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Design and Problem Solving Guidelines

Engineering design involves management of people, resources, money, and time. Success depends on planning, resource, and time management. Time is usually the driver.

When discussing the importance of teaming with one company, the response was, “teaming isn’t important – it is everything.” The very success of a company depends upon people skills and the ability to work with others as a team member. Pete Carroll, while head football coach at the University of Southern California, says, “Winning players don’t always win. It’s the winning plays that win.”

Planning is a matter of thinking through the activities and tasks that will be necessary to achieve the stated goal. This is somewhat experience dependent. For large projects, it may be useful to divide tasks into major activities, such as design, fabrication, installation, and commission, which are usually conducted in tandem. In other projects, where several activities are conducted simultaneously, major groupings may be needed. An example would be a military operation involving various branches.

General Dwight Eisenhower, along with his staff, spent months developing a plan for the invasion of Europe. His team of officers generated and evaluated various plans of attack. Eisenhower once said “... the plan itself is not as important as the act of planning.” Thinking through the plan is the key.

Plans need to be flexible. As new information is gathered along the way, the plan may need to be modified. A good manager anticipates problems and deals with them early to avoid crises. A crisis is a situation where a critical problem needs to be solved, but there is little time to solve it. A Gantt chart can be useful in this regard.

Design Methodology

Basic steps for developing a product idea (or service) into a profitable venture are given in Figure 1.1. The first few boxes indicate the importance of a preliminary market analysis and input from customers to determine market reaction to a new product. Also, a preliminary market analysis helps define and refine the attributes of the product. Initial feedback from customers is useful in deciding whether to proceed with further development.

Design specifications are based on specific needs and expected performance. Design specifications represent the initial *engineering baseline* for generating design alternatives. In most cases, design specifications are legal statements of what is expected. They must be established accurately and in concert with users of the future product.

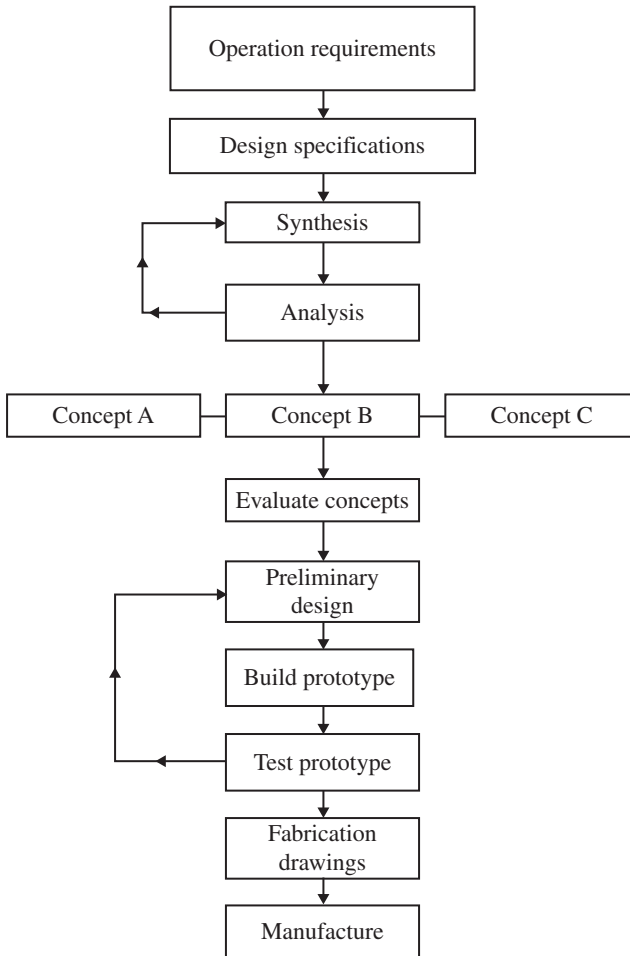


Figure 1.1 Design development process.

Design alternatives are typically generated by a team of professionals with special skills, such as marketing, design, and manufacturing. This activity is sometimes called concurrent engineering where the team considers every aspect of the product from technical feasibility to product life cycle to manufacturing and marketing strategy. Feedback from potential customers is important. The team also evaluates each design alternative and selects the best concept to advance. Depending on the complexity of the concept, technical feasibility studies, requiring advanced computational techniques, may be required during the refinements of design alternatives.

Since design is open ended, there are many possible solutions or design alternatives that satisfy a given set of specifications. Once viable designs have been generated, they need to be ranked so choice can be made. Choosing a preferred concept is based on trade-offs among evaluation metrics identified for a given product; an evaluation method will be described later.

A preliminary design represents an update of the engineering baseline. The preliminary design refines the preferred alternative. It advances the engineering baseline for the final design and fabrication phases.

Developing a final design may require the use of computer-aided-design (CAD), numerical analysis, and other analytical tools to refine dimensions. Prototype testing may also be desirable. Computer simulations may alleviate the high cost of prototype testing.

The product configuration is again evaluated in the marketplace for customer feedback and approval. This is accomplished through market surveys or market focus groups depending on the nature of the product.

The next step is to interface CAD codes with manufacturing (CAM). This requires converting design codes into machine tool codes. Depending on the product and the market, the ability to reconfigure the machining and handling process in a timely manner may be important for “just in time” delivery.

Market Analysis

The purpose of a market analysis is to identify what potential customers want in a new product, establish the size of the market, and determine what price the market is willing to pay for the product. A market analysis will produce a set of product attributes, which more clearly define the main features of the planned product. Using customer input and competitor product features, important features for the new product can be identified and ranked as to their importance. This information identifies customer preferences and competitive differentiation during the conceptual stage of product development.

New products can be either research driven, or market driven. Research-driven products stem from ideas that spawn from basic or fundamental research. In this case, a new technique or device may be the objective or a by-product of the study. The technique or device then becomes a solution looking for a problem, so to speak. The market-driven product is developed in response to a definite market need. In some cases, a market may be developed for a new idea.

Before investing much time and money, it is best to conduct a patent search to make sure the product does not infringe on active patents. This exercise will also give useful information on the state-of-the-art of products as applied to a given market. It may show the patent protection period on a product has expired, offering the opportunity to enter the market with a competitor’s product – with improvements.

In recent years, markets have become more demanding on product delivery. Customer needs may change over a short period. Companies that can retool for “just in time manufacturing” in response to this demand have an advantage. One tool company, that makes diamond drill bits for oil and gas well drilling, built its business on making diamond drill bits overnight; each diamond was handset. Each diamond bit was and still is tailored to suit a set of design specifications stipulated by an oil company. The main reason for a quick response capability (or “just in time manufacturing”) is moderate demand for high cost of diamond drill bits. It is not good business to stockpile high-cost products for a limited market application. Warehoused products may become outdated. It is costly and risky.

Operational Requirements

Operational requirements or product attributes describe the expected functional performance of a new product. Product description may come out of a business plan for a new product concept, a government need for a new weapon, or an oil company’s need to develop an oil field in a given geographic location.

Product Development

Top management may define the operational requirements for a product, based on a market analysis. Company engineers then develop a set of design specifications before proceeding. Product design may be conducted within a company or contracted outside.

Government Procurement Procedure

The federal government has very strict guidelines for procuring products and services [1]. Government procurement is normally through the General Service Administration (GSA). The need for a product may come to the GSA from any government agency, which in turn coordinates the Federal Product Description (FPD). An FPD describes the operational requirements and required functions.

For example, assume that the Joint Chief of Staff decides that the military needs a new type of aircraft. They would make their request to the GSA and describe the aircraft in terms of expected operational requirement, such as:

- Range
- Speed
- Landing capabilities
- Weapon weight
- Weather considerations.

The GSA would expand the requesting agency's description of operational requirements.

Effective market research and analysis must be conducted to assure that user need is satisfied. During the market research and analysis phase, the preparing activity should advise potential agency users that a FPD is being developed. Ask potential users to provide a statement of their needs in essential functional or performance terms to the maximum practical extent.

In addition to a clear description of operational requirements, FPDs will also develop a comprehensive list of design specifications for a new product. The tender document would be reviewed at various levels with GSA before it is released to contract bidders.

Petroleum Industry Procedure

An economic analysis is conducted on each new oil reservoir to determine its profitability and the best way to develop it. Following this, operational requirements are set before proceeding. Operational requirements may include such factors as

- Ocean water depth
- Size of reservoir
- Oil, gas, water content of reservoir
- Reservoir pressure
- Production rate (barrels per day).

Design specifications would document detailed engineering constraints on the design, such as environmental conditions, ocean floor mud line load-bearing capabilities, material specifications, expected loads, 100-year storm conditions, etc.

Considerable time is spent in gathering this information to establish operational requirements and design specifications. Company engineers build a set of design specifications to form a “tender document” for contractor bid preparation.

There are two contract approaches: turnkey and cost plus. Turnkey simply means that the contractor will deliver a product at a fixed price. The contractor is responsible for every detail, including identifying and satisfying all codes and standards relevant to the design. Since the price is fixed, oil companies would be concerned about delivery dates. Missing the planned delivery date could greatly increase future monetary returns and profit.

A cost plus is based on an agreed hourly rate. The equipment and supplies are additional costs to the buyer. Usually there is a percentage tacked on to these costs. Company representatives are directly involved in day-to-day decisions.

Design Specifications

Design specifications are an itemized set of constraints placed on a design. They identify product performance expectations: what the product is supposed to do and how the product should perform. They are contractual and represent the initial “engineering baseline” from which all concepts are generated. They are an important part of a contract between customer and designer. Usually, the customer signs-off on a set of specifications once they have been documented. Any changes, for any reason, after the development work starts, will cause delays, and increase costs. The cost of making changes is usually written into a contract.

Once operational requirements have been set, design specifications are documented. They may be expanded by outside contractors in conjunction with company engineers. The contract usually puts the burden of completeness on the contractor, such as all relevant Codes and Standards are the responsibility of the design contractor.

Specification Topics

Design specifications are usually subdivided into key topics. Topics normally considered are discussed below.

Performance Requirements

Performance requirements identify specifics, such as loads, motions, flow rates, operating pressures, and temperature limits, to name a few. In addition, the technical specifications may include physical and chemical properties of materials to be used. Material properties may include such items as yield strength and hardness. Weld procedures (including preheating) and welder qualification requirements, special heat treatment and annealing may be specified.

Environmental and climate conditions may affect design. Examples are wind, oceanographic conditions, such as wave height, wind-driven current velocities, and tidal currents.

Performance requirements define the physical constraints in the design. Depending upon the size of the project, the specification document can be as small as a few pages or several volumes.

Sustainability

Sustainability means being good stewards of the resources on planet earth. A 1987 UN report defines sustainable development as: “Meeting the needs of the present without compromising the ability of future generations to meet their own needs.” This specification is relevant, ethical,

and makes good economic sense. Earlier business strategies were based on planned obsolescence, where products were intentionally designed to wear out after a given period [2].

A few metrics relating to sustainability are:

- a) design efficiency in terms of materials, weight, cost, energy consumption
- b) quantity and type of waste from fabrication
- c) minimal friction, wear, maintenance, reliability
- d) use of renewable energy sources, such as wind and solar
- e) environmental impact of a possible failure
- f) environmental recovery plan in case of an unexpected failure/disaster
- g) design for modular replacement instead of product throw-away
- h) disposal at end-of-life cycle (computers, TVs)
- i) automation verses human control (cause of many disasters)
- j) redundancy in monitoring system performance.

Codes and Standards

During the midst of the industrial revolution of the nineteenth century, it became apparent that mechanical components needed to be standardized to assure, for example, bolts made in one place could fit together with nuts made in another place. The American Society of Mechanical Engineers (ASME) took a leading role in standardizing mechanical components, such as pulleys, gears, and key seats. Even shop drawing symbols needed to be standardized.

During the early days of the steam engine, it was common for steam boilers to explode causing personal injury and death. In 1884, the ASME established a uniform test standard for boilers; this was ASME's first standard. This standard was followed by a boiler construction standard, which was published in 1915. Such standards became the foundation of ASME's current Boiler and Pressure Vessel Code. Since the development of this Code, boiler disasters have been essentially eliminated.

What is a Code? A code is a standard that has been mandated by one or more government bodies. A code has the force of law behind it. When a standard is specified in a business contract, it becomes a code, as well. Therefore, the words, codes, and standards, are sometimes used interchangeably.

What is a Standard? Standards are a set of technical definitions and guidelines or a set of instructions for designers and manufacturers. Their use is strictly voluntary, and they do not have the force of law. Standards serve as a vehicle of communications, defining quality, and establishing safety criteria for producers and users.

Many professional organizations develop Standards; however, they must follow procedures accredited by the American National Standards Institute (ANSI). These procedures must reflect openness, transparency, balance of interest, and due process.

Many turnkey contracts make the contractor or design company responsible for applying all relevant codes and standards to a design. While specific codes and standards are not listed in a tender document, they are implied through legal contracts.

Environmental

Designers should consider the environmental impact of a new product throughout the product's life cycle, i.e. from fabrication to product disposal. Even in the early stages of offshore platform design, disposal of a structure at the end of production life (about 20–30 years) is considered.

The most vulnerable or highest risk components in the design should be identified and environmental consequences associated with possible failure considered. The designer needs to consider the “what if” scenarios. If a failure occurs, how would it affect public health, public safety, public image of company, property damage, as well as damage to the environment. Goodwill is an asset on the balance sheet of any company.

Social Considerations

People, who will be affected by the implementation or use of a given product or project, should be consulted and brought into design deliberations as early as possible – the sooner the better. This is not only right but, by doing so, misunderstanding is alleviated, and public resistance will be reduced as the project develops. People simply want to be consulted and given the opportunity to make input on issues that affect their lives. If not given this opportunity, citizens may unite and work against a worthwhile project.

Aside from human reaction, there are legitimate reasons for considering social factors in design, such as safety and preservation of a culture. When oil companies began to develop oil fields in the northern part of the North Sea, oil transportation from the offshore platforms had to be resolved. Crude oil could be off-loaded directly onto tankers or transported to land by a pipeline and then loaded onto tankers in a protected harbor for transport to refineries. The closest land point from the platforms was to the small fishing village of Solom Voe, Shetland Islands. An extensive study was conducted to design a port that would not destroy centuries-old lifestyle of the people living in this area. There were also benefits to local economies.

Reliability

There are two methods of design which relate to the safety and reliability of products: (i) factor of safety and (ii) statistical or reliability.

The factor of safety method is commonly used in engineering design. It is a time-proven design tool and when used properly, safe and reliable designs are developed. Factor of safety (FS) is the ratio of failure stress to an allowable design stress.

Material yield strength, σ_{yld} , is often used as the failure stress. In this case

$$FS = \frac{\sigma_{yld}}{\sigma_{allowable}} = \frac{\sigma_{yld}}{\sigma_a} \quad (1.1)$$

where σ_a is the allowable stress level used throughout a design. When the factor of safety is given, then

$$\sigma_a = \frac{\sigma_{yld}}{FS} \quad (1.2)$$

Designs are configured (size, dimension) according to the allowable stress.

Factors of safety are intended to cover all uncertainties not identified in a set of specifications. In general, the higher the factor of safety, the higher the product weight and cost. So, it is important to keep the FS as low as possible. Computation accuracy affects factor of safety too. Computer software based on numerical techniques, such as finite element methods, provide very accurate

predictions of local stress in complex geometries, and thus reduce the uncertainty of stress predictions.

The statistical or reliability approach seeks to establish design parameters so that the product performs to an expected level of reliability [3]. Reliability is a statistical measure of performance. For example, a product reliability of 0.9 means that there is a 90% chance that a given product will perform its proper function without failure. The method requires statistical data on all random variables, such as strength, size, and weight. With this approach, products can be designed to a required level of reliability.

Cost Considerations

Economics should be considered during the early stages of concept generation. Concepts that allow for early return on investments may be critical. Oil companies want to begin oil production as early as possible, maybe prior to the completion of the overall production system. Time is money and if it takes three years to bring a reservoir online that's three years without return on investment if early production is not achieved.

Aesthetics

Product appearance is not usually a concern of engineers. However, aesthetics could be an important marketing feature and should not be overlooked. *Actual* performance capabilities versus *perceived* performance capabilities can be important. The customer may perceive a feature to be weak or strong depending on the history of a product. Perception of certain product features should be considered in some cases.

Aesthetics does not mean that a design must be ornamental or that geometry controls the shape of the design or its components. Manufacturing complex geometries is impractical and costly. However, if a design is balanced (cost effective and functional), it is usually artful.

Product Life Cycle

Every product has a life cycle, which includes periods of:

- 1) Development
- 2) Market growth
- 3) Market maturity
- 4) Market decline
- 5) Product disposal

During the first phase, the product is developed and introduced to the market. This creates negative cash flow, so developing the product in a timely and cost-efficient manner is important. During the second phase, the product finds its way into the market and can generate cash flow while establishing itself in the marketplace. Products then reach a level of maturity and are usually able to capture a portion of the market and generate revenue. During this time, the product generates maximum return on investment. At some point in time, the market for a product declines and eventually vanishes. This could be the result of new products entering the market or simply the lack of demand for a product. For these reasons, investors look for new products.

In setting design specifications, remember *cost* and *safety* override everything.

Product Safety and Liability

Currently, there are no federal product liability laws. Each state has developed its own legal approach in this area. Under Tennessee's product liability laws, there are four theories of recovery [4, 5]:

Negligence – In legal terms, negligence is the failure to do what people of ordinary care and prudence would do under the same or similar circumstances. When applied to design and manufacturing, the question becomes: are decisions, that affect product safety, being made professionally, objectively, and fairly? Prior to 1970, many personal injury claims were filed under the negligence theory of law. The plaintiff's attorney had to establish the standard of due care required of engineers and manufacturers.

Strict liability – The emphasis under this theory of recovery is on product defect and not on the person or person's negligence. The focus of the court is solely on the performance of the product. In this case, the plaintiff needs to only prove that the product had an unreasonable dangerous defect when it left manufacturing. The court recognizes three types of defects: manufacturing defects, design defects, and warning defects. Design as used by the courts encompasses the entire process by which a product is created and marketed. This theory is more favorable to the plaintiff because it exposes the entire product development chain to liability, allowing the plaintiff to choose the most advantageous defendant.

Fraud/misrepresentation – Fraud is a false representation of fact, by words, or conduct, which is intended to and does deceive another, who then makes decisions based on the false information and suffers legal injury. The elements required in an action of law are representation, falsity, knowledge of falsity, intent to deceive the plaintiff, justifiable reliance by the plaintiff, and damages. Examples are falsifying test data to deliver a product to the customer to meet a deadline, approving a design that does not meet required codes to eliminate redesign and fabrication costs and misuse of Professional Registration approval.

Breach of warranty – Product does not satisfy the expressed warranty or implied warranty for fitness.

Engineering Ethics

Ethics deals with the principles of human duty, moral principles, and rules of conduct. Engineering ethics deals with the moral conduct of engineers in serving the public, their employers, and their clients. What is at stake can be expressed in terms of public safety, public health, and the environment to mention a few. The challenge is to design and manufacture a product for profit without undue risk to the general welfare of the public and environment. Ethics comes into play when a company and its professional staff knowingly produce a product that has a high risk for personal injury and/or damage to the environment. Unethical decisions are usually made for selfish or monetary reasons.

Engineers make many ethical decisions independent of others. A good check list for these decisions is:

- Is it legal?
- Is it fair?
- Is it morally right; can I live with the outcome?

The ASME has adopted the following Code of Ethics of Engineers for its members¹

- 1) Engineers shall hold paramount the safety, health and welfare of the public in the performance of their professional duties.
- 2) Engineers shall perform services only in the areas of their competence.
- 3) Engineers shall continue their professional development throughout their careers and shall provide opportunities for the professional and ethical development of those engineers under their supervision.
- 4) Engineers shall act in professional matters for each employer or client as faithful agents or trustees and shall avoid conflicts of interest or the appearance of conflicts of interest.
- 5) Engineers shall build their professional reputation on the merit of their services and shall not compete unfairly with others.
- 6) Engineers shall associate only with reputable persons or organizations.
- 7) Engineers shall issue public statements only in an objective and truthful manner.
- 8) Engineers shall consider environmental impact in the performance of their professional duties.

Creating Design Alternatives

Once design specifications have been set, design alternatives can be generated. Since design is open ended, i.e. there are many possible solutions, it is desirable to generate several design concepts, evaluate them as a group before choosing the best direction for the design. The objective at this point is to create design concepts that satisfy the specifications. Realistic concepts are ones that are technically feasible and cost effective.

Innovation is a matter of synthesis and analysis of ideas. It requires time, focus, and effort of thought. The quality of each concept depends on the ability to think conceptually.

Parker [6] lists some traits of the creative personality:

- curiosity
- risk taker
- emotionally stable
- uninhibited
- imaginative, original
- intuitive
- high energy level
- independent
- task committed
- sense of humor.

Innovation is an individual activity. The foundation of science is built on the genius of individuals. Great ideas were not usually generated by committees. Once a fundamental concept or hypothesis is presented, others will add value. Design innovation usually starts with individual thought. Don't be afraid to propose novel ideas. You may be the leader others are waiting to follow.

Tools of Innovation

Ullman [7] discusses useful concept generation tools.

Patents

Some new products are based on a modification or direct extension of established products, in which case, the objective is to provide a higher quality or improved version of what is already on the market. Legally, this is allowed, provided the patent right period has expired. US patent law provides a 20-year life of a patent from the date the patent application was filed, and no shorter than 17 years from issuance. A patent survey will show whether your idea is truly novel or is infringing on an existing patent. A patent search early in the development process is worth the cost, time, and effort. It could eliminate legal problems later.

Reference Books and Trade Journals

Reference books are a good source of information on existing design concepts or designs that are currently in use. They may give analytical discussions of related designs. These discussions sometimes suggest alternatives based on direct extensions of current design concepts. Many trade journals feature new products, which may spark new ideas.

Experts in a Related Field

Experts can sometimes provide insight for new concepts. Experts can be research and development oriented in each technical field or they can be a company representative, such as a salesperson or a customer service representative, who have detailed knowledge about a product type.

Brainstorming

Ideas are generated spontaneously. Successive ideas feed off the group discussion; “piggyback” is sometimes used to describe this type of idea generation. All the ideas are reviewed and evaluated for relevance and practicality. Features of the better ideas will merge and come together.

The rules for brainstorming are:

- 1) Record all the ideas generated.
- 2) Generate as many ideas as possible.
- 3) Think wildly. Impractical ideas sometime lead to a useful one.
- 4) Do not evaluate or criticize ideas while they are being generated.

Existing Products and Concepts

Many hours have gone into developing existing products and most have the benefit of being tested in the marketplace. Existing products can be extrapolated into new product variations. This also eliminates reinventing the wheel so to speak. Types of modifications that may be considered are:

- Geometric modifications
- Energy-flow modifications
 - Change in the path
 - Change in the form
- Materials used in the product.

Remember, there is no need to redesign every component in a new product. Use as many off-the-shelf items as possible. Take advantage of current and established technology, such as gears, bearings, and motors. On the other hand, some components may have to be tailored.

As part of the creative process, new ideas (untried techniques) must be proven technically feasible before they can be accepted as viable alternatives. Feasibility studies may be required to show concepts are fundamentally sound and will work. Some concepts may be evaluated experimentally, analytically, or both. The results may expose risk and cost of untried concepts.

This is a screening activity to move the better ideas forward and remove alternatives that are not technically sound. More detailed analyses may be required during the design stage of the development process. Concept development may include iterations involving synthesis and analysis as shown in Figure 1.1. Also, every aspect of product life cycle needs to be considered by the product development team.

Concurrent Engineering

It is generally accepted that there are three basic activities for developing a profitable product. They are marketing, designing, and manufacturing. Until the 1980s, these activities were conducted sequentially, i.e. market data were passed on to designers who subsequently transmitted their design to manufacturing. These three activities were conducted separately with essentially little or no collaboration among the three disciplines.

World competition brought about competitive pricing and quick response to a dynamic market. In response to this challenge, marketing, designing, and manufacturing issues are now being considered by a team. Marketing seeks and monitors customer input to the new product. Designers seek the latest customer feedback from market analyst. Manufacturing issues are considered throughout the conceptual work to avoid costly redesigns brought about by impractical or inefficient manufacturing requirements. Collaboration of marketing, design, and manufacturing throughout the development process is commonly called Concurrent Engineering. It substantially reduces development cost over the sequential operations approach.

Feasibility of Concept

Each concept must prove to be technically feasible before it is evaluated. This means that some engineering may be required, and even drawings made to advance an idea beyond a hand sketch. A preliminary study may be needed to show an idea is workable, realistic and satisfies all design constraints or specifications, including cost constraints. In engineering practice, feasibility analyses may require extensive computer calculations and/or laboratory testing.

Evaluating Design Alternatives

Innovation will produce several design alternatives, each of which satisfies the given set of design specifications. The problem now is to choose the “best” concept among many alternatives.

Each of us make choices every day. Without realizing it, trade-offs are made leading up to a decision. The basic elements in making decisions are performance, cost, risk, and availability. Consider the purchase of an automobile. The buyer has established mentally a set of performance criteria (city driving, off road, mountain terrain, luxury, etc.), the price compatible with the family budget, maintenance, or track record of the car (is it a new model), and availability. The final choice is a trade-off among these four evaluation elements. The same rationale is used to purchase a suit or buy a house.

Evaluation Metrics

Four metrics (performance, cost, risk, and availability) are basic in choosing a preferred design concept [8]. The following defines these metrics as they relate to mechanical design:

Performance – Capability to achieve needed operational characteristics, plus reliability.

Cost – Estimated cost of the design, including development and manufacturing costs.

Risk – Possibility that performance may not be met because of the design approach, absence of testing, or some specific technical consideration.

Availability – Availability of a design depending upon the stage of development.

A procedure for scoring several alternatives is to divide each of these four metrics into key sub-metrics and give each an appropriate weight. Each design alternative can then be scored under each submetric. The scoring is strictly judgmental, so experience is important. The more experience, the better the judgment of scoring. Once each concept has been scored for each submetric, the numbers are totaled for a composite score for each concept. The total scores provide a means of comparing each concept against the others.

This numerical evaluation scheme has two key objectives. The first is to have a way to quantify one's judgment against a fixed scale so that each design concept can be rated in the same manner, thus, showing their truest level of merit in comparison with each other. The second objective is to give a way to examine the rationale of the final scores by looking at the subelements of each concept to see the strong and weak features of each. Since all design selections are the result of trade-offs, the scoring system aids in selecting a preferred concept.

Scoring Alternative Concepts

Table 1.1 illustrates the evaluation of four design alternatives and a hypothetical score for each. All constituents affected by the outcome of the project work together to set the weight given each metric and scoring. Each of the four basic metrics will have sub-metrics, as well.

This example indicates that concept C is the best because it scored the highest among the four alternatives. Other alternatives may have ranked higher in certain categories, but overall concept C scored the highest. There may a discussion over individual scores in the various categories, but the table provides a good basis for discussing the strengths and weaknesses of each alternative. Results from this scoring method give a rationale for recommending a preferred concept and a justification for the choice.

Table 1.1 Evaluation summary (hypothetical numbers).

	Weight	Concepts			
	(%)	A	B	C	D
Performance	35	20	35	30	25
Cost	20	15	10	18	16
Risk	25	10	20	23	18
Availability	20	20	18	16	12
Total score	100	65	83	87	71

Once each alternative has been evaluated and ranked and the preferred design concept selected, it is always a good idea to revisit the marketplace to see if the customers agree and to get further feedback for the preliminary design. Keep in mind that each stage in the progression along the development process represents an upgrade of the engineering baseline. The description and specifics of the preferred concept are an expansion of the initial set of design specifications and represent the most recent engineering baseline for the remaining steps in the development process. Design specifications have therefore been greatly refined beyond the initial set. The design can now move forward with a detailed description of the product.

Starting the Design

Mechanical devices typically contain a power source and a means of transmitting the power to bring about a desired end effect.

A design may start with the end effect, which establishes the magnitude of loads throughout the device, transmission linkages, and power requirements. This sets the overall size of the device and nominal dimensions of the subparts. Force magnitudes, power requirements (output torque and speed), pump requirements (flow rates and pressure demand), materials, and criteria of failure, fasteners should have been established earlier during the feasibility studies. Forces affect stress magnitude and component dimensions. Types of stresses (bending, torsion, shear, etc.) and how they combine should be visualized and understood. Are stresses the result of static or dynamic loads? These initial calculations can be made by hand. More precise calculations, based on computer models, can be made later.

Design for Simplicity

Keep the design simple. Use off-the-shelf components where possible. Commercial items have already gone through development and testing and have a proven performance record. Vendors for commercial products are happy to discuss performance details and quote prices. Also, keep the number of parts to a minimum. This increases product reliability. One company in East Tennessee rewards individual performance on reduction of design components. In addition, always consider how each part is to be fabricated. Curved shapes look good but are costly to make. Each of these considerations will make the device more reliable and easier to maintain in the end. Underlying principles of good design practice are:

- a) Minimize the number of parts. Reliability varies inversely with number of parts.
- b) Keep the design simple, Complexity reduces reliability.
- c) Use standard parts when possible; there are plenty of statistical performance data.

When configuring the design, it is helpful to consider whether starting the design from the outside-in or inside-out. If the design centers on a specific technical concept, such as a microcantilever sensor, it may be helpful to start there, and work inside-out, i.e. let the cantilever be the center point of the design and build outward from it. The sensor itself becomes the center point of the device and will dictate other features, such as how it is to be held and how information is to be retrieved.

Other projects may be constrained by space or how it links with other devices or subsystems. In this case, it may be useful to start with the geometric constraint and work inward. For example, the design of a house starts with the available space on a lot. Many times, the shape of the lot dictates

the shape of the house, including the foundation, exterior walls, and roof. These subsystems, of course, are based on the preferred concept, established earlier. The details of the inside, such as heating and air conditioning, are designed after the size and shape of each room has been determined.

Identify Subsystems

Consider the total design as a combination of subsystems. This is typically done in very large projects, but it is helpful in small projects, too. Breaking the whole design into subsystems helps visualize and organize how the whole design goes together. It also gives a clear division of responsibility for different team members. Subsystems may include

- Frame or fixture
- Power unit, such as motor
- Transmission linkages
- “Use” mechanism, final form of design
- Controls.

This approach is common in industry especially for huge projects involving several subcontractors. It provides a clear division of effort and responsibility. Subsystems may also be broken down into smaller units or sub-subsystems, etc.

The human body is a good example of subsystems. The body contains a frame (skeleton) or bone structure with consideration of joints and flexibility. The skeleton supports other subsystems, such as the lungs, heart, kidneys, brain, and all the plumbing. The gastrointestinal subsystem converts raw fuel into useful energy. Medical doctors specialize in each subsystem.

Innovation continues during this activity and therefore teaming is important. Each team member has something unique to add and the division of responsibility makes efficient use of each team member. Team meetings allow ideas to be integrated and refined.

An objective at this point is to configure the design in terms of its shape and subsystems and how they all fit together. This activity is best made by using classical engineering calculations; simple hand calculations are fine. These initial calculations establish component sizes, which are refined later. It is important to get a feel for the magnitude of loads, stress levels, and deflections as you begin to work through the design.

Development of Oil and Gas Reservoirs

Significant advances in two technologies allowed oil companies to increase production over the past 50 years. They are (i) geophysical mapping of underground rock formations and (ii) directional drilling, which allows navigation through multilayered formations to reach specific locations in deep and complex reservoirs. A third technology, which has almost doubled oil and gas reserves, is horizontal drilling and fracking. The later technology substantially increases oil and gas recovery.

While seismic surveys can map geologic formations and identify possible oil and gas traps, exploratory drilling must be performed to determine the existence of hydrocarbons and chemical composition. Once an oil reservoir has been delineated by directional drilling, an economic evaluation is conducted to determine the best plan for developing the reservoir for maximum recovery.

Oil companies typically identify business activities according to the following categories.

- 1) Geophysical surveying
- 2) Exploratory drilling
- 3) Production drilling
- 4) Production of oil and gas
- 5) Transportation of crude oil and gas
- 6) Refining crude oil and gas
- 7) Marketing.

Perhaps 80% of a company's budget is directed at the first four (4) categories, which are classified as upstream activities.

Design of Offshore Drilling and Production Systems

The design, fabrication, installation, and operation of offshore production system require an overall plan that may take a few years to complete. The project begins only after an economic analysis has been made, including current cost and future value of the asset.

In many cases, an offshore reservoir may extend across multiple sections licensed by different oil companies. The proportional ownership is determined seismic survey maps. The oil company possessing the largest portion of the reservoir becomes the operator of the field. All companies pay their share of development costs and benefit proportionately.

Planning is usually divided into the major activities mentioned above. One of the first activities is documenting a thorough and complete understanding of design specifications. This may require extensive data gathering on environmental, oceanographic, soil, and other specifics as mentioned earlier. Results of these efforts are compiled in a sizable specifications document often called a tender document. The tender document is used to gather additional information on contractor capabilities as well as for contractor bids on certain portions of the project. The bidding process, involving a few contractors is an opportunity, through discussions, to expand design specifications.

The design, fabrication, installation of offshore oil and gas production systems are multifaceted, high risk, and costly. The total effort involves a team, including operator, design contractors, fabrication contractors, installation contractors, and drilling contractors to mention a few. An Engineering Management contractor is often used to coordinate and interface each contractor's activities. The tow-out date of offshore platforms usually depends on the weather pattern for a specific location. For example, the tow-out and installation window for platforms in the North Sea starts in May and ends in September. Delays in design or fabrication could result in costly losses of early production. Upstream planning for this weather window is of the essence.

Major subsystems in offshore drilling and production platforms include

- 1) Base structure (steel jacket, concrete, tension leg, compliant structure).
- 2) Operating facilities, including personnel facilities, oil and gas processing for transportation to land.
- 3) Drilling and production equipment.
- 4) Transportation, such as pipelines, of crude to onshore facilities.

Each of these subsystems has its own subparts, etc. Each can be viewed as specific designs, which interface with the total system. For example, the drilling system typically includes

- 1) Derrick
- 2) Hydraulic system

- 3) Blow Out Preventer system
- 4) Drillstring including bottom hole equipment
- 5) Power system.

A few considerations in designing oil well drilling programs are

- Location of entry point into the oil and gas reservoir relative to the rig.
- Assessment of directional drilling equipment needed to reach the entry point as well as the well path.
- Formations to be encountered and anticipated drill bit types to penetrate these formations.
- Anticipated formation pressures (normal as well as abnormal pressures).
- Reservoir pressures to be controlled and blow out prevention concerns and strategies.
- Casing programs from surface to total depth.
- Implementing optimum drilling practices.

Connection of Subsystems

An early consideration in any design is the attachment of subsystems. Bolt-type attachments allow removal and replacement of subparts. Bolted connections can also be adjusted. Welded connections can't. It may be desirable in some cases to weld subsystems, such as the frame. Warpage and machining of surfaces should be considered.

Torsion Loading on Multibolt Patterns

Bolts are often used to fasten beams to form a frame or support a given load, such as illustrated in Figure 1.2. Four bolts are shown even though multiple bolts making up various patterns could be used. The design objective is to determine the total shear force in each bolt to establish bolt size and material strength.

The total shear force on each bolt is the vector sum of direct shear force and force caused by the torsion moment at the support. The first force is simply the total shear force divided by the number of bolts (assumes the connection is rigid). The direction of the shear force on each bolt is downward. The second force is caused by a moment on the bolt pattern and is determined as follows.

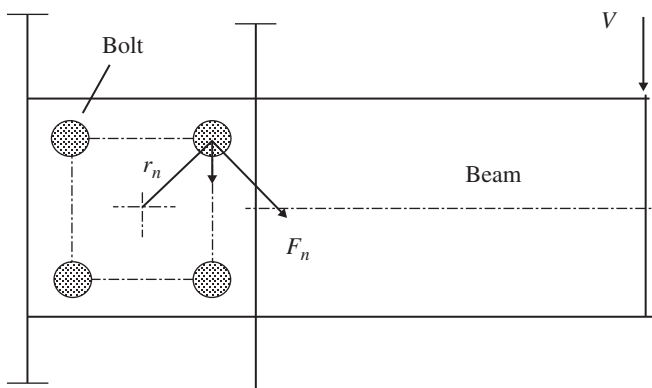


Figure 1.2 Bolted connection.

The total torque, T , applied to the bolted joint relates to shear force in each bolt by

$$T = F_1r_1 + F_2r_2 + F_3r_3 + \dots \tag{1.3}$$

Assuming the shear force, F , taken by each bolt depends on distance from the centroid of the bolt pattern,

$$\frac{F_1}{r_1} = \frac{F_2}{r_2} = \frac{F_3}{r_3} = \dots = \frac{F_n}{r_n} \tag{1.4}$$

Combining these two equations gives the force in each bolt.

$$F_n = \frac{Tr_n}{r_1^2 + r_2^2 + r_3^2 + \dots} \tag{1.5}$$

The above formula is very similar to the shaft shear stress formula,

$$\tau = \frac{Tr}{J} \tag{1.6}$$

which states that shear stress is proportional to radius, r . The shear stress formula is modified as follows to match the above bolt analysis.

$$\tau_n = \frac{F_n}{A_n} = \frac{Tr_n}{\sum r_i^2 A_i} \tag{1.7}$$

$$F_n = \frac{Tr_n A_n}{\sum r_i^2 A_i} \tag{1.8}$$

Only when all bolts are the same size,

$$F_n = \frac{Tr_n}{\sum r_i^2} \tag{1.9}$$

which agrees with Eq. (1.5). The direction of shear forces caused by torque on a bolt pattern is perpendicular to the r vectors as shown.

With reference to Figure 1.2, assume

$V = 2000 \text{ lb}$

Length = 12 in. (from center of bolt pattern)

Bolt diameter = 0.25 in.

Bolt spacing = 2 in.

Direct shear force	$F_V = \frac{2000}{4} = 500 \text{ lb}$
Torsion shear force	$F_n = \frac{Tr_n}{4r_n^2} = \frac{T}{4r_n} = \frac{24\,000}{4(1.414)} = 4243 \text{ lb}$
Total shear force	$\vec{F} = \vec{F}_V + \vec{F}_n$ where each force is a vector $\vec{F} = -500j + 4243(i \cos 45 - j \sin 45)$ $\vec{F} = -500j + 3000(i - j) = 3000i - 3500j$ $F = 4610 \text{ lb (scalar magnitude)}$

The cross-sectional area of each bolt is $A = \frac{\pi}{4}d^2 = \frac{\pi}{4}(0.25)^2 = 0.0491 \text{ in.}^2$ The maximum shear stress in the n th bolt is $\tau_n = \frac{4610}{0.0491} = 93\,885 \text{ psi}$. This shear stress level occurs in both inside bolts.

Make-Up Force on Bolts

A consideration in bolted attachments is the level of pretightening. Often bolted connections are subjected to externally applied forces, which may cause further extension of the bolt leading to possible separation of contacting surfaces.

Consider the two situations illustrated in Figure 1.3. The left drawing shows a bolt compressing a spring of stiffness, k_s . As the bolt is tightened, the shank of the bolt elongates while compressing the spring. The extension of the bolt shank relates to bolt force by

$$\delta_B = \frac{PL}{E_B A_B} = \frac{P}{k_B} \quad \text{where } k_B = \frac{E_B A_B}{L} \quad (1.10)$$

At the same time, the spring is compressed by

$$\delta_S = \frac{P}{k_S} \quad (1.11)$$

The internal force, P , in the bolt and the spring are the same (Figure 1.4a). The force level is established by the make-up torque.

If an external force, F , is applied to the connection, forces in the bolt (P_B) and spring (P_S) are no longer equal (Figure 1.4b). The challenge is to determine the magnitude of these two forces in relation to the externally applied force, F .

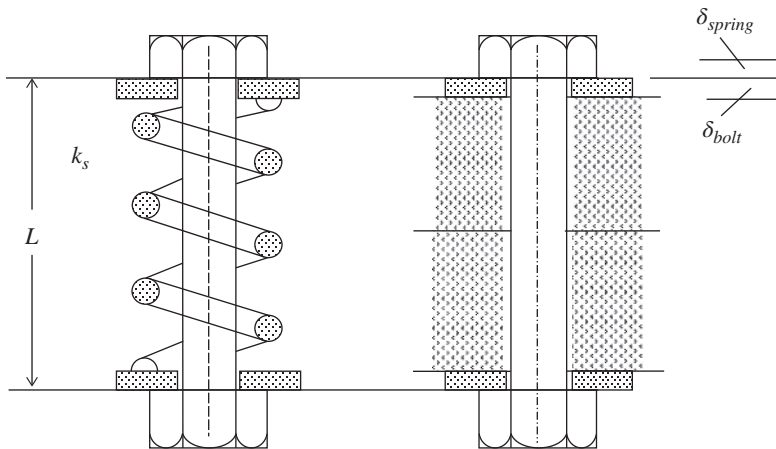
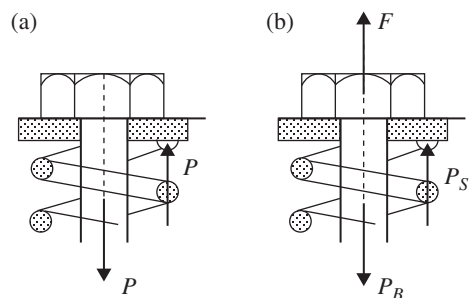


Figure 1.3 Make-up force in bolted connection.

Figure 1.4 Force response to an external load.



Consider the freebody diagram in Figure 1.4b. For equilibrium

$$F = P_B - P_S \quad (1.12)$$

Since there are two unknown forces in this one equation, it is necessary to consider deflections in the bolt and spring.

$$F = (P + \Delta P_B) - (P - \Delta P_S)$$

$$F = \Delta P_B + \Delta P_S$$

where ΔP_B is increase in bolt tension and ΔP_S is reduction in spring force. F is the externally applied force.

When load, F , is applied, the bolt stretch increases while the spring compression is relaxed by the same amount.

$$\Delta \delta_B = \Delta \delta_S \quad (\text{deflection equation}) \quad (1.13)$$

In terms of force changes

$$\frac{\Delta P_S}{k_S} = \frac{\Delta P_B}{k_B} \quad \text{where} \quad k_B = \frac{EA}{L} \quad (1.14)$$

By substitution

$$F = \Delta P_S + \frac{k_B}{k_S} \Delta P_S \quad (1.15)$$

giving

$$\Delta P_S = F \left(\frac{k_S}{k_B + k_S} \right) \quad (1.16)$$

Also

$$F = \Delta P_B + \frac{k_S}{k_B} \Delta P_S \quad (1.17)$$

$$\Delta P_B = F \left(\frac{k_B}{k_B + k_S} \right) \quad (1.18)$$

The resulting forces in the spring and bolt are

$$P_S = P - \Delta P_S$$

$$P_B = P + \Delta P_B$$

These relationships are shown in Figure 1.5.

$$P_S = P - F \left(\frac{k_S}{k_B + k_S} \right) \quad (1.19)$$

$$P_B = P + F \left(\frac{k_B}{k_B + k_S} \right) \quad (1.20)$$

The force required to separate the surfaces or created zero force in the spring is determined by setting $P_S = 0$

$$F_{cr} = P \left(1 + \frac{k_B}{k_S} \right) \quad (1.21)$$

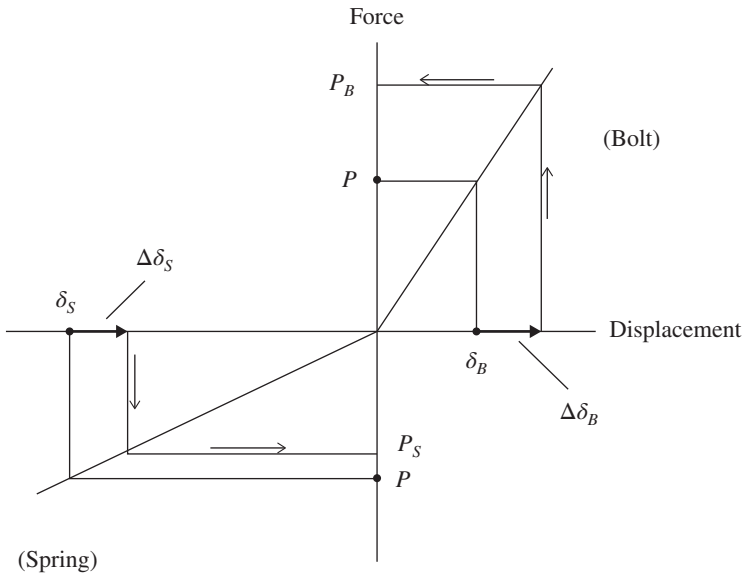


Figure 1.5 Force changes in connection.

In this case, by substitution into Eq. (1.20)

$$P_B = P \left(1 + \frac{k_B}{k_S} \right)$$

which is the same expression as Eq. (1.21) as expected.

When two plates are bolted together as shown in Figure 1.3b, the elastic compression in both plates have been modeled as two springs in series. A common math model for this rather complex state of strain is a truncated cone under uniaxial loading. Various formulations can be found in Ref. [9].

Example The arrangement of a weight (W) is held in place by a bolt tightened against a spring (Figure 1.6). Assume the initial compression of the spring is 0.1 in. The frame experiences base motion defined by

$$u(t) = u_0 \sin \omega t \quad (1.22)$$

This motion may cause the spring to disengage from the frame due to the acceleration of the weight. Ignoring the mass of the bolt and spring, determine the frequency at which the bolt becomes loose from the frame.

Other variables are quantified as

W	-	100 lb
L	-	2 in.
d	-	3/16 in. (bolt diameter)
k_S	-	2000 lb/in.
u_0	-	1/16 in.

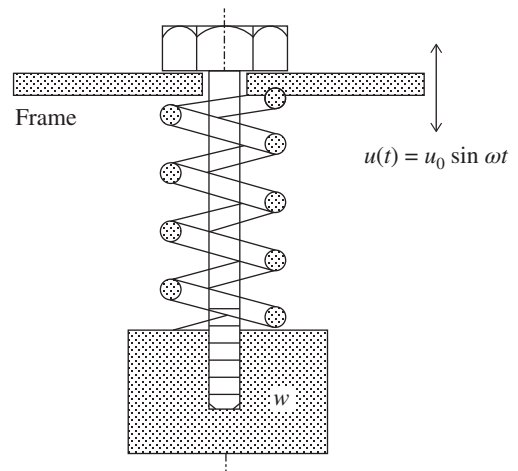


Figure 1.6 Spring-mounted weight.

To solve, we use Eq. (1.21) with the parameters below.

$$P = k_s \delta_s = 2000(0.1) = 200 \text{ lb (initial spring force)}$$

$$A_B = \frac{\pi}{4} \left(\frac{3}{16} \right)^2 = 0.0276 \text{ in.}^2$$

$$k_B = \frac{30 \times 10^6 (0.0276)}{2} = 414\,000 \text{ lb/in.}$$

$$F_{cr} = u_0 \omega^2 M = 0.0625 (\omega_{cr})^2 \frac{100}{386} = 0.0162 (\omega_{cr})^2$$

Substituting the numbers gives

$$0.0162 (\omega_{cr})^2 = 200 \left(1 + \frac{414\,000}{2000} \right)$$

$$\omega_{cr} = 1602 \text{ rad/s}$$

$$f = 255 \text{ cps}$$

Preload in Drill Pipe Tool Joints

In oil well drilling, joints of drill pipe are connected by “tool joints” welded to the pipe body. At one end is the pin joint, at the other end is a box joint (Figure 1.7). As the total string of pipe is drilled down, new joints of drill pipe are added. The connections are critical. If joints are torqued to lightly, then bending stress may be created within the pin leading to fatigue. Also, if the shoulder in the connection is loose, high pressure of the drill fluid could literally cut through the threads causing a washout. Proper make up torque of each joint is therefore critical.

The American Petroleum Institute (API) recommended (or allowable) preload in the shoulders of both box and pin for new pipe/tool joints is 50% of the force required to yield either box or pin. This preload is generated by make-up torque. For used drill pipe tool joints, it is 60%. This level of preload allows for additional pin loading due to direct pull, such as drillstring weight and over-pull.

After the tool joint is made up by the tongs (special torqueing tools), drill pipe is lifted vertically, and the slips removed. At this point, both shoulder and internal pin forces change from their make-up values. The questions then become (i) What is the new shoulder contact force? and (ii) How much direct pull would cause shoulder separation?

The following explains how pin force and box shoulder force change when external pull forces are applied across

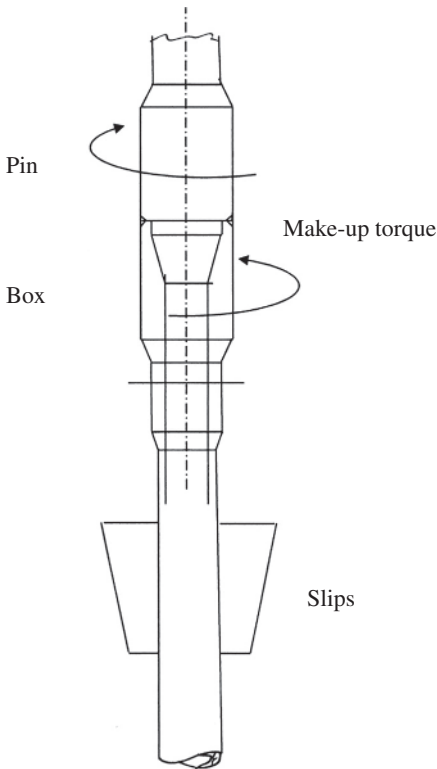


Figure 1.7 Tool joint make-up torque.

tool joints. The problem is statically indeterminate, so deflection equations are required along with the static forces.

For the sake of discussion, let the pin and box be represented by a cylindrical bar and tube as shown in Figure 1.8a. The tube is slightly longer than the bar. If the two heights are brought together and fixed, the preload (tension) in the pin is equal in magnitude to the preload (compression) in the box (Figure 1.8b). The pin is extended by

$$\delta_p = \frac{FL_p}{EA_p} = \frac{F}{k_p} \quad (1.23)$$

The box is compressed by

$$\delta_b = \frac{FL_b}{EA_b} = \frac{F}{k_b} \quad (1.24)$$

where

F	-	preload in pin and box after make up, lb
A_p, A_b	-	cross-sectional area of pin and box at the pitch point, in. ²
L_p, L_b	-	active length of pin and box (~0.75 in.)
k_p, k_b	-	effective spring constants in pin and box, lb/in.
E	-	modulus of elasticity, psi.

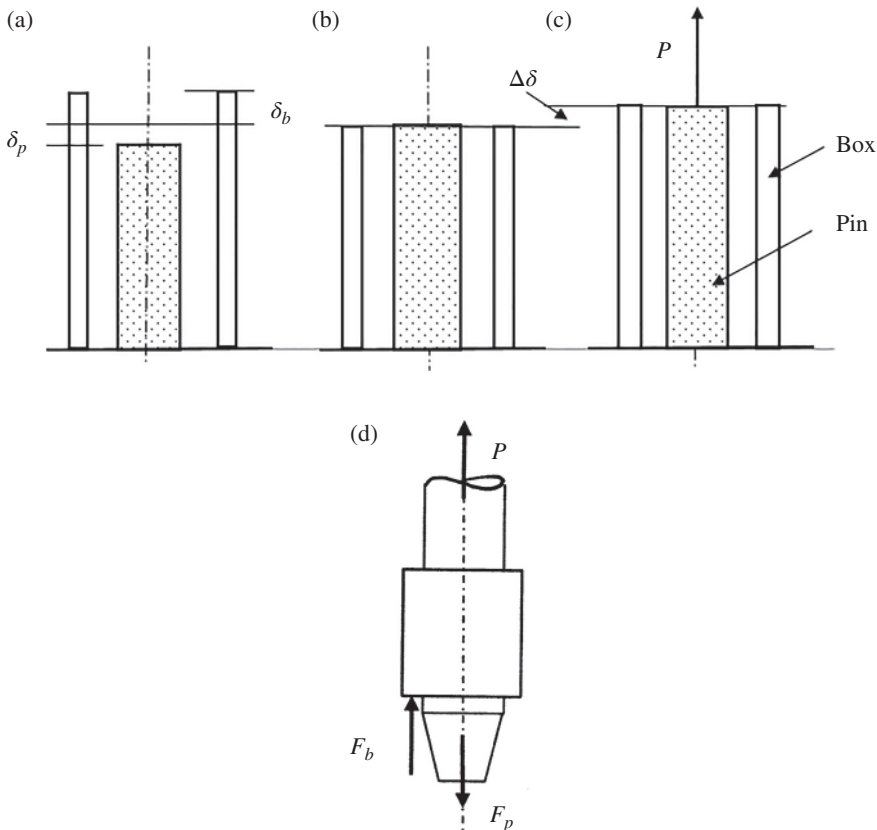


Figure 1.8 Internal forces due to preload and pull.

Now assume that a pull force, P , is applied across the tool joint (Figure 1.8c). The pin is stretched by $\Delta\delta_p$ while the box is relaxed by $\Delta\delta_b$; note that $\Delta\delta_p = \Delta\delta_b = \Delta\delta$. Therefore, the corresponding increase in the pin force is related to the corresponding reduction in the box force by

$$\frac{\Delta F_p}{k_p} = \frac{\Delta F_b}{k_b} \quad (1.25)$$

where ΔF_p and ΔF_b are changes in pin and box forces.

Using the freebody diagram shown in Figure 1.8d,

$$P = F_p - F_b \quad (1.26)$$

where F_p and F_b are new forces in pin and box resulting from the force, P , across the tool joint. These forces can be expressed as

$$F_p = F + \Delta F_p \quad (1.27)$$

$$F_b = F - \Delta F_b \quad (1.28)$$

Bringing Eqs. (1.25)–(1.28) together gives

$$\Delta F_p = \frac{k_p}{k_p + k_b} P \quad (1.29)$$

Therefore, the new force in the pin due to both preload and direct pull is

$$F_p = F + \frac{k_p}{k_p + k_b} P \quad (1.30)$$

where

P	–	pull force across tool joint
F	–	initial preload in box/pin
F_p	–	new force in pin.

Similarly, the new force in the box is

$$F_b = F - \frac{k_b}{k_p + k_b} P \quad (1.31)$$

Two load conditions are of interest: (i) magnitude of P , which causes shoulder separation and (ii) possible yielding in the pin caused by P .

Shoulder Separation

Shoulder separation occurs when $F_b = 0$. Using Eq. (1.31) with $F_b = 0$ gives

$$P = \frac{k_p + k_b}{k_b} F \quad (1.32)$$

which is the pull force across the tool joint required for shoulder separation.

Possible Yielding in the Pin

Rewriting Eq. (1.30) in terms of yield force in the pin

$$(F_{yld})_{pin} = F + \frac{k_p}{k_p + k_b} P \quad (1.33)$$

The force across a tool joint causing yielding is

$$P = \frac{k_p + k_b}{k_p} (F_{yld} - F) \quad (1.34)$$

This equation applies only if there is no shoulder separation.

Combining Eqs. (1.30) and (1.32) and assuming separation when $(\Delta\delta = \delta_b)$ and $F = 0$,

$$F_p = P \quad (1.35)$$

as expected.

Example Consider an oil field drill pipe tool joint as shown in the figure. Assuming the make-up contact force on the two shoulders of the pin and box is 472 000 lb, determine the shoulder force after a hook force of 250 000 lb is applied across the tool joint when the slips are removed. Determine the magnitude of a pull force required to separate the shoulder (zero contact force).

The dimensions for calculating these areas are:

Box OD = 6 3/8 in.

Pin ID (bore) = 3 3/4 in.

Pitch diameter = 5.04 in. (first thread on pin, see API RP 7G).

From the given dimensions, $A_p = 8.93 \text{ in.}^2$ and $A_b = 11.97 \text{ in.}^2$ and the active pin and box lengths ($L_p = L_b \sim 3/4 \text{ in.}$) are the same. Then

$$\frac{k_b}{k_p + k_b} = \frac{A_b}{A_p + A_b} = \frac{11.97}{8.93 + 11.97} = 0.573$$

$$\frac{k_p}{k_p + k_b} = \frac{A_p}{A_p + A_b} = \frac{8.93}{8.93 + 11.97} = 0.427$$

Force in the pin is

$$F_p = F + \frac{k_p}{k_p + k_b} P \quad (1.36)$$

$$F_p = 472\,000 + 0.427(250\,000) = 578\,750 \text{ lb}$$

Similarly, the new force in the box is

$$F_b = F - \frac{k_b}{k_p + k_b} P$$

$$F_b = 472\,000 - 0.573(250\,000) = 472\,000 - 143\,250 = 329\,000 \text{ lb} \quad (1.37)$$

This represents the new shoulder force after the 250 000 lb load is applied.

The pull force required to separate the pin/box shoulder is (using Eq. (1.32))

$$P = \frac{1}{0.573} (472\,000) = 823\,700 \text{ lb}$$

This force is felt by the pin at separation. It is less than the 944 000 lb required to yield the tool joint. This number, P , far exceeds the strength capacity of each of the four pipe grades (4 1/2 in.), which means that the drill pipe body would fail before tool joint shoulders separation.

Make-Up Torque

There are various formulas used to predict make-up torque, which account for friction in the threads and shoulder. One that is commonly used to predict make-up torque in drill pipe joints is called the screw jack formula.

$$T = \frac{F}{12} \left[\frac{p}{2\pi} + \frac{R_t f}{\cos \theta} + R_s f \right] \quad (1.38)$$

where

T	-	torque, ft-lb
p	-	lead of threads, inches ($p = 1/4$ in. for 4 threads/in.)
R_t	-	average mean radius of threads, in.
f	-	coefficient of friction (~0.08)
R_s	-	mean radius of shoulder, in.
θ	-	$1/2$ of included angle of thread ($2\theta = 60^\circ$)
F	-	contact force between mating shoulders, lb

The screw jack formula shows that total make-up torque is distributed among three areas. One component of the torque drives the mating shoulders together creating the contact force. If there were no friction in the connection, all the applied torque would create this force. From energy considerations, the work done by a torque over one revolution is equal to the work to move an axial force, F , over one thread pitch.

$$2\pi T(12) = Fp \quad (1.39)$$

The second component of torque is the torque required to overcome friction in the threads. The third torque component overcomes friction in the shoulder.

If tool joints, connecting drill pipe, are made up too tight, the pin could be overstretched. If tool joints are made up too low, threads can be exposed to washouts or bending fatigue. In practice, tool joints are generally made up too low. According to one drilling engineer, “if tool joints are made up too low, they will not make up downhole. On the other hand, drill collar connections will make up downhole. If drill collar connections are difficult to break out, it usually means they were made up too low initially.”

The make-up force or internal contact force between the two mating shoulders directly affects the structural integrity and pressure sealing capacity of the tool joint. Consider, for example, the torque components in a new NC50 ($6\frac{3}{8}$ in. \times $3\frac{3}{4}$ in.) tool joint using the following set of numbers:

p	=	0.25 in.
f	=	0.08
θ	=	30°
R_t	=	2.385 in.
R_s	=	2.922 in.

Substituting these numbers into Eq. (1.28) gives

$$T = \frac{F}{12} \left[\frac{0.25}{2\pi} + \frac{2.385(0.08)}{0.866} + (2.922)0.08 \right]$$

$$T = \frac{F}{12}(0.0398 + 0.2203 + 0.233)$$

$$T = \frac{F}{12}(0.4931)$$

This calculation shows that only 8% of make-up torque drives the shoulders together. The remaining 92% is used to overcome friction. The coefficient of friction of thread dope is therefore critical. Make-up torque recommendations [10] are based on a coefficient of friction of $f = 0.08$.

If the actual coefficient of friction is less than 0.08, contact force between the mating shoulders will be higher than expected when the recommended API make-up torque is developed. This condition could over stretch the pin or damage the shoulder area. If the actual coefficient of friction is greater than 0.08, contact force between the mating shoulders will be lower than expected when the recommended API make-up torque is developed. This condition allows bending stresses to reach the pin causing fatigue damage and creates an inadequate pressure seal leading to a washout through the threads.

Bolted Brackets

Things to consider in bracket design are indicated in Figure 1.9. The bracket supports a force, F , which is resolved into vertical (F_V) and horizontal (F_H) components. Forces in both bolts (A and B) are the superposition of several types of loads. First, the vertical force component is supported evenly by both bolts. The horizontal component creates shear forces evenly in both bolts as well. In addition, the horizontal component creates a moment (bF_H) about point “a,” which adds to bolt forces.

This moment creates a statically indeterminate problem, which requires deflection considerations. Equations to be considered are

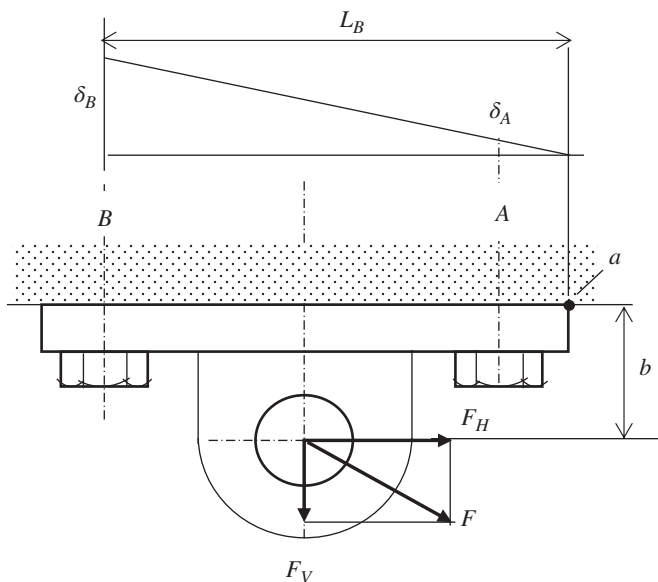


Figure 1.9 Bracket attached by two bolts.

$$bF_H = F_B l_B + F_A l_A \quad (\text{one statics equation, two unknowns}) \quad (1.40)$$

$$\frac{\delta_A}{\delta_B} = \frac{l_A}{l_B} \quad (\text{deflection equation}) \quad (1.41)$$

The stretch in both bolts is

$$\delta_A = \frac{F_A L}{EA} \quad \text{and} \quad \delta_B = \frac{F_B L}{EA} \quad (L \text{ is bolt length}) \quad (1.42)$$

Combining Eqs. (1.41) and (1.42) gives a second equation for determining the forces in each bolt.

$$\frac{F_A}{F_B} = \frac{l_A}{l_B} \quad (1.43)$$

Substituting this result into Eq. (1.40) gives

$$bF_H = F_B l_B \left[1 + \left(\frac{l_A}{l_B} \right)^2 \right] \quad (1.44)$$

Welded Connections

Torsion Loading in Welded Connections

The analysis of welded connections is similar to bolted connections. In this case, total shear stress at any point in a weld is the superposition of direct shear and torsion shear. Direct shear stress is determined by

$$\tau_F = \frac{F}{A_{total}} \quad (1.45)$$

where F is total shear load on the joint and A_{total} is the total throat weld area (tL). Local shear stress due to applied torque, T , is assumed to follow classic shear stress predictions.

$$\tau_T = \frac{Tr}{J_0} \quad (1.46)$$

where J_0 is the polar moment of inertia of the weld pattern.

When the size and shape of each weld pattern is known, these equations can be used to determine both shear stress components. The resulting shear at any point in the weld is the vector sum of both stress components.

Consider for example a steel plate attached to a vertical post by two fillet welds (Figure 1.10). For this weld pattern

$$dJ_0 = r^2 dA = (h^2 + x^2) dA \quad (1.47)$$

$$J_0 = \int_{-l}^l h^2 t dx + \int_{-l}^l x^2 t dx \quad (1.48)$$

$$J_0 = h^2 t (2l) + \frac{2}{3} l^3 t \quad (1.49)$$

Combining parameters, $l = \frac{L}{2}$ and $A = Lt$.

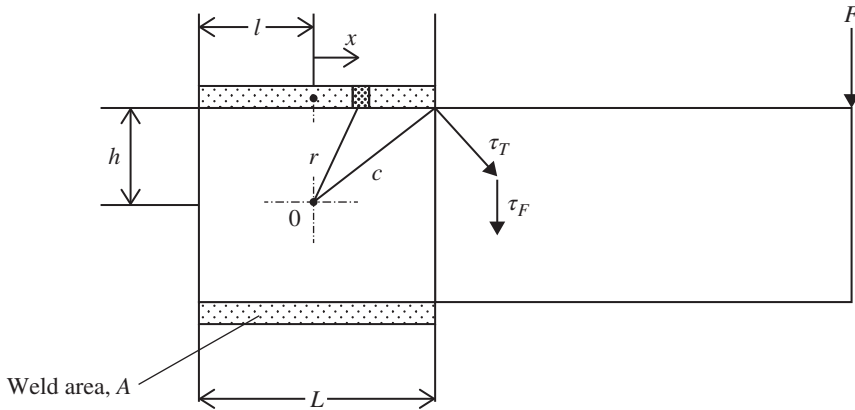


Figure 1.10 Welded connection in torque.

$$J_0 = h^2 A + \frac{2}{3} \left(\frac{L}{2} \right)^3 t \quad (1.50)$$

$$J_0 = h^2 A + \frac{1}{12} L^2 A \quad (\text{one weld}) \quad (1.51)$$

$$A = tL \quad (t \text{ is measured across triangular weld})$$

Maximum shear stress occurs at the end of the weld. This stress is the vector sum of two components.

$$\tau_{\max} = \tau_T + \tau_F \quad (\text{vector summation}) \quad (1.52)$$

$$\tau_{\max} = \frac{Tc}{2J_0} + \frac{F}{2A} \quad (1.53)$$

Example Consider the specific numbers shown below.

$$L = 8 \text{ in.}$$

$$t = 0.25 \text{ in.}$$

$$h = 3 \text{ in.}$$

$$F = 250 \text{ lb}$$

$$T_0 = 3000 \text{ ft-lb (assumed)}$$

$$A = tL = 0.25(8) = 2 \text{ in.}^2 \quad (A_{\text{total}} = 2A = 4 \text{ in.}^2)$$

$$J_0 = 2 \left[3^2(2) + \frac{1}{12} 8^2(2) \right] = 57.3 \text{ in.}^4 \quad (\text{both welds})$$

The stress components are

$$\tau_T = \frac{3000(12)5}{57.3} = 3141 \text{ psi (torsion load)}$$

$$\tau_F = \frac{250}{4} = 62.5 \text{ psi (direct load)}$$

The shear stress produced by the direct loading is minor compared to the shear stress produced by the torque.

Attachments of Offshore Cranes

Cranes are essential in the operation of offshore structures. They load and unload necessary equipment and supplies from supply boats. Off-loading cranes are often attached to a base structure, such as a platform or floating vessel by weldments. A weldment with gusset plates is illustrated in Figure 1.11.

The stresses in the weldment are due to a bending moment produced by a hook load in the crane. The crane is rotated about a vertical axis after the equipment has been elevated to deck level. The classic calculation is based on

$$\sigma = \frac{Mc}{I} \quad (1.54)$$

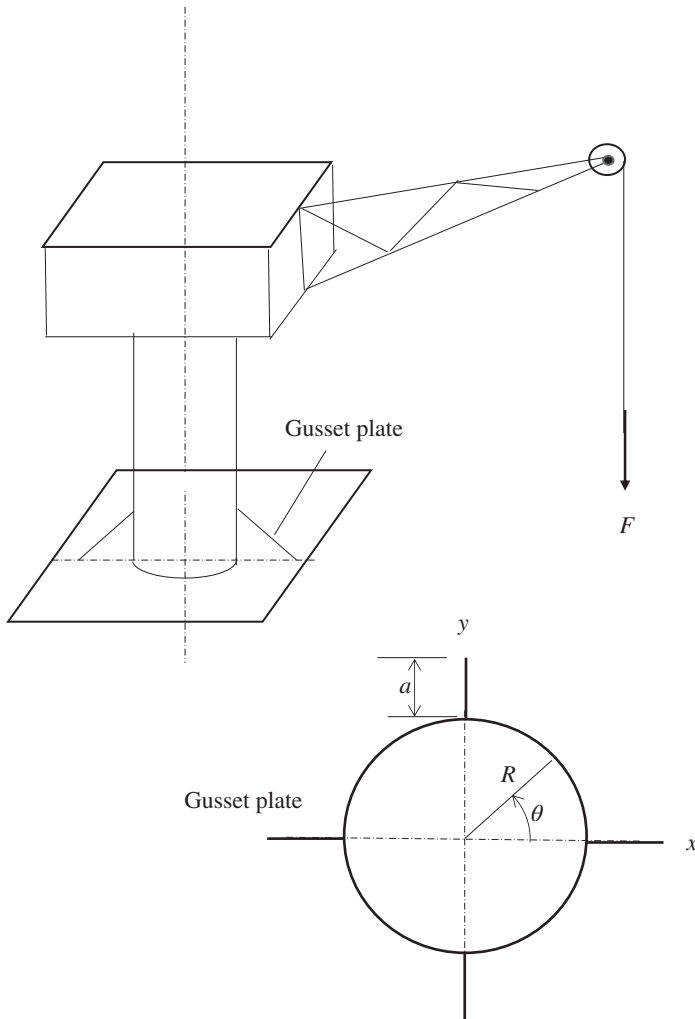


Figure 1.11 Offshore crane weldment.

By inspection we note that moment of inertia, $I_x = I_y$, and each are principal moments of inertia. They are both principal moments of inertia and are represented by a point in the Mohr inertia circle. Furthermore, the moment of inertia about every diametrical axes is the same. Bending stress magnitude varies by distance, c . The c value is maximum when bending occurs about the x or y axis. One of the engineering challenges is to determine the moment of inertia. We choose to use the x axis as the reference line.

The moment of inertia of the ring is determined as follows.

$$dI_x = (R \sin \theta)^2 t ds \quad (1.55)$$

$$I_x = 4R^3 t \int_0^{\frac{\pi}{2}} \sin^2 \theta d\theta \quad (1.56)$$

$$I_x = 4R^3 t \left[\frac{\theta}{2} - \frac{\sin 2\theta}{4} \right]_0^{\frac{\pi}{2}} \quad (1.57)$$

$$I_x = \pi R^3 t \quad (1.58)$$

The moment of inertia of two gusset plates with respect to the x axis (using the transfer formula) is

$$I_x = 2 \left[\frac{ta^3}{12} + \left(R + \frac{a}{2} \right)^2 at \right] \quad (1.59)$$

Total moment of inertia with respect to the x axis is

$$I_x = \pi R^3 t + 2 \left[\frac{ta^3}{12} + \left(R + \frac{a}{2} \right)^2 at \right] \quad (1.60)$$

If gusset plates are placed evenly around a cylindrical stand, bending moments of inertia about any diameter are the same. This means the Mohr circle of inertia is a point.

Quality Assurance

Performance evaluation is necessary for nearly every product or service. Evaluation can be based on quality assurance at the assembly line, laboratory testing, product performance in the marketplace, and customer feedback, to mention a few. The metrics for any evaluation should be established early. The metrics provide a baseline from which to evaluate performance. It is useful to include the stake holders and end user in setting the metrics. Performance should be given a numerical score and the rationale behind the score.

- Functionality
- Root cause analysis
- Maintenance and reliability
- Market response
- Assessment/feedback

Engineering Education

Engineering education is a good example of program assessment and feedback. A few years ago, engineering programs were based on curricula containing certain required components, such as mathematics, humanities, engineering science, and engineering design. In 2000, the Accreditation Board for Engineering and Technology (ABET) initiated a different set of criteria based on objectives, curricula, and a continuous improvement process.² Each academic unit can design or modify existing programs to satisfy these criteria. The flow diagram (Figure 1.12) illustrates such a feedback process.

Mission Statement

The mission statement provides focus. It sets direction. It is much like the operational requirements of Figure 1.1. For example

To provide a broad-based integration of courses and experience
That prepares its graduates to practice their profession successfully, to apply their skill to solve current engineering problems collaboratively, and to help advance the knowledge and engineering practice in their field.

This statement is reviewed from time to time with the constituents of the program.

Academic Design Specifications

Design specifications are set by the ABET. Each engineering program must satisfy each of these components. These criteria offer the opportunity to redesign or modify existing undergraduate programs. There is a lot of flexibility in how programs are designed. It is very open ended. Typically, well-established programs are modified to satisfy these criteria and continually improved.

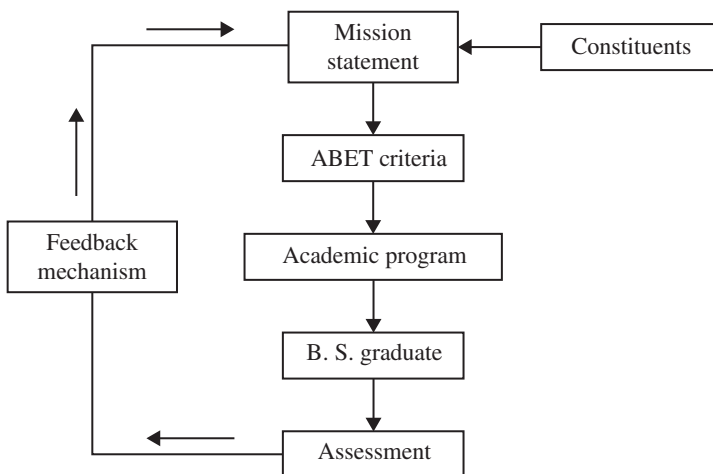


Figure 1.12 Feedback process of continuous improvement.

Design of the Academic Program

An academic program includes the integration of every component (students, curricula, faculty, facilities, and resources) as spelled out by the eight ABET criteria. Curricula are at the center of the academic program.

Perhaps the biggest improvement in engineering education has been the requirement that all seniors must have a major design experience. While the basic engineering science courses are fundamentally the same, the use of computers, modern laboratory equipment, and classroom equipment have brought about big changes in how courses are taught. In my opinion, the greatest improvement to engineering curricula has been the Professional Component (Criteria 4), which requires a major capstone design experience by each student prior to graduation. These projects bring seniors face to face with the realities of applying engineering principles to solve practical engineering problems. These experiences help engineering graduates step directly into an industrial setting and immediately take on projects with confidence.

Graduate engineers are the product of this service. Just as industry evaluates the quality of its service products, academia should do the same. The question becomes one of how prepared are graduates to enter the work force. Have the graduates gained proficiency in the expected outcomes as specified in Criteria 3 and 5?

Outcomes Assessment

What are the tools for measuring the results of the educational program? Evaluation and assessment must be quantified in some way to measure improvements in the educational service from year to year. The outcomes assessment process should involve all constituents involved or those who have a stake in the outcome.

Once the outcome of the educational service has been evaluated, how are the conclusions fed back into the educational process?

Saturn – Apollo Project

A few years ago, I had the pleasure of visiting with Albert C. Martin, Director of Launch Operations for Stage II, Saturn/Apollo Project (Albert C. Martin, personal communication). We discussed the steps leading up to each launch. Testing was a huge part of launch preparation.

During the early 1960s, the digital computer was just emerging as an engineering tool. Software, as we have today, was not yet available for making numerical calculations of critical aspects of the rocket. Thus, reliability of design, along with improvements, depended heavily on testing.

Test results were fed back to the design team for improvements. This cycle was made until each team could say "... that everything that can possibly be done to assure success has been done." Final testing was conducted at the Kennedy Space Center, Cape Canaveral, prior to rocket assembly and launch. Over 400 engineers and technicians conducted multiple tests on critical component of the Saturn Stage II under the direction of Lyle C. Bjorn, Manager of Testing. There were no launch failures during the Saturn/Apollo Project.

Important aspects of design in the Saturn/Apollo project were

- Produce ability
- Reliability
- Safety.

A "Design Review and Change Board" reviewed results after each test. Information gained from testing was evaluated for possible improvement to the overall second stage design. Before any

design changes were made, the Change Board scrutinized the recommendations. Representatives from various contributors attended these meetings, including

- Manufacturing
- Design and engineering
 - Structures
 - Aerodynamics
 - Testing
 - Combustion
- Quality control
- Financial
- Contracts

These types of meetings were held regularly since second-stage testing was conducted around the clock and hundreds of data had to be evaluated. While every component was essential, the turbo pump was central to the overall operation of each engine. To produce the necessary thrust, a high rate of fuel burning was vital. That meant the turbo pumps operated at near 80 000 rpm. Bearings that held the turbine shaft were pushed to the limit at this speed. Also, turbine blades were susceptible to vibration and fatigue, and had to be monitored.

Since then, computer capability in both size and speed, along with computer software, make it possible to accurately predict expected performance of critical components. Computer simulation of complex systems (airplanes, for example) gives accurate predictions of expected performance, essentially eliminating the need for many tests.

Notes

- 1 http://www.asme.org/Education/PreCollege/TeacherResources/Code_Ethics_Engineers.cfm.
- 2 Established by the Accreditation Board for Engineering and Technology (ABET)..

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