XII. CONCURRENT ENGINEERING (CE)

INTRODUCTION

Concurrent engineering (CE) is changing the way U.S. managers think and conduct business. Loosely defined CE is the practice of using a multidisciplinary team to conduct conceptual thinking, product design, and production planning all at one time. It is also known as simultaneous engineering or parallel engineering. The team is composed of specialists from business, engineering, production, and the customer base. Suppliers of process equipment, purchased parts, and services are also included on the team at appropriate times. Concurrent engineering has recently encouraged changes in management structures. Some managers claim to have used it informally before it became popular.

In the past, the major functions within an organization would complete their task by "throwing it over the wall" to the next department in the sequence and would not be concerned with any internal customer problems that might arise. Hence, the term sequential engineering was used to describe the process. Concurrent engineering requires the major functions to be performed at the same time. This system provides for immediate feedback, which prevents problems with quality and productivity from occurring:

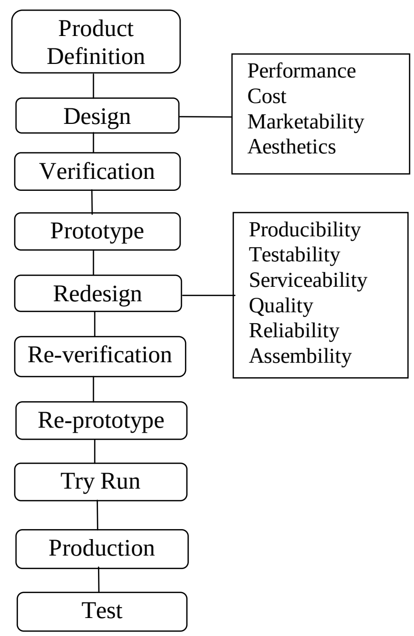
A broad definition of CE is a team of specialists who simultaneously design and develop a product to ensure ease of producibility and customer satisfaction. Figure 12-1 shows the flow diagrams for both sequential or traditional engineering on the left and CE on the right. In CE, engineering (i.e., mechanical, electrical, structural, quality, material), production, and business (i.e., purchasing, marketing, finance), as well as suppliers and customers brainstorm together to develop a product that considers all facets of its functionality as well as its costs. When each of the specialists has early input to the product definition and specifications, cost is minimized and performance is maximized. Thus, better-quality products are manufactured for less cost with shorter time to market.

Getting input at the beginning from all areas eliminates engineering changes later in the project. Communication flows better and people are more apt to compromise to assure better manufacturability instead of unknowingly creating more work for the next discipline. As mentioned previously, designs were thrown over the wall to the next area. For instance, it would be difficult for the electrical engineers to know why the structural engineers designed sections in a component that would require special processes in order to run wires through the product. These simple problems, which arise from ignorance of other specialization areas, are eliminated from projects and thus, lead times to market are shorten.

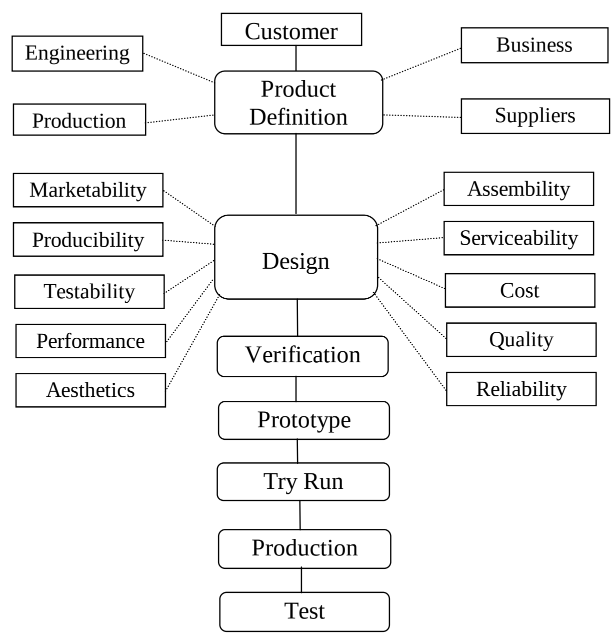
As can be seen from Figure 12-1, sequential engineering requires repeated steps of redesign, re-verification, and re-prototype in order to compile all previous design stages. For example, during the first design phase in sequential engineering, only performance, cost, marketability, and aesthetics might be considered. After verifying the design and building the first prototype, it is determined that the product needs to be redesigned for producibility, testability, serviceability, quality, and reliability. In the CE model, however, the initial design phase encompasses all of the aforementioned attributes, thus eliminating the need for redesign.

There is obviously a longer lead time involved in the traditional method, because each step is performed independently, one after another. As problems arise, the project is sent back to the corresponding area and the process starts over. Because there is a high level of technical specialization at each step, numerous cycles are common. The concurrent method combines all these steps into one. The product is designed to be successful at each stage of its life cycle. It is designed correctly the first time, considering all attributes and facets of its life, such as marketability, assembly, and serviceability, before release to testing and finally production.

SEQUENTIAL ENGINEERING



CONCURRENT ENGINEERING



RATIONALE FOR IMPLEMENTATION

Project budgets for all industries are becoming more crucial to any product's marketability. In the 1970s, U.S. producers were able to pass unaccounted costs to the consumer through price increases. Accounting methods and budgets were not as critical as they are today. In the past, consumers had only a few brands to choose from, so the price was dictated by the cost of production plus a reasonable profit. Imported products helped balance the demand for quality products at reasonable prices and allowed consumers to set the market price. Oftentimes, there is little to no markup on goods, forcing inefficient suppliers to close their doors or produce specialized products that have higher contribution margins.

Design changes that occur late in the product development cycle cause increased lead times and. thus, higher costs. Concurrent engineering helps control this by shifting all the design to the beginning of the project rather than throughout its whole life cycle. The shifting of all design to the beginning of the project increases the time required for initial design, however, the future benefits outweigh this increase. For example, a change made during the design stage could save up to ten times as much as one made during the testing stage. Spending ten times as much to change features that could have been designed into the product at the beginning justifies the purchase of high-powered product development software. The amount of time required in the CE model for product definition and specifications can be significantly greater than that required in the sequential engineering model. However, the increased time is warranted because the brainstorming sessions among specialists results in a more complete final product definition.

Fewer design changes and shorter product lead times both equate to a quicker response to customer needs, however, there are even better reasons for using CE. Lower reject and scrap rates on the shop floor instantaneously improve profits.

Cash flow is crucial to an organization s operating budget. Sales dollars pay the present period expenses, which keeps the facility producing the products that will be sold tomorrow. Customer returns can take a large bite out of an organization's operating budget and can hinder product scheduling in order to perform rework.

Concurrent engineering designs the product within production capabilities in order for statistical process control to be effective. Producing products well within process capabilities will cause a chain reaction of customer satisfaction. Customer returns will decrease, and rework costs will also decrease. Obviously, profit margins will become larger, because the time that was previously used to rework in-house non-conformities and customer returns can now be used to produce new products. Thus, organizations are taking two steps forward and one giant step back every day they continuously inspect products that could have been designed within process capabilities rather than at or below process capabilities.

BENEFITS

Because consumer trends drive market demands, the ability to react six months before your competition can significantly improve profits. Obviously, timing is important, but consumers will switch brands if they can get a similar product of the same quality for less money. Furthermore, if a product is not designed with costs in mind, inefficiencies will soon erode the profits gained from short lead times. CE provides manufacturers with the tools as well as communication and management techniques required to develop products in a timely and cost-efficient manner from the beginning and throughout a product's life.

The primary benefit of implementing CE techniques is a significant decrease in time to market. Other benefits of CE are

- Faster product development
- Better quality
- Less work in progress
- Fewer engineering change orders
- Increased productivity

Although listed separately, the aforementioned benefits are the underlying reason for a decrease in a product's time to market. According to the National Institute of Standards and Technology implementation of CE methods can reduce engineering changes by 65% to 90%. This decrease in engineering changes can cut product development times by 30% to 70%, reduce time to market by 90%, and increase quality by as much as 200% to 600%. Furthermore, due to the improvements in quality, less rework has significantly reduced direct labor costs.

TEAMS

Concurrent engineering utilizes teams to take advantage of prior experience, emphasize early high quality decisions, and support the fulfillment of customer requirements, feedback constraints, and the efficient management of risk and change as the product moves from conceptual design to sales. These teams include product developers from marketing, research and development, design, production, test, and logistics, to name a few, along with project and program management. Suppliers and customers should also be included as part of the team when appropriate. To work concurrently, these developers must share ideas and work toward a common goal.

In order for CE to work, a change in the way business is done must occur. Concurrent engineering requires a change in the "business as usual" philosophy by removing the walls that stand in the way of faster product development and, consequently, lower costs. People can no longer be concerned with only their own function--an exchange of ideas must travel upstream as well as downstream. The input from production, quality, and service departments, in addition to supplier and customer input, are invaluable to the design and development of a product. Implementing the CE philosophy requires a top-down commitment. Bring together team members from business, engineering, and production requires either that they be co-located or that a system to share information be installed. Team members must be committed to the project, not to their functional departments. The right people need to be put into management roles, and it is vital to know the strengths and weaknesses of all team members. The job needs to be done right the first time by statistically validating every process to assure producibility.

More producible designs will be achieved through better interaction between design team members. This process begins when design, testing, production, and other members provide input during the final revisions of the product proposal from marketing instead of after the product has already been designed.

Studies have shown that somewhere between 60% and 95% of the overall product cost is determined during the design phase. A product's parts, assembly, test, and service costs are dictated far more often in the product's design than in the actual production, testing, or servicing. The earlier these design decisions are made, the larger their impact.

To avoid problems with teams, reward team members for extra work, level the playing field, and compensate team members more or less equally. Suppliers must have the trust of the team to keep highly engineered parts confidential. Team members should treat other team members as internal customers. These are just a few examples of how the benefits of CE can be increased.

COMMUNICATION MODELS

The communication flow for sequential engineering is in series, compared with concurrent engineering, which has a communication flow in parallel. The traditional model for communication in organizations across the United States uses a hierarchy of units, as shown in Figure 12-2. For simplicity, not all departments are included within each discipline (i.e., design and finance could have also been included in engineering and business, respectively). Although needed for the effective management of resources, this hierarchy does not foster communications across the organization, but rather only up the chain of command. The traditional model allows for a great many structured communication paths among similar functional units in the organization. For example, all the various engineering groups in the organization can usually easily communicate with any other engineering group. However, this model is structured to impede communication between product engineering and marketing, for instance.

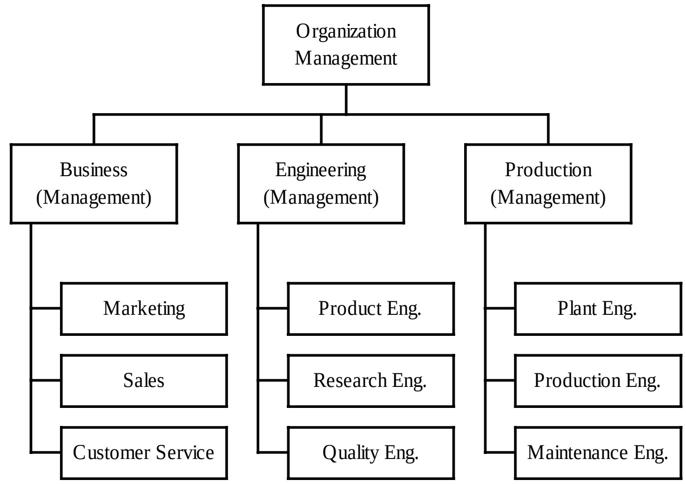


Figure 12-2 Traditional organization structure and information paths

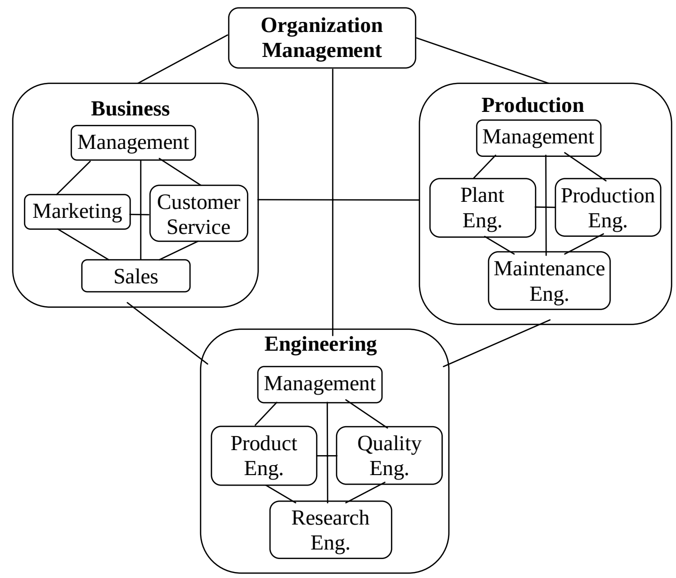


Figure 12-3 Concurrent engineering organization structure and information paths

In the traditional organizational structure, each level in the hierarchy should only perform duties that are assigned from the level above. Thus, if the system is designed well, cross communications need not be necessary. This system worked well in the face of no competition. However, as can be seen by U.S. industry in the 1970s and 1980s, this system had difficulty surviving against the more advanced organizational systems of other countries. In order to circumvent the lack of flexibility in the traditional organizational structure, a CE organization structure should be adopted, as shown in Figure 12-3.

In the CE structure, information paths are opened up between departments in different disciplines. In other words, a field service employee can talk directly with a production engineer about a common service problem that could be easily remedied in the production phase of product development. Similarly, design engineers can consult with production workers about difficulties in assembling their designs. The primary advantage of the CE structure is the opening of communication paths between employees and their subsequent empowerment in the decision making process.

IMPLEMENTATION

The implementation of CE is no easy task for any organization. A great deal of time, effort, and money needs to be expended in order for the culture of the organization to accept the various basic concepts that make CE work. These concepts, which include looking at the whole product life cycle, agreeing that there are indeed both internal customers and suppliers as well as outside ones, and having a commitment to quality for the entire process of making the product and not just the product itself, are key to the success of CE.

The easiest way for an organization to progress toward a CE environment is to simply gather together everyone who will be involved in a project at its beginning and allow the communication channels to open. This meeting of all project members can reap great rewards. The first of such benefits is that project members can meet face to face all their internal and external customers and suppliers, which has the effect of personalizing the project for each member. It also opens personal channels of communication, because there are now people, not just faceless names, associated with each phase of the project. Another important feature of the initial meeting is that the members of the project come to understand the overall goals of the project. The meeting can also be used to quickly clear up any misconceptions project members may have about the project.

Once this initial meeting has taken place, there should be regular meetings at set intervals to allow the project members to renew communication paths and to exchange ideas and complaints about various phases of the project. The intervals between project meetings must be long enough to allow for meaningful questions to develop but short enough so that important design decisions can be discussed by the group. With this in mind, the project leader must schedule the meetings while also considering the constraints on the schedules of each member of the group. This scheduling quickly becomes a logistics nightmare.

By using dedicated project teams, the hindrance of regular meetings can be eliminated. This is a system in which members of each functional unit are either recruited or assigned into a persistent project team that stays together from project to project. By implementing such a system, the organization can establish project teams that have a sense of togetherness, whose paths of communication are already in place, and where each member fully knows everyone's capabilities. This approach is a very elegant solution to implementing CE; however, it is only a partial one. The reason that the system is flawed is due to the aging of the project team. As the team does more and more projects together, a sense of stableness and settling occurs in communication between the members. They no longer try to find better and better solutions to problems that the project faces, but instead rely on solutions that the team has arrived at in past projects. This limitation can be attributed to the fact that newer solutions require more communication.

By placing the team members in the same location (co-locating), the project team can be continuously stimulated to find solutions to the problems of the project. Co-location dramatically increases communication between project members and, thus, stimulates continuous improvements However, there are a number of disadvantages associated with co-location. The first is the high cost of moving and providing for the project members Secondly, by moving individual members out of their functional unit environment, the organization takes away the paths of communication that previously existed within the respective units. For example, in moving a die designer out of his or her department, the designer can no longer effectively communicate with other designers, which can result in a sub-optimal die design.

Computer network technology allows the organization to get the advantages of a co-located team but still retain all advantages of a functional organization. By networking the team together, the project is turned into a managed set of resources and applications, through which the team communicates. This technology gives a threefold advantage. First, it eliminates the cost of co-location. Second, it allows for maximum communication between project members and outside consultants. Finally, it records the progress of the project for management and accounting uses.

Although each of the aforementioned steps toward implementing CE adds advantages, it also increases costs. These costs, both in time and in money, must be considered before any model is applied to an organization. Each solution also requires progressively more difficult culture changes in the organization for it to be effective. By first establishing project meetings, management can slowly begin to change the culture of the organization. After these cultural changes have become ingrained, the organization may add a project facilitator or go directly into dedicated project teams. Once these teams have been established, the organization may wish to co-locate each project team or even try to network all the projects.

The implementation of CE can be viewed as a path of stepping-stones on the way to true CE. The pace of the travel on the stepping-stones should be dictated only by how far the organization wants to step and how much they want to risk falling off the path.

TOOLS

Computer-aided drafting (CAD) and computer-aided manufacturing (CAM) have bridged the gap between design and rapid prototypes. Computer-aided drafting files can be converted to tool path geometry and then downloaded directly to a computer numerically controlled (CNC) machine. A model can then be cut for the CE group to evaluate and discuss in terms of design options. In the following sections, many of the tools needed to make CE work are discussed. Without these tools, CE is not as effective. It is only when a proper mix of the following tools is judiciously implemented that CE will radically reduce lead times.

Chronology of Concurrent Engineering Tools

Many CE tools were not readily available to the business, engineering, and production departments of an organization until the late 1980s and early 1990s. The prime mover for the explosion of CE tools has been the exponential growth of desktop computer processing power with advanced computer graphics capabilities. To realize the phenomenal growth in CE tools resulting from the personal computer revolution, we need to look only at the advances in word processing, drafting, and engineering analysis.

Until the early 1980s, secretaries throughout the world relied on typewriters for the word processing of all documents. Editing of these documents and bulk mailings required substantial amounts of time and organization resources in addition to the original effort. Often, organizations employed more secretaries and support staff than employees directly related to product development and production. Since the late 1980s, almost every office assistant has had access to a personal computer with word processing software. These software programs make bulk mailings as simple as writing a single letter, and editing a document can take a fraction of the time required for the original manuscript.

Major aircraft manufacturers have used CAD software since the late 1970s. However, it is only since the late 1980s that small to medium sized organizations have utilized the power of personal computer-based CAD. Computer-aided drafting software allows engineers at small organizations to draw designs and make changes in a fraction of the time required by the old pencil-and-paper techniques.

An even more dramatic example is the explosion of personal computer-based engineering analysis software packages such as finite element analysis. The theoretical background for finite element analysis was first developed in the 1950s and 1960s and coincides with the early advances in digital computers. Until the late 1980s, only aircraft manufacturers, automobile manufacturers, and government laboratories utilized the advantages of engineering analysis software because of their access to high-powered supercomputers. In the 1990s, even the smallest of organizations could purchase a personal computer-based finite element software package.

Organizational Tools

Many of the tools implemented by an organization need to be understood by all employees. The primary organizational tools for a CE environment are

- Total Quality Management philosophies
- Computer networks
- ISO 9000
- Quality function deployment

Total Quality Management (TQM) is a new way of doing business. Ail employees must understand these principles so they can also understand the organization goals and help achieve them.

Computer networks consist of both local area networks and global information networks. Local area networks allow users to share information between interconnected personal computers within an organization. On the other hand, global information networks allow users to share information between different computer systems separated by thousands of miles.

ISO stands for International Organization for Standards. The ISO 9000 series is a standardized quality system. It is expected that the standard will become a de facto requirement in the United States. The standard requires the quality system to be in place for a number of elements, such as management responsibility, contract review design control, document control, purchasing, process control, inspection, and test, non-conforming product, corrective action, and statistical techniques.

Quality function deployment (QFD) relates customer requirements or expectations with engineering characteristics and production processes. It is a means to translate the voice of the customer into design parameters that can be deployed horizontally through product planning, design, engineering, production, assembly, and field service. Results of QFD are measured based on the number of design and engineering changes, time to market, cost, and quality. Thus, QFD is considered by many experts to be a perfect blueprint for CE.

Product Development Tools

Concurrent engineering tools that decrease the time required for product development from initial conceptual designs to first prototypes and eventual production utilize high-powered software programs and the latest in desktop computers. The primary CE tools for product development are

- Computer-aided drafting software
- Solid modeling software
- Finite element analysis software
- Rapid prototyping techniques
- Design for manufacture and assembly techniques

Computer-aided drafting (CAD) software is used by organizations to produce engineering production drawings. These drawings can be done in planar view, isometric, and/or three-dimensional perspectives, with complete dimensioning and tolerancing. The power of CAD allows engineering changes to be easily incorporated into the drawings in a fraction of the time required by the old pencil-and-paper techniques. Another major advantage of the use of CAD is in downstream engineering and production. Drawings from CAD software can be easily incorporated into software packages such as finite element analysis, computer-aided manufacturing, design for manufacture, and CNC machines.

Geometric modeling software is used to create a visual verification of a component or a system of components. By viewing a three-dimensional solid model, problems between part interactions can be easily identified prior to analysis and production. Geometric modeling is often referred to as solid modeling, rendering, and light source shading. Numerous geometric modeling software packages are available; however, the major computer-aided drafting packages are equipped to handle add-on modeling software.

Finite element analysis (FEA) software packages are widely regarded as the most powerful tool available for a design engineer. The scope of finite element techniques encompasses all engineering fields, such as solid mechanics, fluid mechanics, heat transfer, vibrations, and electromagnetics, to name the broadest categories. The advantage of a finite element analysis software package lies in its power to analyze and optimize the response of a system prior to prototype development and testing. This tool can help detect problems early, allowing the CE team to implement alternative changes together and, almost instantly, test the product changes and see the effect on quality and performance.

Rapid prototyping techniques are used to quickly produce a physical "one-piece" model of a component or product. These techniques utilize information from CAD and geometric modeling software to produce exact geometric replicates. Stereolithography, one of the most popular techniques, can produce a plastic model of an engineering design in significantly less time than traditional machining processes. In stereolithography, a three-dimensional model of a part is produced by curing liquid plastic with a laser. It should be noted that rapid prototyping techniques do not produce a model with realistic mechanical characteristics.

Design for manufacture and assembly (DFMA) is a design philosophy that identifies production and assembly problems.

Software programs are being developed to alert engineers of design problems prior to production. Potential problems, such as excessive costs due to part complexity, number of parts, difficult assembly procedures, increased assembly times, and unreasonable or unwarranted tolerances, can be identified, and changes in a design can be made before design effort continues or, more importantly, before full production commences.

Production Tools

Improving the quality of manufactured parts and decreasing the production cycle time requires the use of high-powered software programs integrated with computer controlled machine tools and modern facilities. The primary CE tools for production are

- Computer-aided manufacturing
- Computer numerical controlled tools
- Continuous process improvement
- Just-in-time production

Computer-aided manufacturing (CAM) software is used to identify machine tool paths and other production parameters to optimize the machining of a part. After a part has been completely drawn using a CAD or geometric modeling program, CAM software identifies critical machining parameters based primarily on the part geometry, size, dimensions and tolerances, and material. Critical machining parameters include machine tool feed rates. stock required, bit size, and optimum tool path, to name a few.

Machine tools, such as mills, lathes, and presses, that are completely controlled by a microprocessor are called computer numerical control (CNC) machine tools. Advanced CNC machines and modern facilities also can automate material handling. Specialized computer languages, such as G and M codes, and coordinate locations are used for programming CNC machines. Once a part has been completely drawn using a CAD or geometric modeling program, it can be easily transferred to a CAM program and then machined through an interface between the CAM program and CNC machine. Typically, the operator needs little knowledge of the actual programming languages involved because of user-friendly interfaces between the software packages.

Continuous process improvement (CPI), as it applies to CE, is a systematic year-after-year study to improve the production processes involved in production. Production processes are continuously improved by making them effective, efficient, and adaptable to changes. This process involves eliminating waste and rework, reducing scrap and cycle time, eliminating activities that do not increase product value, and eliminating non-conformities wherever they occur.

Just-in-time (JIT) production is a process-control method and production philosophy that provides parts, components, and assemblies to production at the exact time they are needed. The result of JIT production is less inventory of raw materials, smaller inventories of parts, less work in process, and shorter lead times. Benefits of JIT production are a significant reduction in floor space, less overhead, and, most importantly, a reduction in cost. A possible pitfall of JIT production is a reduction of inventories to critically low levels. Consequently, care must be made in the choice of suppliers with good track records and knowledge of production lead and process times.

Statistical Tools

Quality engineers are the primary users of statistical tools associated with a CE environment; however, all employees should be able to use statistical tools where appropriate. The primary statistical tools that cover all facets of design, testing and production are

- Design of experiments
- Statistical process control

Design of experiments (DOE) is a numerical study that identifies the variables in a process or product that are the critical parameters or cause significant variation in the process. By using formal experimental techniques, the effect of many variables can be studied at one time. Changes to the process or product are introduced in a random fashion or by carefully planned, highly structured experiments. There are three approaches to DOE: classical, Taguchi, and Shainin. The wise practitioner will become familiar with all three approaches and develop his or her own methodology.

Statistical process control (SPC) is the primary TQM tool. It is a charting technique used to monitor process variations and correct problems before producing scrap. Because DOE identifies the critical parameters and their target values, its use should actually precede SPC in most circumstances. It is not unusual to find after an experiment that SPC was controlling the wrong variable or the target was incorrect

Pitfalls of Concurrent Engineering Tools

Note that, by the title of this section, there are no negatives to implementing CE tools. Keep in mind that before any of the aforementioned tools will help in the CE process, employees must have experience--and often expertise--with them. In fact, due to inexperience, these tools will initially lengthen lead times. For example, when a design engineer/drafter is first introduced to computer-aided drafting software, his or her first production drawing could take triple the previous time. However, after proper training and even limited experience, the same drawing could take one-third less time and significantly reduce the time allocated towards future modifications.

Without proper training, many of these tools can be dangerous in the wrong hands. Therefore, it is important to have technical people who are proficient with the tools in the CE group. An organization intending to implement a CE philosophy needs to allocate significant resources toward employee professional development and education. Because of the initial capital investment, the rewards of a CE environment are very rarely realized in the short term. On the positive side, an investment in the CE tools often results in an increase in employee retention and satisfaction.

MISCONCEPTIONS AND PITFALLS

Some organizations claim to have been using CE for quite some time. This may be so, but it is also possible that they have redefined CE to fit their methods rather than changing their present management styles. The following is a list of some of the common misconceptions that need to be understood by those claiming to have used CE.

1. Concurrent engineering is not simultaneous design and production; it encourages just the opposite. Nothing is produced until all designs are agreed upon between all the producers required to fabricate the product.
2. Concurrent engineering is not a quick fix or magical formula for success, it is a way of thinking. The people involved in the CE group must be specialists before they are incorporated in the group. If this technical expertise is not present, little will be gained with CE.
3. Concurrent engineering does not require multiple tests of the product to be conducted until the optimum design is achieved. Concurrent engineering applies a one-pass design, where the product passes testing the first time.
4. Concurrent engineering is often confused with inspection techniques used in TQM. Concurrent engineering is highly dependent upon a TQM environment, but the same inspection methods are not required. Concurrent engineering incorporates repeatability into its products, either automatically or manually. Concurrent engineering considers and applies what was learned about process capabilities in the TQM setting. Thus, products are stringently designed well within process capabilities to facilitate SPC.

With the promise of huge savings, many organizations may see the benefit of CE and invest in massive amounts of technology, hire consultants, tear down walls between departments, and purchase software and hardware, only to be disappointed with the return on their investment. The following is a list of some of the common pitfalls to avoid if an organization is considering implementing CE.

1. Team members should be assigned to functional departments, as in sequential engineering; however, their primary loyalty lies with the CE team. Do not eliminate the sequential engineering process; instead, perform all design up front as a group with improved communication.
2. Avoid promising an unobtainable schedule because missing an unobtainable schedule carries a more severe penalty than meeting a longer one
3. Avoid using tight tolerances and stringent requirements to obtain a one-pass design.
4. Avoid changing product definition and specifications during the design phase. Costs increase exponentially when features are added through the development cycle that cause design, tooling, and production systems to change.
5. Avoid "business as usual" parts vendoring by using the low bidder.
6. Avoid automating the product development phase before it is simplified.

Of course, these are only some of the possible pitfalls, and the manner in which an organization implements CE depends on its size, structure, and product line.

EXAMPLES

There are numerous examples of organizations employing CE techniques in product development and production. The following examples concentrate on some of the larger organizations in the United States; however, there are also small organizations throughout the world benefiting from CE.

1. Chrysler Corporation used a CE approach to bring the Viper model from an auto-show concept car to full production in less than three years with a budget of $50 million. This was accomplished by collocating the team and knocking down walls between design and production to maximize communication and working relationships. Chrysler flattened the vertical hierarchy of the organization into three levels, consisting of team members, team leaders, and a project manager. Experts and outside suppliers were brought in on an as needed basis to help resolve problems before they occurred.
2. For the big three U.S. automakers, implementing CE techniques has increased their profits and helped regain their market share and dominance. For instance, General Motors eliminated 900 parts from the 1995 Chevrolet Lumina compared to the 1994 model and reduced assembly time by 33%. General Motors also expects to reduce the costs of producing a car by $3000 by 1996. At Ford Motor Company, the 1994 Mustang was redesigned in just 35 months using CE. In the new Plymouth Neon, only 300 kinds of fasteners are used, compared to 650 for most vehicles, making the Neon one of the big three's first profitable small cars.
3. General Electric Aerospace applied CE to a ground-based radar system. What normally would have taken six to nine months to design and put into production only took three months equating to a 60% reduction in engineering and testing time.
4. Westinghouse Electronic Systems decreased development lead times from twenty months to nine, a 55% decrease in lead time.
5. Ingersoll-Rand Corporation incorporated CE in a recent product development project. They designed a hand-held air-powered grinder that normally would have taken four years for the total development cycle. It took only one year using CE

These are success stories of organizations that implemented CE properly, but one must keep in mind that many of these organizations had mastered the technical tools needed. They just maximized the use of the technical tools by improving communication at the beginning of the project.

XIII. EXPERIMENTAL DESIGN

INTRODUCTION

Industry has become increasingly aware of the importance of quality. It is being used as a business strategy to increase market share. Organizations are achieving world-class quality by using designed experiments. Experimental design is one of the most powerful techniques for improving quality and increasing productivity. Through experimentation, changes are intentionally introduced into the process or system in order to observe their effect on the performance characteristic or response of the system or process. A statistical approach is the most efficient method for optimizing these changes. An engineer can do investigation without statistics using ad hoc and heuristic approaches. However, an engineer can be much more efficient in his or her investigation if armed with statistical tools.

Any experiment that has the flexibility to make desired changes in the input variables of a process to observe the output response is known as experimental design. Experimental design is a systematic manipulation of a set of variables in which the effect of these manipulations is determined, conclusions are made, and results are implemented. The primary goals of a designed experiment are to

- Determine the variable(s) and their magnitude that influences the response.
- Determine the levels for these variables.
- Determine how to manipulate these variables to control the response.

A good experiment must be efficient. It is not an isolated test but a well-planned investigation that points the way toward understanding the process. Knowledge of the process is essential to obtain the required information and achieve the objective. Resources in the form of money, people, equipment, materials, and, most important, time must be allocated. Efficiency does not mean producing only conforming units. Knowledge is also gained from non-conforming units.

Statistical process control (SPC) methods and experimental design techniques are powerful tools for the improvement and optimization of a process, system, design, etc. SPC assumes that we are controlling the right variable, and have the right target and that the tolerance is correct. In SPC, the process gives information that leads to a useful change in the process --hence the term passive statistical method. On the other hand, experimental design is known as an active statistical method. Information is extracted for process improvement based on tests done on the process, changes made in the input, and observations of the output. Consequently, experimental design should precede SPC except when specifications are given by the customer.

Statistically designed experiments provide a structured plan of attack They are more efficient than one-variable-at-a-time experiments, complement SPC, and force the experimenter to organize thoughts in a logical sequence. Experimental design can be used to

- Improve a process by increasing its performance and eliminate troubles.
- Establish statistical control of a process variable, that is, identify the variables to control the process.
- Improve an existing product or to develop a new product.

The following terminology will be used:

Factor: A variable such as time, temperature, operator, etc., that is changed and results observed.

Level: A value that is assigned to change the factor. For example, two levels for the factor temperature could be 110°C and 150°C.

Treatment condition: The set of conditions (factors and their levels) for a test in an experiment.

Replicate: A repeat of a treatment condition. Requires a change in the setup.

Repetition: Multiple results of a treatment condition.

Randomization: Treatment conditions are run in a chance order to prevent any build up in the results.

Orthogonal array: Simplified method of putting together the treatment conditions so that the design is balanced and factors can be analyzed singly or in combination.

Interaction: Two or more factors that, together, produce a result different than their separate effects.

BASIC STATISTICS

For any group of data, two parameters are of greatest interest, the mean and variance. For a group of data, $X_1, X_2, ..., X_n$, where n is the number of observations in the group, the mean or average is a measure of the central tendency of the group of data; that is,

$$\overline{X} = \tfrac{1}{n}\sum_{i=1}^{n} X_i$$

The variance is a measure of the dispersion about the mean of the group of data; that is,

$$s_X^2 = \frac{\sum_{i=1}^{n}(X_i - \overline{X})^2}{n-1} = \frac{\sum_{i=1}^{n} X_i^2 - \frac{1}{n}(\sum_{i=1}^{n} X_i)^2}{n-1}$$

The standard deviation is often stated as the square root of the variance. The variance is also referred to as the mean square, MS, which is the sum of the squares, SS, divided by the number of degrees of freedom, ν, that is,

$$s_X^2 = MS = \frac{SS}{\nu}$$

The variance consists of n quantities, $(X_i - \overline{X})$, in the numerator; however, there are only n-1 independent quantities, because a sample statistic is used rather than the population parameter. In this case, $\overline{X}$ is used rather than μ. Thus, the number of degrees of freedom, ν, is given by

$$\nu = n - 1$$

As the sample size of a population increases, the variance of the sample approaches the variance of the population; that is,

$$MS = \lim_{n\to\infty} \frac{\sum_{n=1}^{n}(X_i - \overline{X})^2}{n-1} = \frac{\sum_{n=1}^{n}(X_i - \mu)^2}{n}$$

HYPOTHESES

Hypotheses testing is a statistical decision-making process in which inferences are made about the population from a sample. A probability statement is made regarding the population. Thus, hypotheses testing is subject to error. No difference, change, guilt, etc., between the samples is assumed until shown otherwise.

Primarily, hypotheses testing is concerned only with whether or not two samples from identical populations differ--that is, whether or not their respective means differ. Statistical hypotheses are stated in null form as

$$H_0\!:\mu_1 = \mu_2 \ \text{ or } \ H_0\!:\mu_1 - \mu_2 = 0$$

The probability of error is shown in Table 13- 1

Table 13-1 Probability of error for hypothesis testing

Decision	Sample Says	
	Parts Are Different (Reject H_0)	Parts Are the Same (Accept H_0)
Parts are really different (reject H_0)	No error (OK)	Type II (β) error (e.g. 10% or 0.10)
Parts are really the same (accept H_0)	Type I (α) error (e.g. 5% or 0.05)	No error (OK)

A Type I error occurs if the null hypothesis is rejected when, in reality, it is true. Conversely, a Type II error occurs if the null hypothesis is accepted when, in reality, it is false. If either a Type I or II error occurs, alternative hypotheses are stated as

H_1: $\mu_1 \neq \mu_2$ (non-directional, both tails)
H_1: $\mu_1 > \mu_2$ (directional, right tail)
H_1: $\mu_1 < \mu_2$ (directional, left tail)

Alternative hypotheses are quantified by assigning a risk to the relative degree of Type I or II errors. The degree of risk in making a decision can be alternatively stated as the confidence in a decision. Types of decisions, their risk and/or confidence, and the consequences of the decision are generalized in Table 13-2.

Table 13-2 Level of confidence and consequences of a wrong decision

Designation	**Risk (α)**	**Confidence (1-α)**	**Description**
Supercritical	(0.1%)	(99.9%)	More than S100 million (large loss of life, e.g., nuclear disaster)
Critical	(1%)	(99%)	Less than $100 million (a few lives lost)
Important	(5%)	(95%)	Less than $100 thousand (no lives lost, injures occur)
Moderate	(10%)	(90%)	Less than $500 (no injures occur)

When decisions on process or system improvement, product improvement, and new products are needed, the consequences of the decision need to be evaluated and assigned an appropriate risk and/or confidence.

t-TEST

The t-test utilizes the t-distribution to test the hypotheses of a sample from a population when the sample size is small. It compares two averages by separating difference, if there is one, from variance within the groups. Also, it can compare an average for one sample to a population mean or reference value. The t-test assumes that the population is normally distributed, Furthermore, the t-test can be used only when one or two samples are available for testing. For more samples, the F-test is used.

The t-Distribution

Consider a normal random variable with mean, μ, and standard deviation, σ. If a small sample of a response variable ($y_1, y_2,..., y_n$) is taken from this normal distribution, the average, $\bar{y}$, and standard deviation, *s*, of the sample might not be closely related to μ or σ, respectively. The symbol *X* is defined as a control variable and *y* is defined as a response variable with the relationship

$$y = b_1X_1+b_2X_2+\ldots+b_kX_k$$

Thus, when the sample size is small, the random variable

$$T = \frac{\bar{y} - \mu}{s/\sqrt{n}}$$

is governed by a t-probability distribution with ν degrees of freedom, where ν = n - 1. When n is small, the random variable T is not governed by a standard normal distribution; however, as n approaches infinity, the t-distribution approaches a standard normal distribution, as depicted in Figure 13-1. Consider a t-distribution for a random sample with ν degrees of freedom, as shown in Figure 13-2. A value t on the abscissa represents the 100(1-α) percentile of the t distribution, where the critical value a is the area under the curve to the right of t.

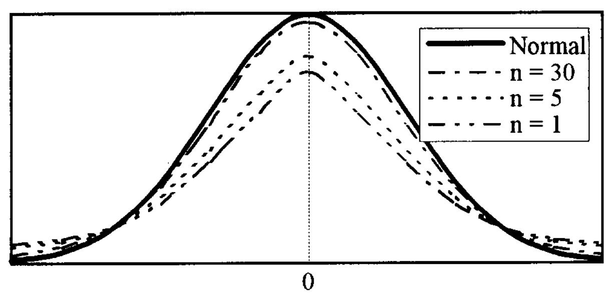


Figure 13-1 Normal and t probability distribution functions

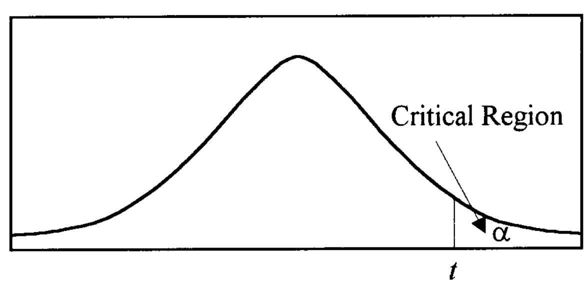


Figure 13-2 Critical region of t-distribution

The value t is often designated by $t_{\alpha,\nu}$ to indicate the critical value and number of degrees freedom associated with the test. This is analogous to the terminology used in the Z test for a normal random variable when the sample size is large.

One-Sample t-Test

The null statistical hypothesis for the one-sample t test is stated as

$$H_0\!:\mu = \mu_0 \ \text{ or } \ H_0\!:\mu - \mu_0 = 0$$

where the test statistic is

$$t = \frac{\bar{y} - \mu_0}{s/\sqrt{n}}$$

If the null statistical hypothesis is false, alternative statistical hypotheses are stated as

H_1: $\mu \neq \mu_0$ (non-directional, both tails)
H_1: $\mu > \mu_0$ (directional, right tail)
H_1: $\mu < \mu_0$ (directional, left tail)

and the corresponding critical regions are given by

$t \geq t_{\alpha/2,\nu}$ or $t \leq -t_{\alpha/2,\nu}$
$t \geq t_{\alpha,\nu}$
$t \leq -t_{\alpha,\nu}$

Values for $t_{\alpha,\nu}$ have been tabulated for various ranges of α and ν.

EXAMPLE PROBLEM

A lawnmower-manufacturing company would like to advertise that their top-of-the-line self-propelled mower can go 250 hours before experiencing starting problems (more than two pulls) and subsequent service. During year-round field tests of 10 identical lawnmowers at a proving ground in a warm climate, the 10 lawnmowers required service after 205, 430, 301, 199, 222, 124, 89, 289, 260, and 214 hours. Based on this data, can the manufacturer make this advertising claim?

$n = 10$, $\nu = n - 1 = 9$, $\mu_0 = 250$

$\bar{y} = 233.3$, $s = 95.64$

$$t = \frac{\bar{y} - \mu_0}{s/\sqrt{n}} = -0.552$$

At levels $\alpha = 0.01, 0.05$, and 0.10, $t_{\alpha,\nu}$ equals 2.821, 1.833, and 1.383, respectively. The manufacturer would like to claim $\mu > 250$, so the alternative hypothesis is $\mu < 250$, and the critical (rejection) region is $t \leq -t_{\alpha,\nu}$. Because $t \geq -t_{\alpha,\nu}$, for all levels, the alternative hypothesis cannot be rejected, and hence the manufacturer cannot make the claim. The primary reason the manufacturer cannot make the claim, after looking at the actual data, is the large spread in the data.

Two-Sample t-Test

Consider two normal random variables with means μ_1 and μ_2 and respective standard deviations σ_1 and σ_2. If a small sample of n_1 random variables ($y_{11}, y_{12}, \ldots, y_{1n_1}$) is taken from the first normal distribution, the mean, $\bar{y}_1$, and standard deviation, s_1, of the sample might not be close to μ_1 or σ_1, respectively. Similarly, if a small sample of n_2 random variables ($y_{21}, y_{22}, \ldots, y_{2n_2}$) is taken from the second normal distribution, the mean, $\bar{y}_2$, and standard deviation, s_2, of the sample might not be close to μ_2 or σ_2, respectively.

The null statistical hypothesis for the two-sample t test is stated as

$$H_0: \mu_1 - \mu_2 = \mu_0$$

where the test statistic is

$$t = \frac{\bar{y}_1 - \bar{y}_2}{s_p\big/\sqrt{1/n_1 + 1/n_2}}$$

where the "pooled" estimator is given by

$$s_p = \sqrt{\frac{\nu_1 s_1^2 + \nu_2 s_2^2}{\nu_1 + \nu_2}}$$

and the degrees of freedom for each sample are

$$\nu_1 = n_1 - 1, \quad \nu_2 = n_2 - 1$$

If the null statistical hypothesis is false, alternative statistical hypotheses are stated as

H_1: $\mu_1 - \mu_2 \neq \mu_0$ (non-directional, both tails)
H_1: $\mu_1 - \mu_2 > \mu_0$ (directional, right tail)
H_1: $\mu_1 - \mu_2 < \mu_0$ (directional, left tail)

and the corresponding critical (rejection) regions are given by

$t \geq t_{\alpha/2,\nu}$ or $t \leq -t_{\alpha/2,\nu}$
$t \geq t_{\alpha,\nu}$
$t \leq -t_{\alpha,\nu}$

where the total degrees of freedom are $\nu = \nu_1 + \nu_2$

EXAMPLE PROBLEM

A study was done to determine the satisfaction with the implementation of a telephone-based class registration system at a small liberal arts college. Twenty undergraduate students were interviewed and asked to rate the current system (sample 1) of seeing an advisor and registering in person. Complaints for the current system included long lines, closed classes, and set hours. The new telephone-based system (sample 2), which is in its infancy, was rated by eight seniors. Complaints for the new system included loss of personal contact, unfamiliarity with the system, and computer down time. The ratings were done on a scale of l to 100, with the following results:

Sample	Data									
1	65	70	92	54	88	83	81	75	40	95
	99	100	64	77	79	81	50	60	95	75
2	55	71	95	88	66	79	83	91		

Based on this data, use $\alpha = 0.05$ to determine whether the college should proceed with implementing the new system.

$n_1 = 20$, $\nu_1 = 19$, $n_2 = 8$, $\nu_2 = 7$, $\nu = 26$

$\bar{y}_1 = 76.15$, $s_1 = 16.78$

$\bar{y}_2 = 78.50$, $s_2 = 13.65$

s_p = 16.00, t = -0.351

At α = 0.05, $t_{\alpha,\nu}$ equals 1.706. The college would like to claim $\mu_2 > \mu_1$ or $\mu_1 - \mu_2 < 0$. The critical (rejection) region is $t \leq -t_{\alpha,\nu}$. Because $t \geq -t_{\alpha,\nu}$ for an α = 0.05 test, the school should not implement the new system.

F-TEST

Completely randomized designs are a very basic type of experimental design. Completely randomized designs involve a single-treatment variable (factor) applied at two or more levels. A random group of subjects are assigned (selected) to different treatment levels. Subjects must be selected from the same population, that is, same process using different levels of one variable of the process.

For a test involving three factor levels, three two-sample t-tests for factor levels 1 and 2, 2 and 3, and 1 and 3 would need to be performed. Therefore, for three t-tests with each α = 0.05, the probability of a correct decision is given by

$$(1-\alpha)(1-\alpha)(1-\alpha)=(1-0.05)(1-0.05)(1-0.05)=0.86$$

when three t-tests are considered. Similarly, for a test involving four factor levels, six t-tests would need to be performed, and the probability of a correct decision is 0.817. Thus, for more than two factors or levels, a more efficient technique is used to compare the means of more than two samples. Comparison between the means of more than two groups is accomplished by the use of the F-distribution and analysis of variance (ANOVA).

The F-Distribution

Consider an F-distribution, as shown in Figure 13-3. Similar to the t-distribution, a value F on the abscissa represents the 100(1 - α) percentile of the F-distribution where the critical value α is the area under the curve to the right of F. In a terminology similar to the t-test the critical value for F is designated by F_{α,ν_1,ν_2}, where α, ν_1, and ν_2 are the risk, degrees of freedom for the numerator, and degrees of freedom for the denominator, respectively. For simplicity, the mathematical expression for the F-distribution function is not stated here.

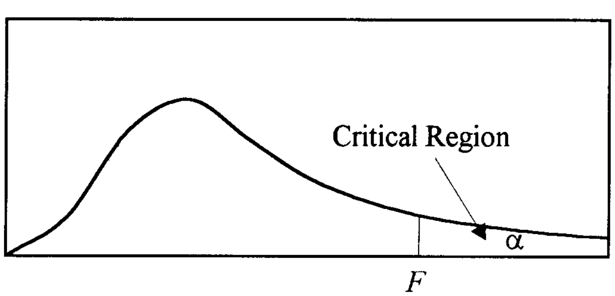


Figure 13-3 Critical region of F-distribution

Analysis of Variance

The observations of an experiment with more than two factor levels are tabulated as shown in Table 13-3. For completeness in the formulation that follows, the number of observations are different at each factor level.

Table 13-3 Data for factor level experimental design

Factor Level	Data			
1	y_{11}	y_{12}	…..	y_{1n1}
2	y_{21}~	y_{22}	…..	Y_{2n2}
.	..	..	…..	..
.	..	..	…..	..
a	y_{a1}	y_{a2}	…..	y_{ana}

In general, the samples selected are known as the levels, the specimens in each level are known as observations, or replicates, and the number of variables under study at a time is the number of factors. For the data in Table 13-3, there is only one level for each factor--thus, the term factor level in the table. The observations of an experiment can be written in a mathematical model as

$$y_{ij} = \mu + f_i + \varepsilon_{ij}$$

where y_{ij} = jth observation at the ith factor level (i = 1,..., *a*, j = 1,..., n_i)
μ = mean value for all of the observations
f_i = difference due to treatment (factor effect) at each factor level (i = 1, ., *a*)
ε_{ij} = error or noise within factor levels (i = 1,…, *a*, j=1,…, n_i)
a = number of factor levels
n_i = number of observation at each factor level (i = 1,..,*a*)

In general, the observations of the experiments are assumed to be normally and independently distributed with the same variance in each factor level. Thus, the sum of the factor effects f_i can be defined as

$$\sum_{i=1}^{a} f_i = 0$$

From the preceding equation, the null statistical hypotheses for the F-test is stated as

$$H_0: f_1 = f_2 = \cdots = f_a = 0$$

If this hypothesis is false, an alternative hypothesis is stated as

$$H_1: f_i \neq 0 \text{ for at least one } i$$

Testing for the validity of the hypotheses is known as analysis of variance (ANOVA). The total variability in the data is given as

$$\sum_{i=1}^{a}\sum_{j=1}^{n_i}(y_{ij} - \frac{T}{N})^2 = \sum_{i=1}^{a}\sum_{j=1}^{n_i}[(y_{ij} - \frac{A_i}{n_i}) + (\frac{A_i}{n_i} - \frac{T}{N})]^2$$

where the total number of observations, total of the observations under the *i*th factor level, and total of the observations under all factor levels are given by

$$N = \sum_{i=1}^{a} n_i; \quad A_i = \sum_{j=1}^{n_i} y_{ij}; \quad T = \sum_{i=1}^{a} A_i$$

respectively. After expanding the square in the relationship for the total variability and simplifying the equation, the total variability in the data can be expressed as

$$SS_T = SS_F + SS_E$$

where the total sum of squares, sum of squares due to the factor, and sum of squares due to the error are given by

$$SS_T = \sum_{i=1}^{a}\sum_{j=1}^{n_i} y_{ij}^2 - \frac{T^2}{N}$$

$$SS_F = \sum_{i=1}^{a} \frac{A_i^2}{n_i} - \frac{T^2}{N}$$

$$SS_E = SS_T - SS_F$$

respectively. If there is a large difference among the means at different factor levels, SS_F will be large. The variability due to changing factor levels and error can be obtained by comparing the magnitude of SS_F and SS_E. To facilitate this, the mean squares of the factor and error are calculated by normalizing the sum of squares by their respective number of degrees of freedom, that is,

$$MS_F = \frac{SS_F}{\nu_F}; \quad MS_E = \frac{SS_E}{\nu_E}$$

where the degrees of freedom for the factor and error are given by

$$\nu_F = a - 1; \quad \nu_E = N - a$$

respectively. Analysis of variance is a technique to determine significant factors based on the F-test that is used to compare ratio of factor variance with error variance; that is,

$$F = \frac{MS_F}{MS_E}$$

If $F > F_{\alpha,\nu_1,\nu_2}$, where $\nu_1 = \nu_F$ and $\nu_2 = \nu_E$, it can be said that the factor-level means are different for a level a test. Results of the F-test for a one-factor experiment can be nicely depicted using a format similar to Table 13-4.

Table 13-4 Results for one-factor experimental design

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	F_{α,ν_1,ν_2}	Significant (yes/no)
Factor	SS_F	ν_F	MS_F	F	F_{α,ν_F,ν_E}	
Error	SS_E	ν_E	MS_E			
Total	SS_T					

EXAMPLE PROBLEM

Consider the following data for four levels of a factor.

Level	Data					Total (A)	$\bar{y}$	s^2
1	26	25	32	29	30	142	28.4	8.30
2	34	31	26			91	30.3	16.33
3	15	16	25	18	13	87	17.4	21.30
4	12	15	13	11		51	12.8	2.92

Based on these data, use $\alpha = 0.05$ to determine if there is any significant difference in the data.

$a = 4, n_1 = 5, n_2 = 3, n_3 = 5, n_4 = 4$
$N = n_1 + n_2 + n_3 + n_4 = 17$
$\nu_F = a - 1 = 3,\ \nu_E = N - a = 13$
$A_1 = 142, A_2 = 91, A_3 = 87, A_4 = 51$
$T = 371$

$$SS_T = \sum_{i=1}^{a}\sum_{j=1}^{n_i} y_{ij}^2 - \frac{T^2}{N} = 9117 - \frac{371^2}{17} = 1020.50$$

$$SS_F = \sum_{i=1}^{a} \frac{A_i^2}{n_i} - \frac{T^2}{N} = \frac{142^2}{5} + \frac{91^2}{3} + \frac{87^2}{5} + \frac{51^2}{4} - \frac{371^2}{17} = 860.65$$

$SS_E = SS_T - SS_F = 159.85$

$$MS_F = \frac{SS_F}{\nu_F} = \frac{860.65}{3} = 286.88; \quad MS_E = \frac{SS_E}{\nu_E} = \frac{159.85}{13} = 12.30$$

$$F = \frac{MS_F}{MS_E} = 23.33$$

At $\alpha = 0.05$, with $\nu_1 = \nu_F$ and $\nu_2 = \nu_E$, F_{α,ν_1,ν_2} equals 3.41.

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	F_{α,ν_1,ν_2}	Significant (yes/no)
Factor	*860.65*	3	*286.88*	*23.33*	3.41	Yes
Error	*159.85*	13	*12.30*			
Total	*1020.50*					

Because $F > F_{\alpha,\nu_1,\nu_2}$, it can be stated that the factor-level means are different.

ONE FACTOR AT A TIME

Consider an experimental design with N_F factors with two levels for each factor, as shown in Table 13-5. At treatment condition 1, all the factors are run at level 1 to obtain the benchmark or reference value. The next treatment condition is to run factor *A* at level 2 while the other factors are kept at level 1. For the third treatment condition, factor *B* is run at level 2 while the other factors are kept at level 1. This sequence is continued until all factors are run at level 2 while holding the other factors at level 1.

Table 13-5 Effects and data for a one-factor-at-a-time experimental design

Treatment Condition	Factors/Levels						Response (Results)
	A	B	C	D	…	NF	
1	1	1	1	1	…	1	y_0
2	2	1	1	1	…	1	y_A
3	1	2	1	1	…	1	y_B
4	1	1	2	1	…	1	y_C
5	1	1	1	2	…	1	y_D
…	…	…	…	…	…	…	…
n_{TC}	1	1	1	1	…	2	y_{NF}

The change in response due to a change in the level of the factor is known as the effect of a factor. The main effect of a factor is defined as the difference between the average response between the two levels. In order to determine the effect of each factor, the responses at level 2 are compared to the reference value (level l); that is,

$$e_A = y_A - y_0; \quad e_B = y_B - y_0; \quad e_C = y_C - y_0;$$

and so on for each factor. In this manner, the factors that have a strong effect on the response can be easily determined. In addition, the sign of the effect indicates whether an increase in a factor level increases the response, and vice versa.

As can be seen, this type of experimental design varies one factor at a time and evaluates its effect. To understand this concept, it is necessary to look at an example of a one-factor-at-a-time experiment that is neither balanced nor efficient.

EXAMPLE PROBLEM

An experiment involves maximizing a response variable. Three factors (speed, pressure, and time) are compared at two levels. The factors and levels are given in the following table.

Factors	Level 1	Level 2
Speed (m/s)	25	35
Pressure (Pa)	50	75
Time (min)	5	10

At treatment condition 1, all the factors are run at level 1 to obtain the benchmark value. The table below shows the results for a one-factor-at-a-time experimental design. The next treatment condition is to run speed at level 2 while pressure and time are kept at level 1. For the third treatment condition, pressure is run at level 2 while speed and time are kept at level 1. Similarly, treatment condition 4 is run with time at level 2, while speed and pressure are run at level 1.

Treatment Condition	Speed	Factors/levels Pressure	Time	Response (Results)
1	1 (25 m/s)	1 (50Pa)	1 (5 min)	2.8
2	2 (35 m/s)	1 (50Pa)	1 (5 min)	3 4
3	1 (25 m/s)	2 (75 Pa)	1 (5 min)	4.6
4	1 (25 m/s)	1 (50 Pa)	2 (10 min)	3.7

The effects of speed, pressure and time are:

$$e_S = 0.6; e_P = 1.8; e_T = 0.9$$

It appears that pressure, time, and perhaps speed have a strong positive effect on the process. In other words, increasing any of the factors increases the response.

ORTHOGONAL DESIGN

Orthogonality means that the experimental design is balanced. A balanced experiment leads to a more efficient one. Table 13-6 shows an orthogonal experimental design for three factors with two levels each.

Although there are more treatment conditions, the design is balanced and efficient. Treatment conditions 1, 2, 3, and 5 are the same as treatment conditions 1, 2, 3, and 4 for the one-factor-at-a-time experiment in the previous section. A review of this particular design shows that there are four level 1s and four level 2s in each column. Although different designs have a different number of columns, rows, and levels, there will be an equal number of occurrences for each level. The idea of balance produces statistically independent results. Looking at the relationship between one column and another, we find that for each level within one column, each level in any other column will occur an equal number of times. Therefore, the four level 1s for factor *A* have two level 1s and two level 2s for factor *B*, and two level 1s and two level 2s for factor *C*. The effect of factor *A* at each level is statistically independent, because the effects of factor *B* and factor *C* for each level are averaged into both levels of the factor *A*. Statistical independence is also true for factor *B* and factor *C*.

Table 13 6 Effects & data for an orthogonal experimental design

Treatment Condition	Factors/Levels A	B	C	Response (Results)
1	1	1	1	y_{111}
2	2	1	1	y_{211}
3	1	2	1	y_{121}
4	2	2	1	y_{221}
5	1	1	2	y_{112}
6	2	1	2	y_{212}
7	1	2	2	y_{122}
8	2	2	2	y_{222}

In order to obtain the main effects of each factor/level, the results need to be averaged. The average of the response for factor *A* due to level *i* (*i* = 1, 2) is given by

$$\overline{A}_i = \frac{1}{2^{N_F - 1}} \sum y_{ijk\ldots m}$$

Similarly, the average of the response for factor *B* due to level *j* (*j* = 1, 2) is

$$\overline{B}_j = \frac{1}{2^{N_F - 1}} \sum y_{ijk\ldots m}$$

and so on for all the factors. While the number of treatment conditions increased by a factor of two, the number of values that were used to calculate the factor/level average increased by a factor of four. This improvement in the number of values used to determine the average makes the orthogonal design very efficient in addition to balanced. The main effects of factors *A* and *B* are then given by

$$e_A = \overline{A}_2 - \overline{A}_1; \quad e_B = \overline{B}_2 - \overline{B}_1$$

and so on for all the factors

EXAMPLE PROBLEM

The following table shows an orthogonal experimental design for the same experiment given in the previous section for a one-factor-at-a-time experimental design.

Treatment		Factors/levels		Response

Condition	Speed	Pressure	Time	(Results)
1	1 (25 m/s)	1 (50Pa)	1 (5 min)	2.8
2	2 (35 m/s)	1 (50Pa)	1 (5 min)	3 4
3	1 (25 m/s)	2 (75 Pa)	1 (5 min)	4.6
4	2 (35 m/s)	2 (75 Pa)	1 (5 min)	3.8
5	1 (25 m/s)	1 (50Pa)	2 (10 min)	3.7
6	2 (35 m/s)	1 (50Pa)	2 (10 min)	2.7
7	1 (25 m/s)	2 (75 Pa)	2 (10 min)	3.1
8	2 (35 m/s)	2 (75 Pa)	2 (10 min)	4.4

The average of the response for the factors due to each level *i* is:

$$\begin{aligned}
\overline{S}_1 &= \tfrac{1}{4}(2.8+4.6+3.7+3.1) = 3.550\\
\overline{S}_2 &= \tfrac{1}{4}(3.4+3.8+2.7+4.4) = 3.575\\
\overline{P}_1 &= \tfrac{1}{4}(2.8+3.4+3.7+2.7) = 3.150\\
\overline{P}_2 &= \tfrac{1}{4}(4.6+3.8+3.1+4.4) = 3.975\\
\overline{T}_1 &= \tfrac{1}{4}(2.8+3.4+4.6+3.8) = 3.650\\
\overline{T}_2 &= \tfrac{1}{4}(3.7+2.7+3.1+4.4) = 3.475
\end{aligned}$$

The main effects of speed, pressure, and time are then given by

$$\begin{aligned}
e_S &= \overline{S}_2 - \overline{S}_1 = 0.025\\
e_P &= \overline{P}_2 - \overline{P}_1 = 0.825\\
e_T &= \overline{T}_2 - \overline{T}_1 = -0.175
\end{aligned}$$

Based on these calculations, an increase in pressure (level 1 to level 2) has a strong effect on the process, whereas the small effects of speed and time are most likely due to the natural variation in the process. Clearly, this information is better than that obtained from the one-factor-at-a-time approach.

POINT AND INTERVAL ESTIMATE

In any statistical study one of the objectives is to determine the value of a parameter or factor. Analysis and calculations yield a single point or value which is called a point estimate. The true value is usually unknown; therefore, an interval estimate is needed to convey the degree of accuracy. It is the range or band within which the parameter is presumed to fall and is

$$CI = \overline{y} \pm t_{\alpha/2}\sqrt{s^2/n}$$

where CI= confidence interval.

EXAMPLE PROBLEM

Data for 24 observations has an average of 25.2 mm and a variance of 2.6 mm^2. Determine the interval that the point estimate lies within with 95% confidence.

From the t-table for 23 degrees of freedom and $\alpha/2 = 0.025$, the $t_{\alpha/2}$ value is 2.069. The confidence interval is

$$CI = \overline{y} \pm t_{\alpha/2}\sqrt{s^2/n} = 25.2 \pm 2.069\sqrt{2.6/24} = 24.5 \text{ to } 25.9 \text{ mm}$$

CONCLUSION

In order for experimental design to be a powerful and useful technique, careful attention must be given to the following considerations:

- Selection of factors and number of factors
- Selection of the value for the levels of each factor and number of levels
- Selection of the response variable

When performing the actual experiment, scientific procedures should be followed to ensure the validity of the results. Once the experiment has been performed, the statistical methods presented in this chapter should be implemented to arrive at conclusion that are objective rather than subjective.