in a variety of other appliances. If the mounting brackets in all your appliances can support all the varieties of motor systems that you want to use, then the motor systems can simply be plugged into any product with no new development.

Manufacturing is simplified: when an existing module is used in a new project, manufacturing already knows how to make it. Testing is simplified, as each module only needs to be tested on its own before the whole is assembled (assuming that each module is robust enough that the other modules in the product do not interfere). If the alternative modules can be handled by the same manufacturing equipment, then, for example, a high-power motor can be substituted for a low-power motor with no changes in the assembly line. New developments can be added bit by bit by changing one module at a time.

Multidisciplinary (electronics, controls, computers, mechanical, etc.) devices are well suited to product structuring. Often the functionality of the product can be modified or improved merely by changing the software. Higher-end versions of the same product can be made by plugging the same control circuits and software into more powerful machinery. Sometimes fully-featured products are "crippled" to make lower-end products that have the same software but fewer hardware features.