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Ten Critical Factors in the Design Process

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ABSTRACT

The engineering design process transforms a need or an idea into the information from which a product or system can be made. Possibilities and abstract thoughts are progressively developed into certainty and then brought into reality through manufacture of the product or system for service within an appropriate lifecycle.

Careful management of multidisciplinary teams, precise communication, effective use of available design tools, appropriate application of materials and a professional respect for the legacy of previous designers all come into the development of a design which will meet user expectations and the environmental constraints within today's aggressive and global markets.

A failure in any aspect of the design process can spell disaster for a project immediately, and unforeseen circumstances can create havoc at any point in the lifecycle of the product or system. We must learn continually from past problems to help us with the task of successfully designing in the more complex web of the future.

INTRODUCTION

Despite great advances in technology, computational tools, information transmission and even in our understanding of human factors, many designs still do not live up to user expectations or they fail in service for a variety of reasons. Interestingly enough, while the current legal climate in the United States encourages the most detailed and expensive investigations into design failures it doesn't always help in forestalling future occurrences of the same nature. A legal dispute once settled is gone, and with it goes the money and the fleeting excitement over design issues. However, those design issues live on and suddenly appear again, causing more mischief in a different guise. The files of the forensic engineer are replete with tales of disaster, and for anyone honestly interested in failure prevention they provide a rich source of educational material. Whether a design failure results in an accidental injury to a user or simply an argument over monetary loss, the underlying problems very often boil down to defects in the engineering design process itself. A systematic analysis of the design process usually reveals the factors leading to the failure.

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Once having identified what went wrong in a particular design process, it is possible to focus on remedial measures. In this paper some common factors leading to design failures are highlighted, with reference to case examples. This sets the scene for the exploration of useful failure prevention techniques in design.

The Engineering Design Process

There is often great discussion over what exactly is meant by the term *engineering design*. For the purposes of this paper the following definition will be used:

Engineering design is the process of converting an idea or market need into the detailed information from which a product or technical system can be produced.

The basic engineering design process is usually described as a sequence of phases beginning with a perceived need and finishing with the detailed description of a particular technical system or product [1,2,3,4,5]. Depending on the product or technical system being designed, the phases may be labeled in different ways and will often be carried out parallel to the design of the manufacturing process [6]. Each phase may be considered as a sub-design process in itself, consisting of an iterative set of steps. Overall, and within each phase, the engineering design process may be considered as a special case of 'problem-solving'. Many design process 'models' in the form of block diagrams have been developed to try and characterize the design process providing the design engineer with a somewhat defined procedure for applying available design techniques. For the purposes of this paper, the following simplified description will suffice:

- **Task Clarification:**
  Through task clarification activities the problem is defined.
  Output is a design specification.

- **Conceptual Design:**
  Through conceptual design activities solutions are generated, selected and evaluated.
  Output is a design concept.

- **Embodiment Design:**
  Through embodiment design activities the concept is developed.
  Output is a final layout.

- **Detail Design:**
  Through detail design activities every component is defined in shape and form.
  Output is manufacturing information.

Systematic Design Process

A systematic approach to carrying out the design process [6,7] instills a disciplined way of thinking about *The Three T's*: the *Task*, the *Team*, and the *Tools*. It helps the design engineer to tackle any problem in a professional way and generally gives the best chance of a successful outcome. It provides a disciplined way of working which inspires confidence in management and in the customer, and it offers working tools and techniques to help ensure that quality solutions will be found within the constraints of the project. There is mounting evidence to show that if a systematic approach is not used in the complex design environments that now exist, the probability of failure is high. For example, asking a simple set of questions within the framework of a systematic design process would have alerted the management to a developing catastrophic situation several years before the Space Shuttle Challenger Disaster [8]. The same holds true for many of the huge number of accidents and failures involving design issues.

Management of the Design Process

The Three T's demand skillful management of the *activities* of the design team, the *output* from the design team and the *influences* on the design team [3]. Design team activities must be directed and monitored for performance. The design output must be assessed against the specification requirements continually. The effect of influencing factors must be actively predicted, monitored and controlled where possible. Management involvement in these issues is crucial to the development of high quality and cost competitive products [9,10]. From the design management point of view the ultimate goal is to produce the highest quality product meeting the user's expectations for the lowest cost in the shortest time.

A particular challenge in the management of engineering design is to be able to cope with issues that range from 'hard' to 'soft'; for example from the dimensional tolerance on a single component to the user's satisfaction with a product in service. Another challenge is that the critical issues must be considered at different levels of resolution and from different points of view. A key skill is to be able to see the overall picture while rapidly windowing in on the details and understanding the effect that even tiny details might have on the overall project. A lack of management skill in this area has contributed to many engineering disasters, such as the failure of the Solid Rocket Booster on Space Shuttle Challenger. Again, simple sets of questions, based on fundamental design principles and asked at the appropriate time by a manager with adequate technical understanding, can highlight design weaknesses long before a disaster becomes inevitable [3].

Forensic Analysis of the Design Process

Obviously, an analysis of what happened during a design project involves reviewing all the available documentary, physical and testimonial evidence, and arriving at opinions as to what occurred. However, just as the design process is best carried out in a systematic fashion, so should the analysis. A typical approach in such an analysis is to ask a series of questions concerning *The Three T's* within each phase of the design process. For example: “Where is the design specification? Who developed it? Who approved it? What changes were made? Who made them? Why? When? How?” By progressing through a checklist of questions for each phase of the design process, problems and weaknesses start to emerge and eventually the critical factors which led to the failure become identified.

In practice it is unlikely that the design process will proceed through the sequential set of project phases previously outlined, but the sequencing is less important than the existence, nature and effectiveness of the actual design activities implied within each phase. For example, there must be some kind of design specification as a starting point and there must be some kind of concept from which a final design evolved. The concept must be developed to a greater or lesser degree to result in a practicable overall design and the details of every component must be defined to the point where the product or system can be manufactured. A combination of human activities is required to reach each of these end points or outputs. It is these activities and their consequent outputs that are the focus when analyzing the design process.

Critical Factor 1: Defining the Problem

Frequently it is found that the real design problem was never clearly defined, was incorrectly defined or the wrong problem was identified [11,12]. For example, what is the problem that the automobile air bag is supposed to solve? Is it a technical problem, a safety problem, a legal problem, a human problem or a commercial problem? In the name of safety we have created and mandated an explosive device placed in front of your face that sometimes helps you, but at other times hurts you and in the meantime is another item with the potential for malfunction, theft and fraud. The airbag does not reduce the number of accidents on the road or improve the way people drive; it does however generate a steady stream of lawsuits.

Once the problem has been defined, the criteria for selection of an appropriate concept must be established in the form of a design specification which lists all the requirements to be met by any solution to the problem. Here again, if the requirements are inaccurate or incomplete then the design process will be flawed from the start. The following example illustrates another pitfall, which is the introduction of fictitious constraints into the requirements. The result is that the concept selected will be over-constrained and therefore will not be an optimum solution to the problem.

A large number of custom-designed vertical lift conveyors were required for use in a series of new automated U.S. mail sorting facilities. These facilities comprise essentially a series of code-reading sorting units at ground level with a vast array of horizontal roller conveyors above. Vertical lift conveyors are used to transport plastic trays of sorted mail from ground level up to horizontal conveyor level and the reverse. The vertical lifting concept was developed to overcome the slippage problem encountered with inclined roller conveyors when plastic trays superceded cardboard trays in earlier facilities.

A voluminous design specification had been prepared for the Post Office by the general contractor. This was to apply to all facilities, but for each particular facility there was also a detailed set of special requirements. Within these documents were embedded the requirements for the conveying systems in general, and within those the requirements for the vertical lift units in particular. Prototype vertical lift units which used twin in-running belts to deliver the trays to three-fingered lift platforms already had been developed and tested off-line to the point of acceptable performance for this application. The Post Office design specification for the lifting units was compiled with the prototype units in mind, even to the point of *requiring* in-running entry and out-running exit conveyors having two or more belts, and lift platforms with three or more fingers. In such a way the specification unnecessarily constrained the design to a specific concept which was known to have inherent operational problems.

The many required units were designed, built, tested, delivered and installed at a cost of more than $500,000. While some design weaknesses and manufacturing problems were evident which detracted from the performance of the units, they did pass the acceptance tests laid down in the design specifications, right up to the final production trials. At this point, however, multiple failures and jams were encountered because the operators were using the vertical lift units on a start-stop basis instead of continuously as intended. It was claimed that the units did not meet the specification and they were all removed and scrapped without payment to the manufacturer. At the same time another supplier was contracted to provide quite different replacement units. Investigation revealed that a modified design specification had been issued to alternative manufacturers who were invited to bid on supplying the replacement units and that the units finally selected were based on a concept which could never have met the requirements of the original design specification. The modified design specification deleted the requirements for belt conveyors and for the lift platforms to have three or more fingers. This removed the fictitious constraints on the design and allowed the use of an articulated slat conveyor, far superior in concept to the suspended tray type of conveyor for this particular application.

The main reason for the failure was a deficient design specification. It resulted in a huge waste of effort, money and materials as well as the bankruptcy of the original vertical lift unit manufacturer.

Critical Factor 2: A Working Design Team

Nowadays it is common for design teams to be created and staffed on a project by project basis, specifically for the duration of the project. Increasingly it is common for the work to be carried out in multiple locations by means of electronic communication. Bringing together and orchestrating a team which will produce a quality design in a timely fashion is not easy and must be recognized as a critical task.

People have a *functional role* in the team, using their particular technical expertise and experience, and obviously this has to be matched to the work at hand. They also have a *team role* using their particular character traits to help make the team work as a team [13]. If the set of team roles is not well balanced then the output will suffer badly, no matter how good the balance of functional roles. A team may be adequate in a functional sense, having the right expertise and experience, yet may not have the right balance of personalities to be productive. Teams need a mix of personalities covering basic 'team-roles', with the addition of 'specialist' roles in technical situations [13].

One of the most frustrating things is the way projects are manipulated by those who have very little to do with the design process itself. It is critical for the design manager or team leader not only to be aware of the impact of various influences but to exercise control over those that can be controlled and compensate for those that can't, in the best interests of the customer, the project and the design team. For example, the *negotiating ability* and the *negotiating power* of the team are critical to the design process [3]. To be successful a design team needs to be good at negotiating, and it needs to negotiate from a position of power. Often design teams have more power than they realize, for without their input the company would fail. The problem is that engineers are taught engineering, not politics or law, and they tend to withdraw when it comes to eloquent speeches. The more incisively the design team can present its case, the better it is able to control the things which matter. This was illustrated by the failure of the Space Shuttle Challenger. The failure of management to comprehend the importance of detail design, coupled with the failure of the design team to get the message across, blew the billions away. If the design team had understood and learned how to use its latent power effectively, Challenger would not have been launched. It is always interesting to note that the world's great engineers such as Eiffel, Brunel and Ford were not only excellent technically, but also were persuasive, entertaining and politically involved individuals.

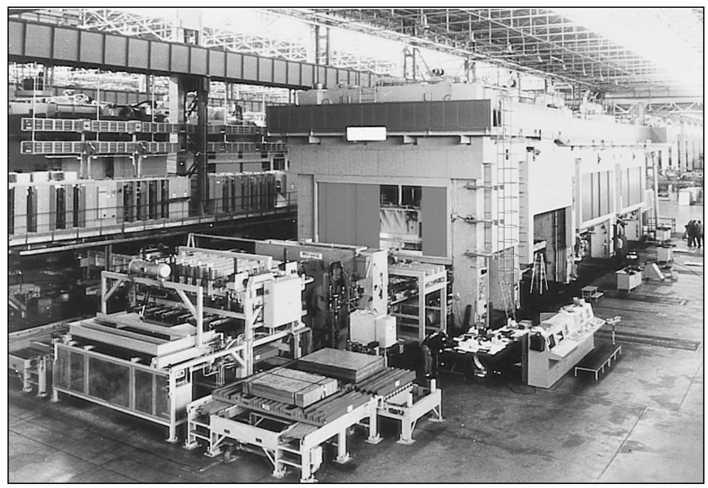
Critical Factor 3: The Right Tools for the Job

A bewildering array of literature, methods, tools and techniques is now available for design [2,3,4]. Many of these tools are effective, but many require experimentation before being used professionally. Which tools should be used depends on the project. The computer has finally become the indispensable tool that it was supposed to be many years ago, but it is still as true today as it always was that the computer is a tool, and is not a design engineer. It is easy to become constrained by *what can be drawn on the computer*, and indeed to let the computer start steering the ship. For example, two new truck engines were being developed, each one being designed by a different team within the same company. There was a simple but puzzling question: "Why do the timing gears for one engine have a helix angle of 15 degrees while the others have a helix angle of 25.4043 degrees?" Answer: for one engine the forerunners had always had a helix angle of 15 degrees and no-one had ever questioned it, while for the other engine the computer said it should be 25.4043 degrees and no-one had ever questioned that either.

Care must be taken to focus on the results required rather than the intricacies of the method, and crosschecks are essential to make sure of catching errors.

Critical Factor 4: Communicating Effectively

Effective communication has become steadily more important as the idea of 'global design teams' gains in popularity. The recent failure of the Mars Orbiter mission due to mixed imperial and metric units highlighted this type of problem, which becomes compounded by differences in language and culture. What used to be a matter of simple transmittal of information is now a matter of ascertaining what someone actually interpreted from the information provided. The following example shows how easy it is to get into serious trouble when the communication is ineffective.



Problematic metalworking transfer presses

To upgrade its production facilities, a European manufacturer ordered two huge custom-built metalworking presses, high on the scales of novelty, complexity and cost, with a short timeframe for delivery. The concept involved a unique automatic transfer system for moving parts longitudinally through a series of operating stations, so the design work was sub-contracted to an experienced North American company with special knowledge of the particular type of machine required. As the timeframe was so short, the documentation of customer requirements was perfunctory, and there was some confusion as to the responsibilities of the various parties. Under pressure to meet unrealistic deadlines, the design was rushed through to detailing with insufficient time spent either on the overall concept or on development of the concept to meet the design specification. Some 4000 drawings were produced by hand, involving translation from one language to another and changes from imperial to metric units. The machines were built according to the translated drawings with almost no communication between the Design Company and the manufacturer. Apparently it was assumed that the knowledge of the Design Company would be fully imparted to the manufacturer through the medium of the drawings. The timeframe was too short to allow for testing and commissioning so the machines were built and put into service without normal shakedown procedures. Although slow speed operation was achieved, the machines could not be run at the speed specified by the customer and agreed to by the manufacturer. Severe damage to components was caused in the attempts to reach full speed. The manufacturer redesigned various parts based on traditional press experience, without adequate knowledge or experience of the design they were working with, and the machines never performed to the customer's expectations. Both the designing company and the manufacturing company were large and well respected in the industry, and both are now out of business. The design work was never paid for and the claims for damages far exceeded the total cost of design and manufacture of the machines. A deficient design specification coupled with inadequate communication and a total separation of design from manufacture guaranteed unacceptable performance of the machine.

Critical Factor 5: Getting the Concept Right

Once the problem has been defined, it is possible to start generating ideas leading to concepts that will solve the problem [14,15]. This is not the same as *invention*. What is meant by conceptual design is the conscious activity of generating numerous ideas, leading to specific concepts that are then selected and evaluated according to how well they meet the requirements of the design specification. Of course a design concept may become patented as an *invention* in intellectual property terms, but an invention is not necessarily a design. There is a fundamental difference between an inventor having an inspiration on Thursday and a design engineer producing an acceptable design concept within time, budget and specification constraints by Thursday. Part of the necessary concept evaluation activity is searching for weak spots. For example, if an otherwise excellent concept has an inherent reliability problem it may have to be passed over for a perhaps less brilliant but certainly more reliable concept.

A Post Office in Michigan was fitted with heavy doors that could swing more than 90 degrees from their closed position in either direction. The doors had alloy frames with large glass panels and were fitted with mechanical door closers that always returned the door to its closed position with a 'damped spring' action after use. In order to save maintenance and inventory costs, the original architect had specified the same doors throughout the building. Although physically the door could be used as an exterior door, a number of features such as the lack of positive sealing indicated that it was primarily a door for internal use. However, there was no requirement to this effect and the interchangeability of the doors meant that if, for example, the glass in an external door was ever broken, one of the internal doors could immediately be moved to replace it so that the building security would not be compromised. The external door closest to the public parking area was the most heavily used door in the building. It was exposed to all weathers and the door closer unit required frequent maintenance.

One windy Saturday, an elderly lady was about to enter the Post Office through this door when a gust of wind blew it first inwards and then outwards, evidently without damper control. The door swung outwards and right around until it hit the edge of the building wall close to its axis of rotation then levered itself from its mounting and fell to the ground, killing the lady.

Investigation revealed that the door closer was not working properly at the time of the accident, allowing the door to swing freely in either direction. In addition, the door had a specially designed hinge system to facilitate the interchange of doors. Mounted on the bottom threshold was a roller that fitted into a fixed socket located within the door, forming the bottom 'hinge.' At the top the door closer itself acted as the 'hinge,' mounted on the lintel overhead with its torsion arm connected to the top of the door by means of a spring-loaded quick release mechanism. Heavy usage had resulted in distortion of the door closer torsion arm, sufficient to displace the spring-loaded plunger almost to the point of release. Uncontrolled swinging combined with a leverage action when the door hit the wall generated enough force to separate the door completely from the door closer at the time of the accident.

The design concept of using such a spring-loaded plunger mechanism as part of the door hinge system was inappropriate in that there was no positive connection between the door and its top 'hinge.' A later model of this door design had been installed elsewhere inside the Post Office, with a bolted connection replacing the quick release mechanism. If this had been fitted to the door in question there would have been no accident.

Critical Factor 6: Keeping it Simple

During the phase often termed *Embodiment Design*, the selected concept must be progressively developed into a practical, reliable and safe design. There are specific guidelines available for this phase of the design process [2,3] and if these are ignored, trouble will result. Four factors are of particular importance, the first of which is *simplicity*. The design should be made as simple as possible by, as examples, reducing the number of components, making components do more than one task and promoting the use of near net shape manufacturing techniques. It is all too easy to become enamoured of exciting new technology or a complex way of doing something, to the detriment of the final result.

For example, some of the vegetables in supermarket display cabinets are misted with water to keep them fresh, and this poses design problems such as control of the spray and making sure that the customers don't get a fright if the water happens to come on just when they are picking out some produce. One new design was fitted with a closed stainless steel trough, level controls, four ultrasonic misting devices, oscillator circuits, a blower and all kinds of electromechanical controls. It was indeed a complex mechatronic marvel which defied any attempt to understand its workings without complete disassembly. Once installed it apparently worked, but of course was a nightmare to clean. The result was that it was left alone and it began to generate bacteria as well as the misted water spray. Finally a series of customers fell victim to Legionnaire's Disease, which was traced back to the mechatronic misting device. In fact the whole job could be done just as effectively with simple valves, timers and sprays, without the risk of harboring bacteria.

Critical Factor 7: Making the Functions Clear

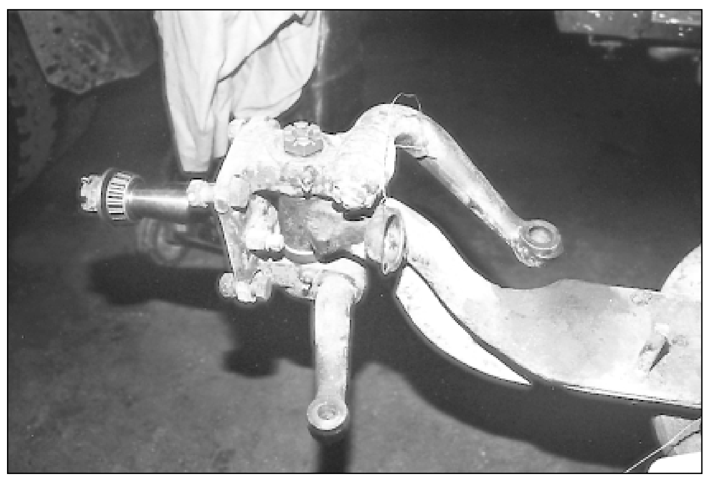
Clarity in design [2,3] means making sure that the design itself explains how the thing is to be put together, what the load paths are, what the function of each component is and what moves relative to what. Specific guidelines are available for addressing this issue in a systematic fashion [3] and, in conjunction with other embodiment design guidelines, failures such as the one described in the following example can be avoided. Lack of clarity in design creates ambiguities and design weaknesses which may not be immediately obvious.

Heavy trucks usually have a beam axle front suspension with a 'kingpin' mounted near vertically through the 'eye' at each end of the axle. The yoke of each front wheel stub axle fits over the corresponding eye of the beam axle and around the kingpin, thereby forming the axis about which the stub axle can swing in order to steer the truck. Kingpins are normally simple cylindrical hardened shafts extending out of the top and bottom of the axle eye into the top and bottom bearings of the stub axle yoke. A thrust bearing is fitted between the bottom of the axle eye and the bottom bearings in the yoke to accept the vehicle weight from the axle eye and transmit it to the yoke while allowing steering action without undue friction. The kingpin is locked in place by means of a cross bolt arrangement through the axle eye.

Fatal accident caused by loss of kingpin from truck steering system

In Ohio, a heavy dump truck was coming around a right hand curve in the road when the front left wheel assembly suddenly collapsed and parted company with the truck. As the steering box was linked to this particular stub axle the driver immediately lost all steering control. The vehicle went straight ahead, colliding head-on with a car going the opposite way and killing the passenger in the car.

Investigation revealed that this particular model of dump truck is fitted with a tapered kingpin which is inserted from the bottom. It is held in place by friction against the tapered hole, together with a nut and washer arrangement at the top. The nut had come loose and the kingpin had dropped progressively as the nut turned. When the nut unscrewed completely the kingpin fell right out of the axle eye, causing the whole wheel assembly to separate from the truck. In conventional arrangements the vertical component of the truck weight is always transmitted from springs to beam axle and from beam axle to stub axle through the thrust bearing below the axle eye. Even if the thrust bearing were to disintegrate, the load path would still pass through the same components. With the dump truck, however, as wear takes place in the thrust bearing the clearance between the nut plus washer at the top of the kingpin and the top of the stub axle yoke decreases to the point where the load path changes. The weight of the truck transfers from the thrust bearing to the nut and washer. It is only a matter of time before the torsional frictional forces are sufficient to shear the pin locking the nut and to start progressively undoing the nut.



Kingpin assembly showing swivelling stub axle connected to fixed beam axle

The embodiment design was deficient in that it allowed an unacceptable load path change with wear or failure of the thrust bearing. This would have been prevented by the use of accepted embodiment design guidelines and the accident would not have happened.

Critical Factor 8: Tackling Safety

Safety is another important aspect of *Embodiment Design* and again there are definite guidelines such as the *Safety Hierarchy* [16] to follow when developing a design concept. Techniques such as safe-life design, fail-safe design, redundant design and hazard analysis [2,3] must be considered as integral parts of the product development, and not simply as 'add-ons' at the end of the project. The focus of Product Liability lawsuits is on the safety aspects of design [17]. It is often claimed that the litigation has the effect of 'improving safety' [18]. However, it is probably more accurate to say that such lawsuits are a very expensive way of addressing safety, and that the results are unpredictable [19]. Sometimes safety is improved, sometimes it is unchanged and sometimes it is compromised. The automobile airbag raises several issues concerning safety in design, as shown by the following example.

A man was driving at night when a deer leapt into the road right in front of his car. The front of the car knocked the deer's legs from under him on impact and as he rolled through the windshield the driver's airbag went off inside, apparently causing the man's hands to be forced upwards into the path of the deer's antlers. An antler caught one of the man's thumbs and took it off. A lawsuit was filed against the manufacturer, claiming that if the airbag hadn't deployed the man would not have lost his thumb.

Would the man have been injured less or more if there had been no airbag? What if the airbag had been there but had not deployed? What if the man had lost control after the airbag deployed and had driven into a tree without any airbag protection? Perhaps the airbag actually protected the man from more serious injuries upon impact by the deer.

Critical Factor 9: Selecting Materials and Parts

A fourth critical factor in *Embodiment Design* is the selection of materials, and the selection of standard components or parts which can be purchased. Of course it is important to select an appropriate material or part to do the job and there are numerous aids which can be used in the selection process. It is obvious that if a wrong selection is made during design then the risk of failure will be high. What is less obvious is the increasing problem of substandard materials and copied or counterfeit parts. Some industries such as the aircraft and petroleum industries, for example, have procedures to ensure that supplied components are in fact what they are claimed to be. However, many others have a long way to go in this area.

A replacement strainer was fitted into a process steam line in a chicken feed plant. Soon afterwards, and luckily during a weekend, the wall of the cast iron strainer blew out. The entire plant had to be cleaned and repainted from the steam damage and of course there were claims and counterclaims over who was at fault. Thickness measurements at the rupture site on the wall of the imported strainer showed the wall thickness to be well below the minimum required by applicable American National Standards. The cut sheet or sales drawing for the strainer indicated 'Quality Assurance' to ISO 9002, yet there was no evidence of any ISO 9000 Registration nor even that the company staff knew what the term meant. This product was held out to be equivalent to those produced by U.S. manufacturers. It demonstrated clearly that it was not.

Critical Factor 10: Details in Design

Once a design has passed through the *Embodiment Design Phase* into the *Detail Design Phase*, it used to be common for it to be 'given to the draftsman (or computer) to finish.' It is a fatal mistake to think that detail design is unimportant and needs less attention than other phases. It is true that excellent detail design cannot compensate for a bad concept, but it is equally true that poor detail design can ruin a good concept. Detail design is critical.

An articulated tractor and low-loading trailer was being driven through some hilly country in Missouri after delivery of a bulldozer to a construction site. The driver noticed that his rear trailer brakes had started to smoke and he found that the brakes were partially applied even though he wasn't using them. He assumed that the brakes were running hotter because he was driving faster through the hills without the load of the bulldozer, and that this heat was causing his brakes to drag. Using a wrench he backed off the brake shoes from each wheel to where he thought they were correctly adjusted. He telephoned his dispatcher from the next rest area, explained what had happened and was told that he should continue with his journey. A few miles later the weather changed to a misty drizzle and way up ahead of him he saw that a minor rear-end accident had just occurred at an intersection. He applied his brakes but found that there were now no brakes on his heavy trailer. People started running about on the road and shoulder ahead of him so he could not steer around. He decided all he could do was to apply his brakes as hard as he could. The tractor-trailer jackknifed completely and collided head-on with a vehicle coming the other way. One person was killed and several were seriously injured.

Large articulated trucks generally have air-operated braking systems and certain types of low-loading trailers require the use of a particular relay valve because of their physical layout. The relay valve directs and releases air depending on signals from the driver's brake pedal, trailer brake controls and the integrity of the air system. An inspection of the valve from the accident trailer showed that a small valve head with a 5mm-threaded stem had come loose. The valve head hangs down from a piston and when the threaded connection came loose it progressively unscrewed to the point where the valve head blocked an air escape port, thus causing the brakes to remain partially applied. Without knowing it, the driver had backed off his brake shoes to the point where they could not come into contact with the drums when the brakes were applied. It was later found that the detail design of this particular threaded connection had been revised and tested numerous times by the manufacturer and that several thread-locking methods had been put into production over the years. The thread involved in the accident had not been locked in place and the loose thread tolerance allowed complete unscrewing to occur.

The detail design was poor in that a critical component was hung vertically inside a valve by a loose 5-mm thread. The unscrewing of the thread resulted in the death of one person and serious injuries to several others. It was a known problem which had been brought to the attention of management and if it had been addressed properly the accident would not have happened.

Summary

The ten critical factors described in this paper are ones observed to have been the primary contributors to failures in design. However, the root cause of failures often lies at a deeper level. In engineering design, there is a continuing quest for *faster, better, cheaper*, and it is this which leads to the shortcuts, mistakes, misjudgments and defects in the design process. Nevertheless, when management takes these ten critical factors seriously, together with all those involved in the product realization process, the chance of success in design can be improved beyond all measure.

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