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An Innovative Engineering Design Model by the Aid of TRIZ Methodology and CAE Technology

By

Ning (Nathan) Yu

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ABSTRACT

Many successful industrial companies aim at improving product development in order to be competitive. This thesis is intended to make a contribution to the work of fulfilling this goal.

There are three methods to shorten the cycle time of the new product development process. First is changing the product development process; second is changing the product design method; third is using new technology. This thesis presents research that advocates process, methods and new technology for performance related robustness improvements in product development.

Rapid advances in technology in recent years have set new demands on product development. As a consequence, an increasing variety of products are built on heterogeneous technologies. Specialists from different engineering disciplines must co-operate to a greater extent than before in order to understand the products. Increased cooperation and heterogeneous technologies in products set high demands on rapid product development models in order to deliver products of high quality in short lead time, at low cost.

One of the most important tasks in robust design is to select an appropriate system output response. The quality of this selection will greatly affect the effectiveness of the robust design project. Currently, this selection process is more like art than science. By using

TRIZ Design principle, several new approaches to enhance robust design are developed. These approaches enable us to select the appropriate system output response in a systematic fashion. The approach developed in this paper was successfully applied and verified in two case studies in two different major automotive companies.

This research consists of theory development, mainly in the field of engineering design, TRIZ and CAE. The research in the papers provides: (1) An approach to problem solving by combining design object analysis with TRIZ and FEA (2) Two case studies carried out with the researcher actively taking part in practical problem solving.

ACKNOWLEDGEMENTS

I have been truly fortunate to work with Dr. Michael H. Wang and to have him supervise my research. I would like to thank him for his extraordinary support, enthusiasm and inspiration over the past three years, without whom I would not be considering the idea of continuing further in academics. Our weekend discussions of thesis direction I will not forget. Additionally, I would like to thank him for giving me the freedom to choose this thesis topic to discover.

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1.1 New Product Development

Many successful industrial companies choose product development as a means of acquiring, strengthening and maintaining market share and competitive advantage.

Product development is the process of creating a new product to be sold by a business or enterprise to its customers. Design is an important step in the product development process. Design refers to those activities involved in creating the styling, look and feel of the product, deciding on the product's mechanical architecture, selecting materials and processes, and engineering the various components necessary to make the product work. Development refers collectively to the entire process of identifying a market opportunity, creating a product to appeal to the identified market, and finally, testing, modifying and refining the product until it is ready for production. A product can be any item from a book, musical composition, or information service, to an engineered product such as a computer, hair dryer, or washing machine. [1]

1.1.1 Concept of Product Design and Engineering Design

Design has two concepts, product design and engineering design. Product Design is concerned with the concretion of a product. It is concept visualization in actual dimensions. A product that is a real object can be touched and handled. One has to plan for handling by a human being or on a human body when considering its shape and weight. It can be ergonomically tested in its usage, working, and handling conditions.

Treatments of surfaces, proper textures, proper interactive devices are all earnestly examined for recommended actions during a product's design. The choice of material, shape formation, molding, cutting and add-ons, joints-all such essential details need to be considered part of "Dimensionality" and evaluated in a prototype. Visible outer surfaces and proper inner clearances for moving parts are crucial aspects of product visibility and function. Since products occupy some space, the consideration of the essential unoccupied area around the product and their proportions to each other is an equally important aspect of Product Design.

Engineering Design is mainly concerned with manufacturing the ingredients / parts of a product: their tooling, surfacing finishing and finally assembly. The interaction of moving parts, their interaction, procedural dependency and the overall performance of individual components and assemblies is of prime importance. At each stage the application of proper tools and technology, reduced production time and improved cost structures make the Engineering Design concept qualitatively superior and hence marketable. Engineering Design is also influenced by a product's usage, maintenance, replacement of parts or innovation, as needed. [2]

1.1.2 Market-pull Products and Technology-push Products

The impetus for a new product normally comes from a perceived market opportunity or from the development of a new technology. Consequently, new products are broadly categorized as either *market-pull* products or *technology-push* products. With a market-pull product, the marketing center of the company first determines that sales could be increased if a new product were designed to appeal to a particular segment of its customers. Engineering is then being asked to determine the technical feasibility of the new product idea. This interaction is reversed with a technology-push product. When a technical breakthrough opens the way for a new product, marketing, then attempts to determine the idea's prospects in the marketplace. In many cases, the technology itself may not actually point to a particular product, but instead, to new capabilities and benefits that could be packaged in a variety of ways to create a number of different products. Marketing would have the responsibility of determining how the technology should be packaged to have the greatest appeal to its customers. With either scenario, manufacturing is responsible for estimating the cost of building the prospective new product, and their estimations are used to project a selling price and estimate the potential profit for the company. [1]

Market-driven companies are aware of their marketplace and try to develop products that meet the needs of that marketplace. They are concerned with growing their market share by concentrating on using the technologies they already have in-house or that are readily available from the outside. Technology-driven companies look beyond the limitations imposed by their current technologies. They assume that the needs of tomorrow's customers will not be met with today's technologies. They try to develop new technologies without necessarily knowing what markets the products developed from these technologies will serve. They believe that, once the new technologies are developed, a search for market opportunities will yield commercially successful products. [3]

1.2 Challenges to the New Product Development

1.2.1 Difficulty of New Product Development (Figure 1.1)

Depending on which engineering discipline is being considered, any or all of the following factors must be evaluated as part of the engineer's design solution. [4]

- **Power.** The amount the product produces or consumes.
- **Speed.** How fast does it operate? How long will it take to manufacture?
- **Cost.** The price to the consumer to purchase, the cost to the company to manufacture, and the cost its implementation will have on society in general.
- **Reliability.** How well does it operate? How long will it last? Is it a quality product?
- **Safety.** Are there any health risks?
- **Functionality.** Does it perform the desired tasks effectively?
- **Ease of use.** Can the customer operate it easily and intuitively?
- **Aesthetics.** Is it pleasing to see, feel, touch, or hear.
- **Ethics and social impact.** Will it benefit or harm people and the social or physical environments in which they live?
- **Maintainability.** How easily and cost-effectively can it be kept in good working order?
- **Testability.** How easily and effectively can it be tested by the manufacturer prior to volume production for the market?
- **Manufacturability.** What issues must be addressed in the manufacture of the product?

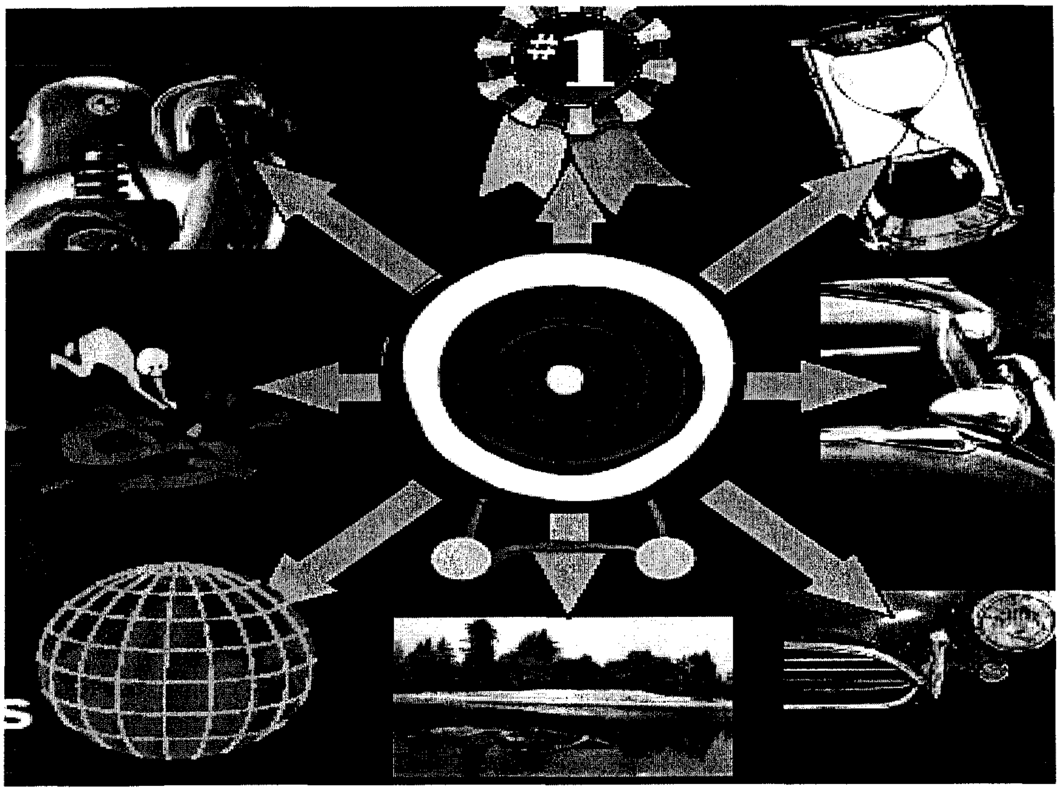


Figure 1.1 the Requirements of Engineering Design

1.2.2 New Product Development is Time Consuming and Costly

The task of developing outstanding new products is difficult, time-consuming, and costly. People who have never been involved in a development effort are astounded by the amount of time and money that goes into a new product. Great products are not simply designed, but instead they evolve over time through countless hours of research, analysis, design studies, engineering and prototyping efforts, and finally, testing, modifying, and re-testing until the design has been perfected.

Few products are developed by a single individual working alone. It is unlikely that one individual will have the necessary skills in marketing, industrial design, mechanical and electrical engineering, manufacturing processes and materials, tool-making, packaging design, graphic art, and project management, just to name the primary areas of expertise. Development is normally done by a project team, and the team leader draws on talent in a variety of disciplines, often from both outside and inside the company. As a general rule, the cost of a development effort is a factor of the number of people involved and the time required to nurture the initial concept into a refined product. Rarely can a production-ready product be developed in less than one year, and some projects can take three to five years to complete.

New product development or improvement on existing products in today's technology–driven markets carries significant risks. Studies indicate that new product failure rates can be as high as one out of every three products. [5]

1.3 Problems in Product Development

1.3.1 Economy Globalization

Globalization is a hot topic today in North America. Three fundamental factors have affected the process of economic globalization and are likely to continue driving it in the future. [6]

First, improvements in the technology of transportation and communication have reduced the costs of transporting goods, services, and production as well as communicating knowledge and technology.

Second, the mood of individuals and societies has generally, but not universally, favored taking advantage of the opportunities provided by declining costs of transportation and communication through increasing economic integration.

Third, public policies have significantly influenced the character and pace of economic integration, although not always in the direction of increasing economic integration.

Increasing globalization and worldwide competition due to significant political changes, open markets, and fostered by the increased communication network's capability, has totally altered international business relationships. There are two major changes to the business models: reduction of product development cycle time and reduction of cost.

Since worldwide competition offers customers more opportunities to fulfill their desires, customer demand and call for innovative, customized products increases. This increased product capability has resulted in highly interrelated development systems, integrating diverse requirements and knowledge. Desire for product variety and customization thus forces a trend toward complexity and integration. To meet open market windows in highly dynamic markets, companies have to reduce their development cycle time, while increasing their total corporate flexibility to respond to changing markets and keep their development efforts on track.

Outsourcing, which can reduce product cost significantly, is another trend to meet the requirement of globalization and worldwide competition.

1.3.2 Timing is always a Key Role in Competition

Suppliers to the engineering community are keen to stress their role in helping their customers get their products to market faster. Making the design process faster and cheaper while maintaining quality is a critical element of this, but what does the engineering design community see as the barriers to making this happen? CAD SPAGHETTI, The Business Advantage Group Plc, interviewed senior decision makers at 250 Mechanical Engineering sites to find out what they perceived as the barriers - if any - to implementing change and improving their design processes. [7]

The chart below shows perceptions of a range of potential barriers categorized as major, minor or non-barriers. Issues of time are identified as a major barrier by one in ten sites, while cost of solution was a barrier identified by the second-highest number of respondents. (Figure 1.2)

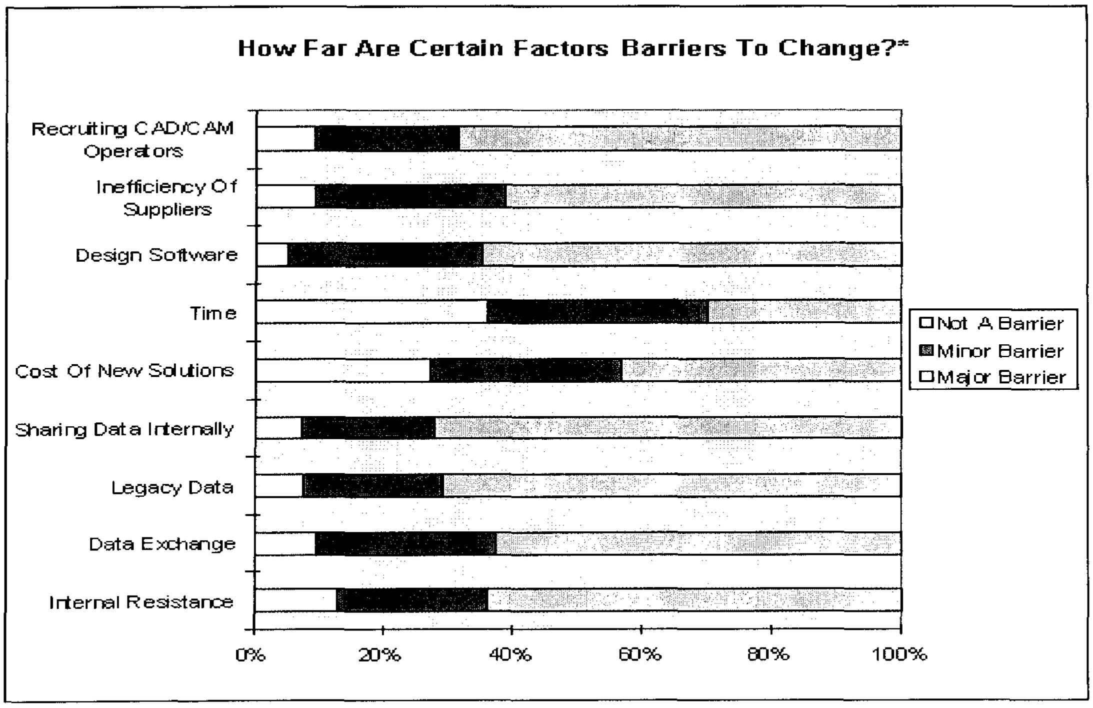


Figure 1.2 the Barrier in Business Development

1.3.3 Requirements of Product Localization

Under the background of globalization, production of parts often needs to be localized. For the following reasons, engineering change was often required in the localization process:

a. Product needs new design to fit the local culture
b. Material is not available
c. Technology is not available
d. Trained workforce is not available
e. Manufacturing equipment is not available

1.3.4 Examples of Changes in Automotive Industry [4]

- The cycle development time from concept to production has been compressed significantly in the past 10 years, for example:

  1992: 60 months
  1996: 48 months
  2000: 18 months

- Vehicle designs are tailored to focused markets
- Vehicles are being manufactured more on a global scale
- Vehicles are designed increasingly through multiple engineering sites around the world
- The need for enabling companies throughout the supply chain and extended enterprise to share information through a web-centric visualization approach

1.4 Robust Design and Design for Six Sigma Meets the Challenge

The Robust Design method, also called the Taguchi Method, pioneered by Dr. Genichi Taguchi, greatly improves engineering productivity. By consciously considering the noise factors (environmental variation during the product's usage, manufacturing variation, and component deterioration) and the cost of failure in the field the Robust Design method helps ensure customer satisfaction. Robust Design focuses on improving the fundamental function of the product or process, thus facilitating flexible designs and concurrent engineering. Indeed, it is the most powerful method available to reduce product cost, improve quality, and simultaneously reduce development interval. [8]

Over the last five years many leading companies have invested heavily in the Six Sigma approach aimed at reducing waste during manufacturing and operations. These efforts have had great impact on the cost structure and hence on the bottom line of those companies. Many of them have reached the maximum potential of the traditional Six Sigma approach. What would be the engine for the next wave of productivity improvement?

Brenda Reichelderfer of ITT Industries reported on their benchmarking survey of many leading companies, "design directly influences more than 70% of the product life cycle cost; companies with high product development effectiveness have earnings three times the average earnings; and companies with high product development effectiveness have revenue growth two times the average revenue growth." She also observed, "40% of product development costs are wasted!"

These and similar observations by other leading companies are compelling them to adopt improved product development processes under the banner Design for Six Sigma. The Design for Six Sigma approach is focused on 1) increasing engineering productivity so that new products can be developed rapidly and at low cost, and 2) value based management.

1.5 TRIZ Methodology is a Key Role in Robust Design and Design for Six Sigma

TRIZ is a Russian acronym for the Theory of Inventive Problem Solving originated by Genrikn Altshuller. TRIZ is the result of more than 45 years of research by Genrich Altshuller and colleagues.

How can the time required to invent be reduced? How can a process be structured to enhance breakthrough thinking? It was Altshuller's quest to facilitate the resolution of difficult inventive problems and pass the process for this facilitation on to other people. In trying to answer these questions, Altshuller realized how difficult it is for scientists to think outside their fields of reference, because that involves thinking with a different technology or "language". In the course of the study of some 400,000 inventions as depicted in patent descriptions, Altshuller noticed a fundamentally consistent approach used by the best inventors to solve problems. At the heart of the best solutions, as described by the patents, existed an engineering conflict, or a "contradiction." The best inventions consistently solved conflicts without compromise. Upon closer examination and classification of innovative solutions, natural patterns of solutions started to emerge. Altshuller had discovered that when an engineering system was reduced to reveal the essential system contradictions, inventive solutions eliminated the contradictions completely. Furthermore, Altshuller noticed that the same inventive solutions appeared repeatedly at different points in time and in different places. Figure 1.3 shows the principle of solution by abstraction, [9].

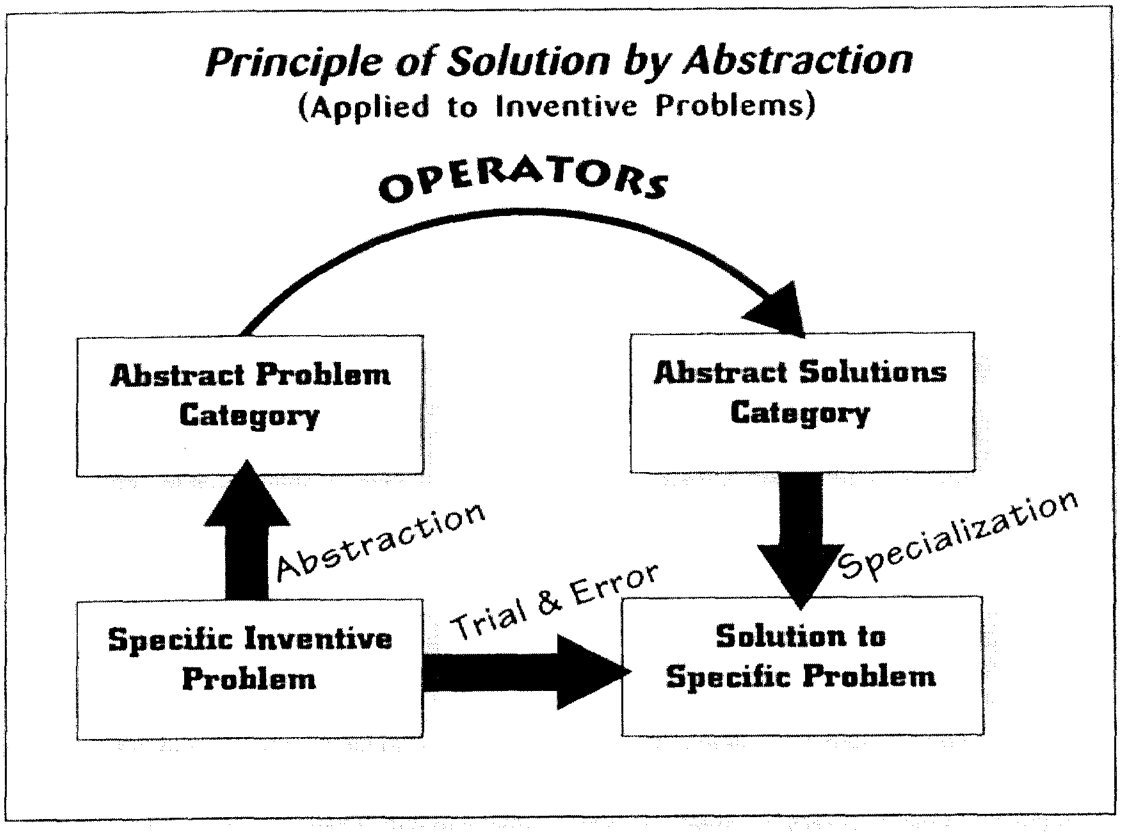


Figure 1.3 TRIZ Methodologies

1.6 Motivation of Thesis

1.6.1 Focus in Early Design Phase (Figure 1.4)

Reducing time to market has become imperative in competition, and the technology to generate breakthrough concepts and ideas has become the real key to success. [10]

Engineering Changes can be made more easily and less expensively earlier in the process rather than later, [Figure 1.4]. For example, if a change occurs during the concept phase, little time or money has been spent. However, as additional materials and manpower are needed with each succeeding step, there is a corresponding increase in cost and effort. The following table gives a typical example of the cost of design changes with each stage of development. [11]

Stage in Product Development	**Cost of Failure Design**
Concept	X
Design	10X
Tooling	100X
Testing	1,000X
Release	10,000X

Figure 1.4 Engineering Change Cost

Cost committed at the end of detail design is approximately 70% of total product cost. [12](Figure 1.5)

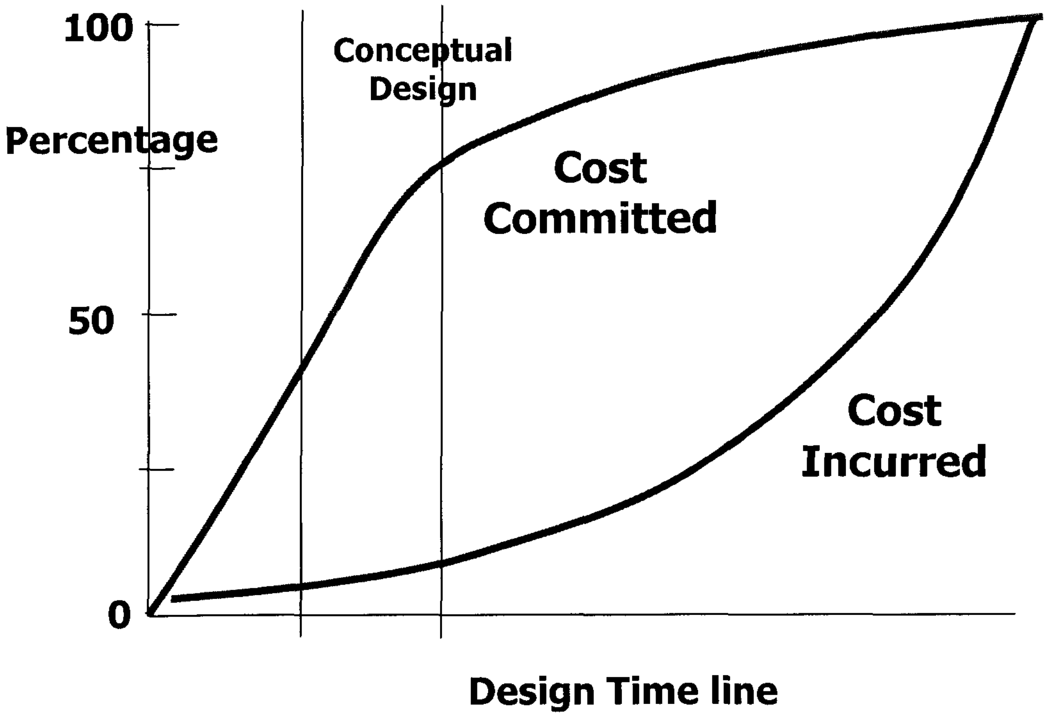


Figure 1.5 Engineering Design Cost and Timing

As we have seen above, early design is very important to save the whole cost of engineering design. However, early design requires more knowledge. This characteristic of early design limits the reduction of design time and increases the risk of failure design. (Figure 1.6)

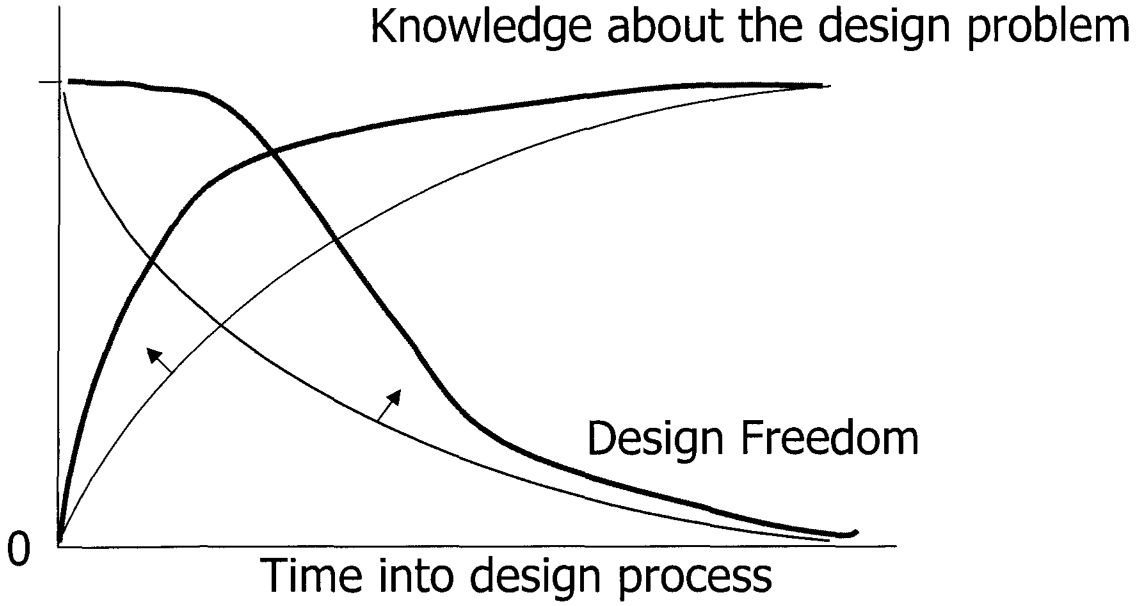


Figure 1.6 Early Designs Needs More Knowledge

It is at the beginning of the design process, during the conceptualization phase, that it is most important to consider alternative solutions. Once the decision to proceed has been made and funding approval has been granted, it becomes increasingly costly and difficult to make changes. Human beings tend to lose their objectivity once they have identified with a particular scheme and have contributed to its formulation and initial planning. Thus, it becomes increasingly difficult for the people involved in the process to recognize the value of, or justification for, making significant changes. [13]

1.6.2 Integration Methods in Product Development

Computer Aid Engineering (CAE)

Simulation Based Design and virtual prototyping can be used to decrease the time required to formalize a system's concept design space, to quantify operational cost effectiveness of new technologies, to quantify risk, and to expedite technology transfer.

CAE (computer-aided engineering) is a broad term used by the electronic design automation (EDA) industry for the use of computers to design, analyze, and manufacture products and processes. CAE includes CAD (computer-aided design) - the use of a computer for drafting and modeling designs, and CAM (computer-aided manufacturing) - the use of computers for managing manufacturing processes.

Examples of CAE Capabilities

- Finite Element Analysis
- Volume and Weight Calculations
- Automatic Dimensioning
- Interference Checking
- Kinematic Simulation
- Circuit Analysis and Simulation

The primary benefit of CAE is that it allows the designer(s) to "quickly and easily" perform a wide variety of complex and computationally intensive analysis procedures. CAE allows the design team to conduct a wide range of analysis procedures and thereby evaluate design performance without need of a physical model of the part. It allows them to more completely analyze the performance of alternative designs before expending resources to develop working prototypes. In addition, the graphics capabilities of today's systems allow the design teams to more completely visualize what the part will look like and, in the case of dynamic analysis, how some mechanisms will work.

Results of CAD & CAE implementation [14]

- Reduced prototypes and testing
- Better integration with suppliers
- Increased reuse of existing designs
- Early prediction of product attributes
- More predictable program results
- Knowledge capture and reuse

Integration of Design Methods & TRIZ

Companies have ever been confronted with the question of development. In the face of competition, the ever more rapid emergence of new products, changing consumer fashions and globalization, they are forced to call into question the efficiency of their design methods to keep a competitive edge and ensure their survival.

An integration of Quality Function Deployment (QFD) in product development is presented in Clausing (1994). Teamwork and other organizational aspects of product development continue to be greatly improved through the introduction of Integrated Product Development Teams and cross-functional teams (see for instance Ulrich and Eppinger, 1995). Concurrent engineering reduces lead times in product development by promoting parallel development tasks. A comprehensive summary of concurrent engineering is presented in Sohlenius (1992) and organizational aspects of concurrent engineering are discussed for instance, in Fleischer (1997). Nevertheless, the new Internet technology and the rapid development of CAD, together with ongoing globalization and the trend toward outsourcing, further increase in complexity and speed in product development by theoretically enabling distributed product development to be carried out 24 hours a day in different parts of the world. [15].

Although we have these robust design methodologies, the high risk of failure in new product development is legendary. Industrial companies often cling to past successes to reduce their chance of failing. For these companies new product development means launching limited extension of their own successful products, imitating successful competitors, or acquiring firms with new products. They often regard truly innovative products as serendipitous. But TRIZ, being an innovation tool, provides a backbone for new product concept development.

Traditional methods of design all involve a phase at some stage in the process when the idea is triggered off. However, they all delegate this ability to come up with ideas to the creative skills of mankind. The problems are reformulated and analyzed from various angles; the conditions that are most conducive to generating ideas are set up for people, but the result – that flash of genius – always and ever stems from a person. The account of TRIZ presented here does not call into question intrinsic creativity, but lifts ones ability to generate ideas to a higher plane by guidance you in the right direction. [16]

TRIZ is the only scientifically based systematic methodology that overcomes this "psychological inertia". TRIZ has been proven to produce a large range of fundamentally strong solution concepts in a much shorter time scale even when resources are very limited. TRIZ solutions directly result in improved products at reduced cost.

Integration of Design Process and Design Methods

Nam Suh, chairman of the Mechanical Engineering Department at Massachusetts Institute for Technology (MIT), developed a very useful model of Product Development as a mapping of elements between various domains. Peter Senge, also of MIT, developed a useful model concerning ways or levels of thinking. When these two models are combined, a new model is created that can be used to understand the history and evolution of quality and the role of Six Sigma and Design for Six Sigma (DFSS) in product development. [17]

Quality in product development began with attempts to inspect quality into products or services either in the process domain (scrap and rework), the design domain (verification tests and durability failures) or the customer domain (warranty costs and complaints). The evolution of quality involved a significant mind-set transition from reacting to inspection events to utilizing process patterns in engineering and manufacturing to build quality into the product. Recent developments in quality engineering involve the use of structural tools to lay the proper foundation for good design and enable the process level methods to work better. Six Sigma is used to react to or fix unwanted events in the customer, design or process domains. DFSS is used to prevent problems by building quality into the design process across domains at the pattern level of thinking. Use of new structural tools such as TRIZ and axiomatic design provide a foundation for future enhancement of Six Sigma methodologies.

The engineers answer, a sequence of build/test/fix cycles, is event thinking. The transition from event thinking to pattern thinking is the transition from find and fix to prevent. (Figure1.7)

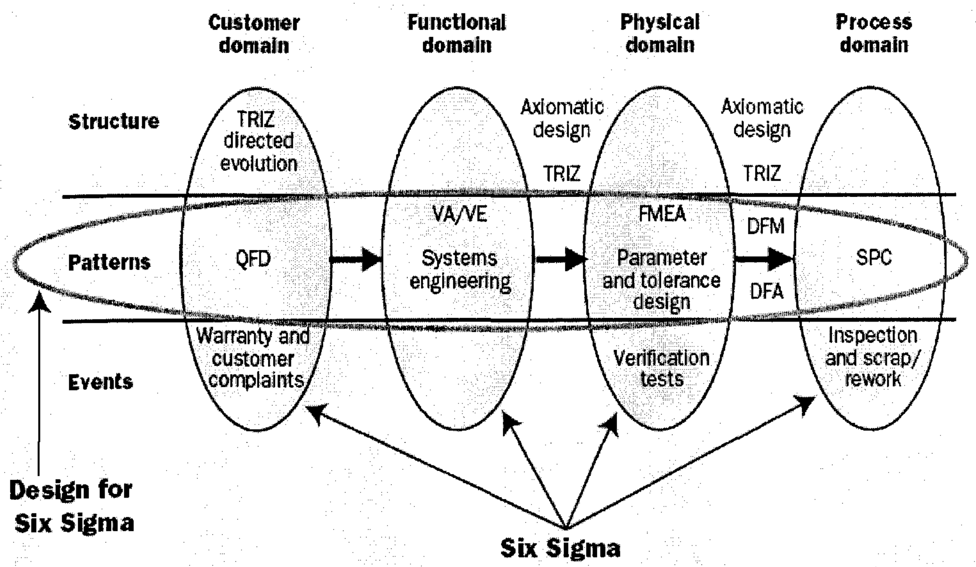


Figure 1.7 Design Process and Design Methods to Achieve Six Sigma

New Proposal

Integration of management & organization, design tools and methods and new technologies can further improve product development. Rapid prototyping provides early field-testing opportunities and thus validation and verification of the envisioned system. Therefore, there exist the need for standardized tools and frameworks, which support the designer in creating new design based on suggestion from TRIZ.

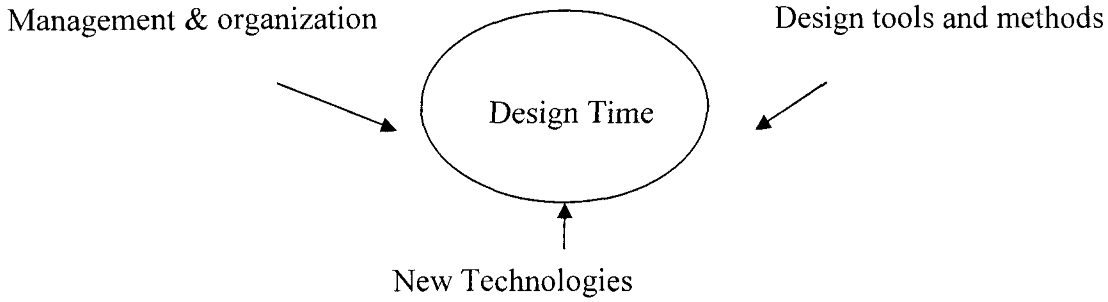


Figure 1.8 Three Elements as Enables for Time Saving in Engineering Design

1.7 Objective

As discussed above, early design is more complicated, risky and important than design during later phases. So this thesis tries to develop a new design model with the application of new design methods and new design technology to overcome the barriers in early design.

Typical elements in concept development include:

- Conceptual design generation is highly interactive and mostly manual
- Inconsistent use of heuristics, rules of thumb
- Successes requires experienced and skilled practitioners

Possibility today:

- TRIZ, Functional Diagrams
- Material- process- section selector
- Topology optimization
- Rapid prototyping

TRIZ tools and applications, which are based on an extensive theoretical base, have been successfully utilized to overcome technological roadblocks and dilemmas. The utilization of TRIZ can focus efforts toward the best design very early in the process, during the idea creation phase. If a design team can get a definite idea at the beginning of a product design, then the CAE engineer can implement the optimal design before or during the design detail phase without worrying about a design change in future. With the help of TRIZ and CAE, a new product design process model is proposed in this thesis. The new product design process model can reduce the cycle time and increase the design capability.

a. Create a new product design process model with the application of TRIZ methodology and CAE technology.
b. Improve the efficiency of product design with the new model by two case studies; one case will focus on product development, the other case will focus on manufacturing process design. These two cases will also show how to solve mechanical problems with the TRIZ Tool.

1.8 Organization of Thesis

This thesis begins with an introduction of the background and previous research performed in key areas, such as this work related to the following: Engineering design, Global sourcing strategy, engineering design methodology, new design methods and new technology application. An engineering design process and design methods are reviewed in Chapter 2 to show how the engineering design process is changed to fit the global competition today. Research on design methodology is then reviewed with a focus on the design methods used in the concept design phase. In Chapter 3, an introduction of TRIZ methodology is reviewed. Robust design and Design for Six Sigma are discussed in chapter 4. The second part of Chapter 4 presents a new integrated design method for the rapid design in the early design phase.

Chapter 5 and Chapter 6 presents the detailed examples of the application of the new proposed early design process to illustrate its use. Chapter 7 concludes the thesis with a summary of the work performed and the proposed new design process in early design phase. Future research areas are identified and discussed.

Chapter 2 Engineering Design Process, Design Methods and CAE Technology

2.1 The Concept of Engineering Design

Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision making process, in which the basic sciences, mathematics, and engineering sciences are applied to convert resources optimally to meet a stated objective. Among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing and evaluation. [18]

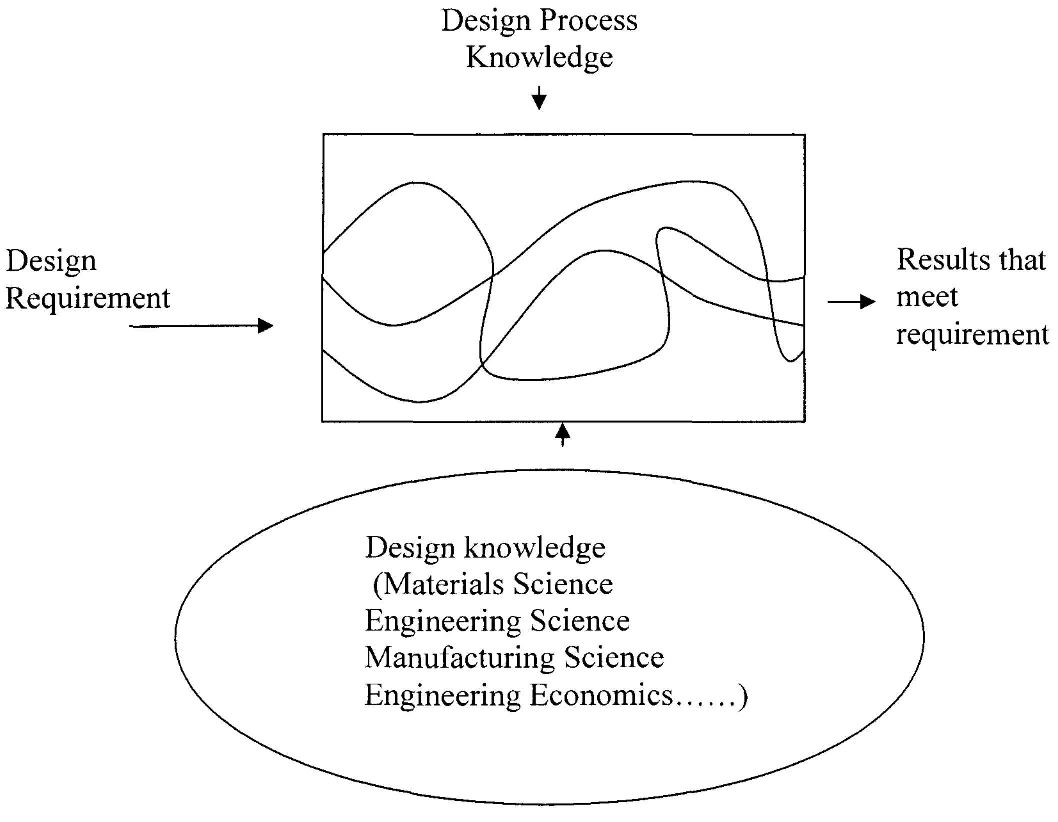


Figure 2.1 Engineering Design Process Diagrams [19]

An experienced professional engineer uses a different approach to a design problem than the typical engineering student. The experienced professional engineer may estimate quick answers, draw on past experience, look up information from a variety of sources, consult a colleague, etc., while the typical engineering student would first look in the back of the text for the answer and then try to find a similar example problem. [20]

2.2 Is Engineering Design Art or Science?

The question of whether design is an art or science has been treated in many books published during the past few years. Most authors recognize the importance of intuitional developing creative solutions to design problems, especially during the concept formulation stage. The intuition of a well-qualified designer is a trait developed over a period of time while the designer is doing design. These accumulated design experience are stored in the brain, and in some miraculous way they are accessed as the engineer develops solutions to new design problems, so that the appropriate elements of each experience are synthesized to formulate a concept. This explanation makes a compelling argument that design can only be taught by doing design and that design is more an art than a science. [13]

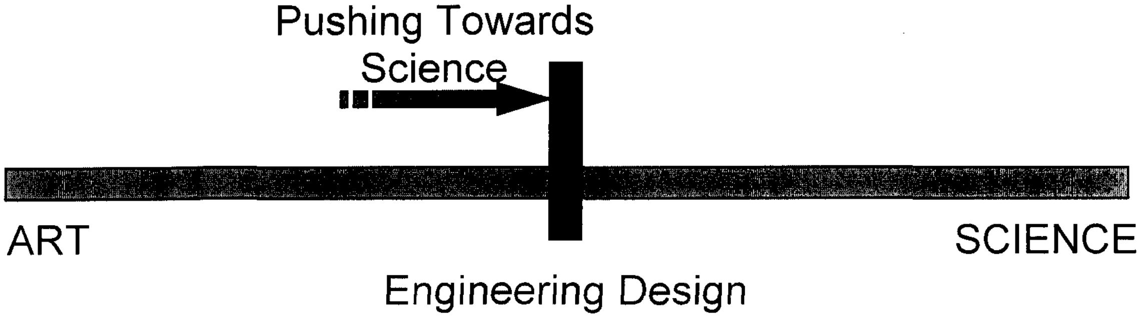


Figure 2.2 Engineering Design Methods Pushing Design to Science

State of Engineering Design is being pushed closer and closer to being a science, yet it cannot shed some of its nature related to art. (Figure 2.2) [12]

2.3 Engineering Design Process

2.3.1 A Few Definitions of the Engineering Design Process

Descriptions of the engineering design process are many and varied. Figure 2.3 illustrates the cyclical nature of the design process and the different stages of activity that an engineer or a design team of engineers goes through in order to complete the design process. This simplistic representation can be made much more elaborate by refining each of the design stages into many sub-processes. It is also implicit to this model that much iteration may occur among the sub-processes. [21]

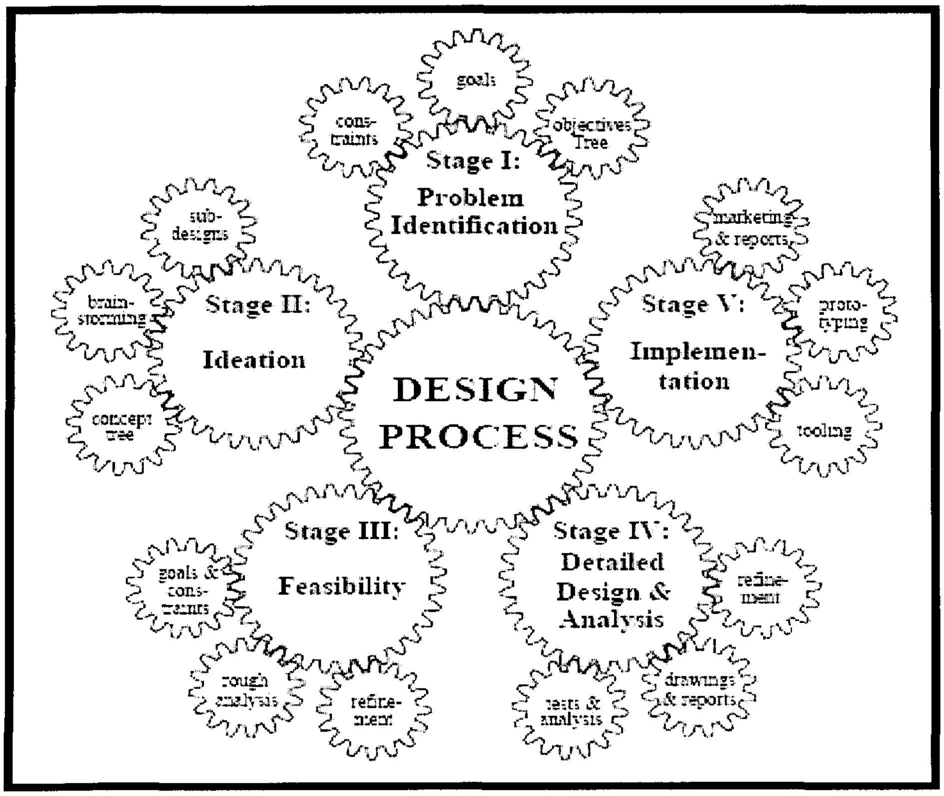


Figure 2.3 Design Process

Clive Dym and Patrick Little in their book, Engineering Design: A Project-Based Introduction, identify 5 steps in the engineering design process. [22](Figure 2.4)

A. PROBLEM DEFINITION PHASE
B. CONCEPTUAL DESIGN PHASE
C. PRELIMINARY DESIGN PHASE
D. DETAILED DESIGN PHASE (OPTIMAL DESIGN PHASE)
E. DESIGN COMMUNICATION PHASE

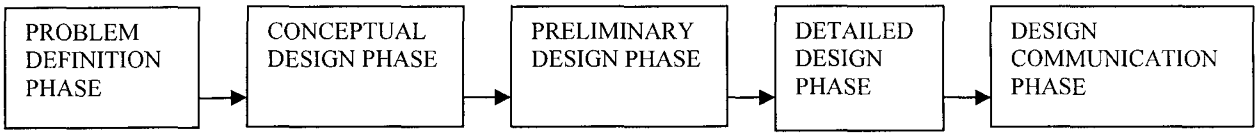


Figure 2.4 Classics Engineering Design Process

Traditional engineering design practices include the following [23].

- Analytical models -- conventional, historical and statistical.
- Design reviews -- peer review and input.
- Experimentation to determine unknown information
- Prototyping.
- Searching & studying patent literature.
- Setting tolerances and the methods used to check them.
- Team collaboration to focus the knowledge and skills of several individuals on the same problem.
- Using standards of all types for components, procedures, CAE, CAD, etc.

Joseph Shigley [24] describes the engineering design process as follows.

1. Recognition of need
2. Definition of Problem
3. Synthesis (Taguchi system selection)
4. Analysis & Optimization (Taguchi parameter & tolerance design)
5. Evaluation
6. Presentation

George Dieter [25] describes the engineering design process as follows...

1. Recognition of a need.
2. Definition of a problem.
    1. Musts -- market driven principal design goals, performance specifications, etc.
    2. Must nots -- government regulations, industry standards, product liability risks, safety & environmental concerns.
    3. Wants -- the voice of the customer, innovative technologies.
    4. Don't wants -- undesirable features or consequences -- the voice of the customer.
3. Gathering information
    1. Identify suitable sources.
    2. Allow sufficient time for order processing.
    3. Stay abreast of the latest research & developments in technology, analysis, materials & processing.

    4. Travel to professional and industrial conferences occasionally.

4. Design.
    1. Feasibility study
        - Do some brainstorming. Don't be constrained by "traditional thinking."
    2. Conceptual design. (Taguchi systems design)
        - 3-D geometric models
        - Adherence to required and accepted standards
        - Functional requirements
        - Marketing requirements
    3. Detailed design. (Taguchi parameter & tolerance design)
        - 3-D geometric models
        - Material and standard component selection
        - Selection of critical dimensions, sizes, speeds, temperatures, flow rates, etc. (Taguchi parameter design)
        - Selection of tolerances. (Taguchi tolerance design)
        - Use standard component sizes where possible to reduce cost.
    4. Planning for manufacture. (Taguchi quality management)
        - 3-D geometric models
        - Look at employee safety (OSHA).
        - Look at environmental concerns (EPA).
        - Look at providing adequate product quality.
    5. Planning for distribution.

        - Look at employee safety (OSHA).
        - Look at environmental concerns (EPA) -- packaging.
        - Look at product marketing.
    6. Planning for use.
        - Look at operator safety & convenience (OSHA).
    7. Planning for disposal.
        - Look at environmental concerns (EPA) -- recycling.

5. Evaluation of the design.
    1. Bayesian decision making methods
    2. Decision matrix
    3. Draw from a wide variety of viewpoints -- design review, quality audit.
6. Communication of the design.
    1. 2-D shop drawings
    2. 3-D geometric models
    3. Business plan
    4. Manufacturing process plans
    5. Written documentation of product goals to guide future modifications

2.3.2 Best Practices of Engineering Design Process

The engineering design is a dynamic process that changes and adapts as needed. The engineering design process should always be evaluated in its context a part of the overall product realization process.

Best practices in engineering design continue to be defined as companies compete in the marketplace. The following are some engineering design "best practices" that have recently been identified [23].

- **Consider the whole product life cycle** "S" curve early in the design process.
- **Design for excellence**, manufacturability, assembly, inspection, etc.
- **Generate metrics** (measures) for evaluating design practices.
- **Implement new management accounting practices** to take into account the less visible contributions of engineering and design to profitability. For complex products, design is often a large portion of the total product development cost. Cost cutting based solely on visible accounting numbers is counterproductive and often disastrous in the long run.
- **Use CAD and CAE** extensively.
- **Use concurrent design** (parallelism) to reduce time to market.
- **Use product quality-cost models** and design rating systems. Upwards of 70% of the product cost is committed to early in the design phase. Simpler products are usually better, as well as cheaper to make.
- **Use Quality Function Deployment (QFD)** -- A QFD team defines and ranks product attributes according to customer wants. They then assign weights to each attribute. They then benchmark competing products according to the weighted list of attributes and compute a final product score, the higher the better.
- **Use Taguchi robust design**.
    - **Phase I: systems design** -- establish the concept, form & initial parameter values (Conceptual design)

    - **Phase II: parameter design** -- selection of parameter values. Critical parts should be high precision, others may be of lower precision. Taguchi experiments using signal-to-noise ratio can be used to optimize the parameter values and identify the inherent variability. Parameters with low variability can have tight tolerances. (Detailed design, part 1)
    - **Phase III: tolerance design** -- adjust the parameter tolerances for maximum yield in the final assembled product. . (Detailed design, part 2)
- **Use the quality-loss function**. (Taguchi)

2.4 Engineering Design Methods

Design methods include Value Analysis (VA), Quality Function Deployment (QFD), Axiomatic Design (AD), the Pahl & Beitz Approach (P&B), Concurrent Engineering (CE), Robust Design (RD), Design for Manufacturing (DFM) and the TRIZ method. After analyzing the various design methods, it was found that people initial reaction was that confusion reign as to what they can offer the designer. Indeed, while they all advocates that they can act as a reference in terms of how a design project should be conducted, they rarely make allusions to what could be perceived as complementarily between them. This state of affairs often leads to redundancy in terms of the answers they provide for the designer. [26]

2.4.1 Value Analysis (VA) [27]

Value Management is a style of management particularly dedicated to motivating people, developing skills and promoting synergies and innovation, with the aim of maximizing the overall performance of an organization.

Value Management has evolved out of previous methods based on the concept of value and functional approach. These were pioneered by Lawrence D. Miles in the 1940's and 50's that developed the technique of Value Analysis (VA) as a method to improve value in existing products. Initially Value Analysis was used principally to identify and eliminate unnecessary costs. However it is equally effective in increasing performance and addressing resources other than cost. As it evolved the application of VA widened beyond products into services, projects and administrative procedures.

The Value Management Approach involves three root principles:

- a continuous awareness of value for the organization, establishing measures or estimates of value, monitoring and controlling them;
- a focus on the objectives and targets before seeking solutions;
- a focus on function, providing the key to maximize innovative and practical outcomes.

The concept of Value relies on the relationship between the satisfaction of many differing needs and the resources used in doing so. The fewer the resources used or the greater the satisfaction of needs, the greater the value. Stakeholders, internal and external customers may all hold differing views of what represents value. The aim of Value Management is to reconcile these differences and enable an organization to achieve the greatest progress towards its stated goals with the use of minimum resources (see figure below)

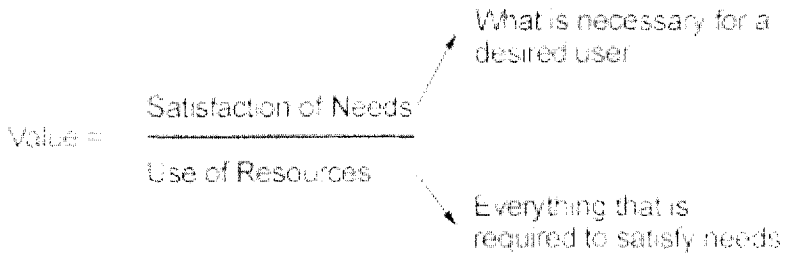


Figure 2.5 Value Design

It is important to realize that Value may be improved by increasing the satisfaction of need even if the resources used in doing so increase, provided that the satisfaction of need increases more than the increase in use of resources.

2.4.2 Quality Function Deployment (QFD)

Yoji Akao introduced the concept of QFD in Japon in 1966. According to Akao QFD is a method for developing a design quality aimed at satisfying the consumer and then translating the consumer's demand into design targets and major quality assurance points to be used throughout the production phase [28].

QFD has been used as an important part of the product development process. QFD is an investment in people and information. It uses a cross functional team to determine customer requirements. QFD is a systematic and analytical technique for meeting customer expectation. QFD is a planning process for translating customer requirements (voice of the customer) into the appropriate technical requirements for each stage of product development and production (i.e. marketing strategies, planning, product design and engineering, prototype evaluation, production process development, production, sales) [29] and [30].

The QFD concept is broken down into the two main activities: Product quality deployment and deployment of the quality function. Product quality deployment translates the “voice of the customer” into product control characteristics. Whereby, deployment of the quality function activities needed to assure that customer required quality is achieved. Deployment of the quality function examines the company response to the customer voice through an organized team approach [31].

The "House of Quality" (HOQ) is one step in the overall process of quality function deployment. The HOQ links the customer needs to the technical requirements. Such a link is essential to relating product characteristics to customer needs in a way that assists engineers in designing the product. [32]

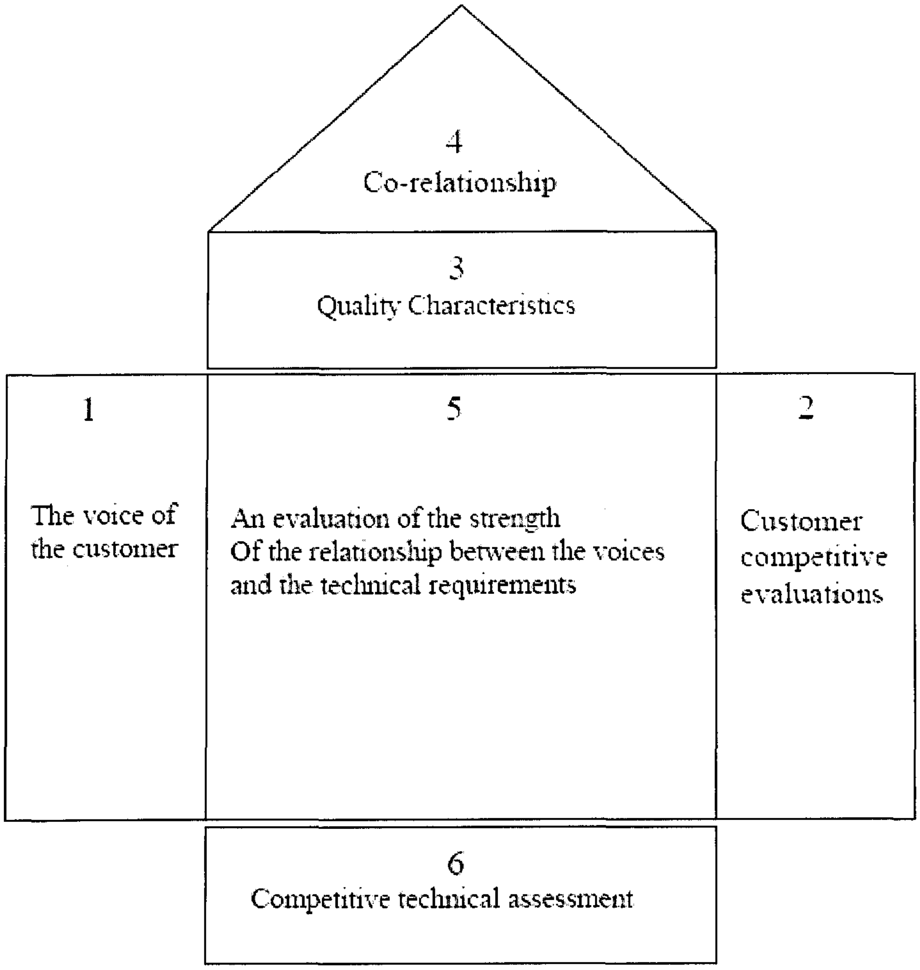


Figure 2.6 the House of Quality

The "Clausing Four Phase Model" is the most widely known and utilized of these approaches [33].

For example to design a copier, the design team must define the technical specifications, the product design that will meet these specifications (motor, gears, belts, cabinet, metal or plastic, etc.), the processes to manufacture these parts, the processes to assemble the copier, and the production plan to have it built. QFD links each of these activities using a series of four maps or houses, as shown in Figure 2.7. [32]

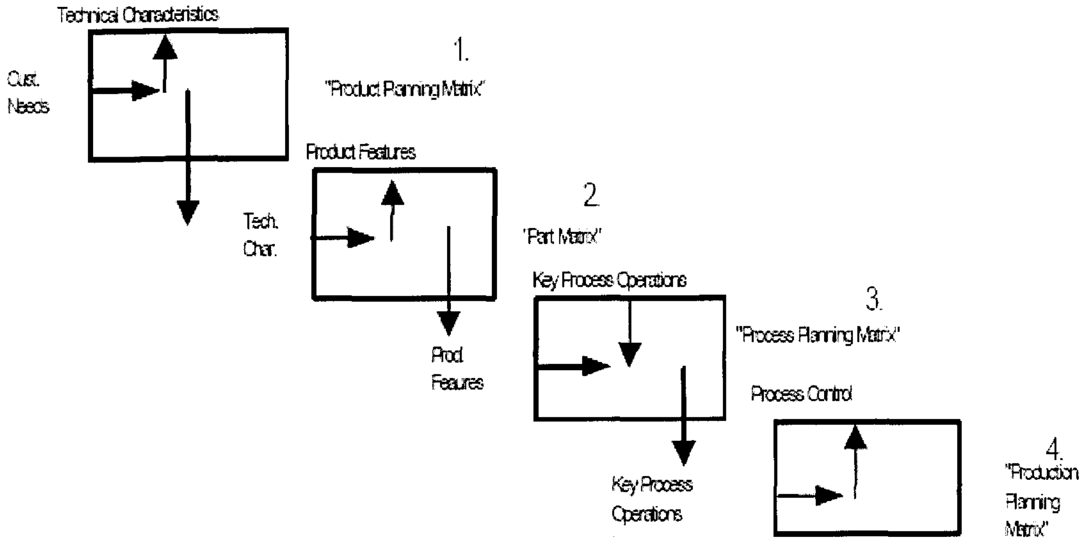


Figure 2.7 Four House Approach to QFD

The First House, known as the House of Quality, links the customer needs to the technical requirements but in a crude fashion: a graphical key indicates qualitatively the relationships as positive or negative.

The next task is to take the target values for the technical requirements, which will be called the technical characteristics and link them to physical attributes: part characteristics or product features. QFD's approach to this task is to use a house diagram again, but in a revised manner. Technical characteristics such as speed become the rows of this Second House (Part Matrix) while part characteristics such as motor type, rotor diameter, etc. become the columns. Again, the relationship is described qualitatively using symbols similar to those in the first house.

Next, product features such as motor type become the rows of the third house while process design parameters such as the r.p.m. of the copper armature machine become the columns. The relationships are qualitative and subjective. This house is sometimes called the Process Planning Matrix.

Finally, in House Four, the process design parameters become the rows and production requirements such as process control, operating training, and maintenance become the columns. These relations, again, are subjective and qualitative.

The use of a QFD approach links customer needs to technical requirements and manufacturing decisions so that products can be designed effectively and manufactured efficiently. By the links provided in these Houses, the design team assures that the customer needs are deployed through to manufacturing.

2.4.3 Axiomatic Design

Axiomatic design was developed by Nam Suh. Axiomatic Design addressed the internal relationships of a design and applies a probabilistic view of design. Axiomatic Design has been chosen as the theoretical basis of the new approach of engineering design process in this thesis. This is due to the fact that Axiomatic design especially addresses the internal relationships of a design and applies a probabilistic view of design.

Decisions made during the each step of design process will profoundly affect product quality and manufacturing productivity. To aid design decision making, Axiomatic Design theory has been developed in the last decade. The Axiomatic Design approach to the execution of the above activities is based on the following key concepts: [34]

(1) There exist four domains in the design world, customer domain, functional domain, physical domain and process domain. The needs of the customer are identified in customer domain and are stated in the form of required functionality of a product in functional domain. Design parameters that satisfy the functional requirements are defined in physical domain, and in process domain manufacturing variables define how the product will be produced. The whole design process involves the continuous processing of information between and within four distinct domains.

(2) Solution alternatives are created by mapping the requirements specified in one domain to a set of characteristic parameters in an adjacent domain. The mapping between the customer and functional domains is defined as concept design; the mapping between functional and physical domains is product design; the mapping between the physical and process domains corresponds to process design.

(3) The mapping process can be mathematically expressed in terms of the characteristic vectors that define the design goals and design solution.

(4) The output of each domain evolves from abstract concepts to detailed information in a top-down or hierarchical manner. Hierarchical decomposition in one domain cannot be performed independently of the other domains, i.e., decomposition follows zigzagging mapping between adjacent domains.

(5) Two design axioms provide a rational basis for evaluation of proposed solution alternatives and the subsequence selection of the best alternative. The two axioms can be stated as follows:

Axiom 1 (independence axiom): *maintain the independence of the FRs.*
Axiom 2 (information axiom): *minimize the information content of the design.*

The first axiom is the independent axiom, and it focus on the nature of the mapping between "what is required" (FRs) and "how to achieve it" (DPs). It states that a good design maintains the independence of the functional requirements. The second axiom is the information axiom and it establishes information content as a relative measure for evaluating and comparing alternative solutions that satisfy the independence axiom.

The four-domain structure is schematically illustrated in Figure 2.8. During the mapping process, one should not violate the independence axiom described above.

In the product design, the creation or synthesis phase of design involves mapping the FRs in the functional domain to design parameters (DPs) in the physical domain. Since the complexity of the solution process necessarily increases with the number of FRs, it is important to describe the perceived design needs in terms of a minimum set of independent requirements. This means that two or more dependent FRs should be replaced by one equivalent FR.

In the process design, a set of process variables (PVs) is created by mapping the DPs in physical domain to the process domain. The PVs specify the manufacturing methods that produce the DPs.

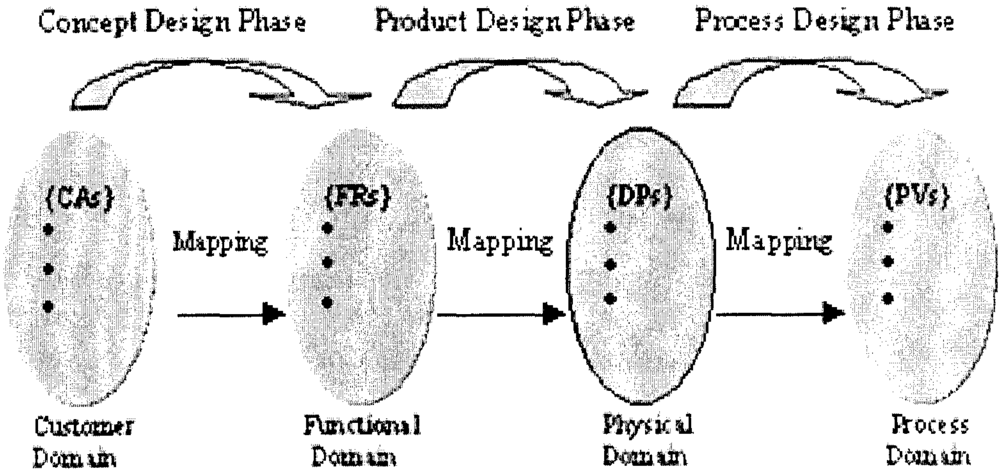


Figure 2.8 Four Domains of Axiomatic Design

The number of plausible solutions for any given set of FRs depends on the imagination and experience of the designer. Thus, the design axioms are used to determine acceptable design solution. Defining {FR} as a vector of functional requirements and {DP} as a corresponding vector of design parameters, and {PV} as vector of process variables, the mapping between the functional and physical domains, between physical and process domains can be expressed mathematically in equation (1) and (2).

In equation (1) and (2), [A] and [B] are called design matrix. To satisfy the Independence Axiom, matrix [A] and [B] must be either diagonal or triangular. When the design matrix, for example [A], is diagonal, each of the FR can be satisfied independently by means of one DP and this design is an uncoupled design. When the design matrix is triangular, the independence of FRs can guarantee if the DPs are changed in a proper sequence, and this design is a decoupled design. When there are many FR&DP, two quantitative measures, reangularity and semangularity in equation (3) and (4), are used to determine the independence of the functional requirements [35].

$$\{FR\} = [A] \times \{DP\} \qquad \ldots\ldots\ldots\ldots \qquad (1)$$

$$FR_i = \sum_j A_{ij} \cdot DP_j$$

$$\{DP\} = [B] \times \{PV\} \qquad \ldots\ldots\ldots\ldots \qquad (2)$$

$$DP_i = \sum_j B_{ij} . PV_j$$

$$R = \prod_{\substack{i=1,n-1 \\ j=i+1,n}} \left(1 - \frac{\left(\sum_{k=1}^{n} A_{ki} . A_{kj}\right)^2}{\left(\sum_{k=1}^{n} A_{ki}\right)^2 \left(\sum_{k=1}^{n} A_{kj}\right)^2}\right)^{\frac{1}{2}} \qquad \ldots\ldots \qquad (3)$$

$$S = \prod_{j=1}^{n} \left(\frac{|A_{jj}|}{\left(\sum_{k=1}^{n} A_{kj}^2\right)^{\frac{1}{2}}}\right) \qquad \ldots\ldots\ldots\ldots \qquad (4)$$

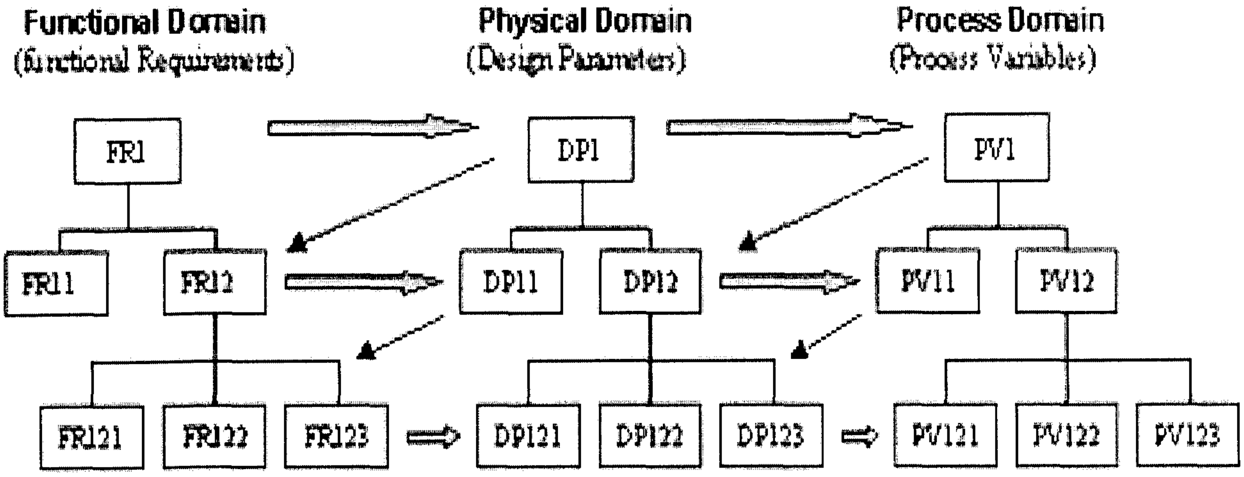


Figure 2.9 Zig-Zaging between Design Domains

Figure 2.9 is a graphic interpretation of the general mapping process between functional and physical domains, and between physical and process domains. The FR-to-DP mapping takes place over a number of levels of abstraction. A given set of FRs must be successfully mapped to a set of DPs in the physical domain prior to the decomposition of the FRs. Iterations between FR-to-DP mapping and the functional decomposition suggest a zigzagging between the functional and physical domains.

2.4.4 Pahl and Beitz [36]

The Pahl and Beitz model presented here is that proposed by Pahl and Beitz (1996). This is one of the most established models of the design process. In this model the design process consists of four main phases which proceed sequentially, these phases are Clarification of the task, Conceptual design, Embodiment design and finally Detail design (Figure 2-10). Their model is closely associated with the German industrial standard for product design VDI 2222.

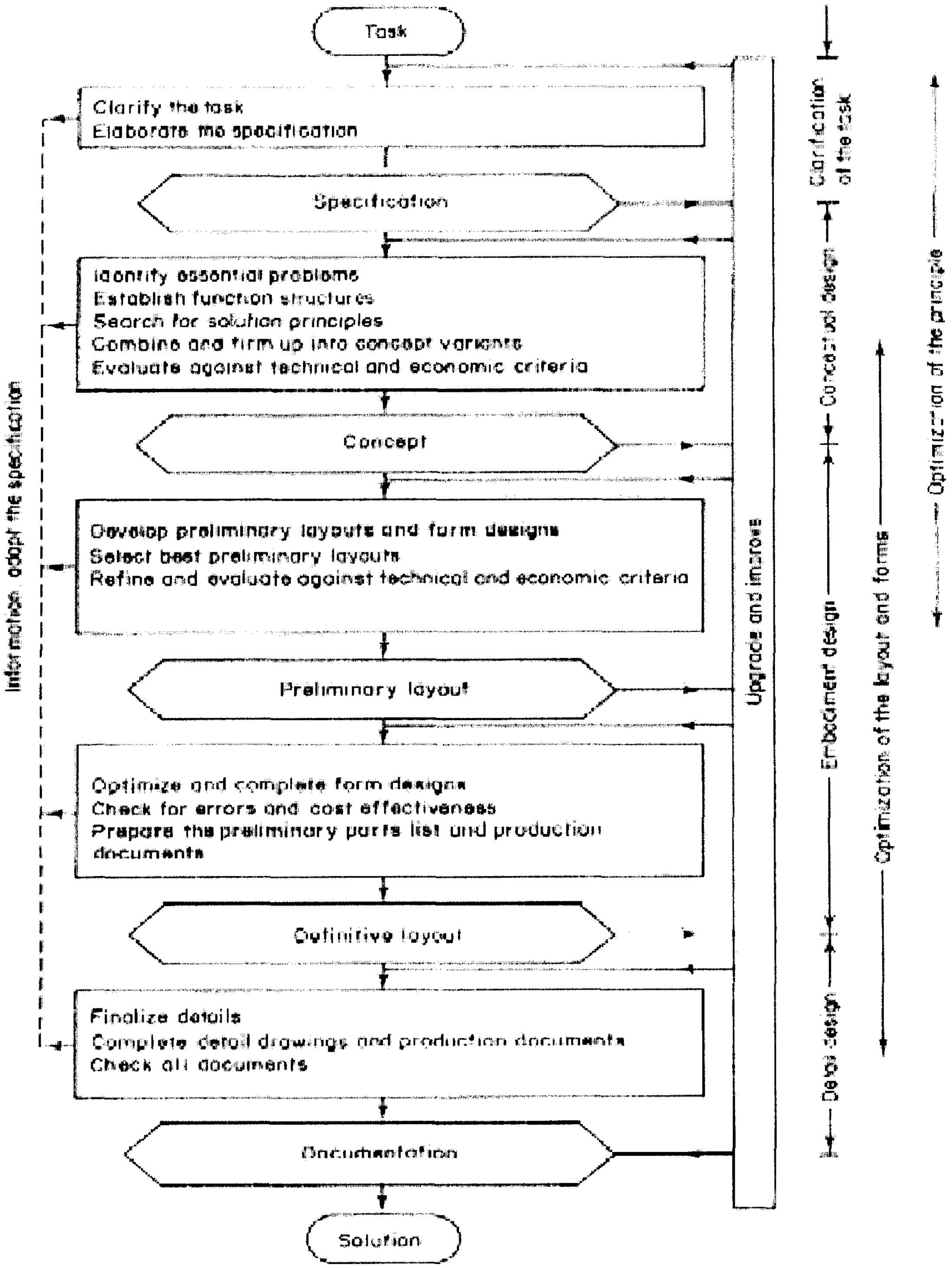


Figure 2.10 Pahl and Beitz Design

2.4.5 Concurrent Engineering (CE)

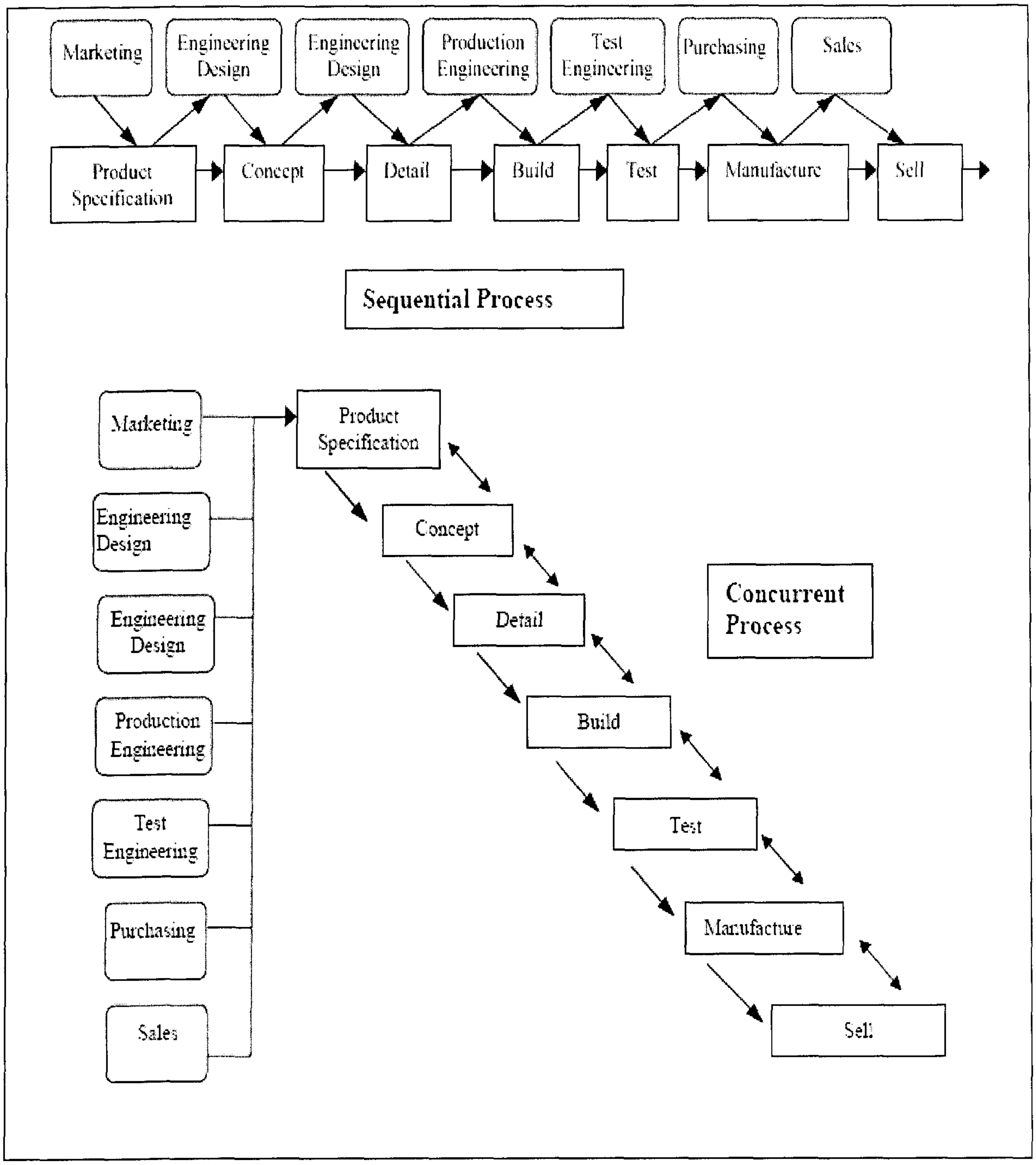


Figure 2.11 Sequential and Concurrent Developments of New Products

CE is a systematic approach to the integrated, concurrent design of products and related processes, including manufacture and support. Typically, concurrent engineering involves the formation of cross-functional teams, which allows engineers and managers of different disciplines to work together simultaneously in developing product and process design. This approach is intended to cause developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements [37].

2.5 Engineering Design Phase and its Methods

The development process is divided into four essential phases: data collection and analysis (Collect); creation (Create); construction (Construct); and growth (Produce). Then illustrates the comparison among these design methods (Figure 2.12) [26]

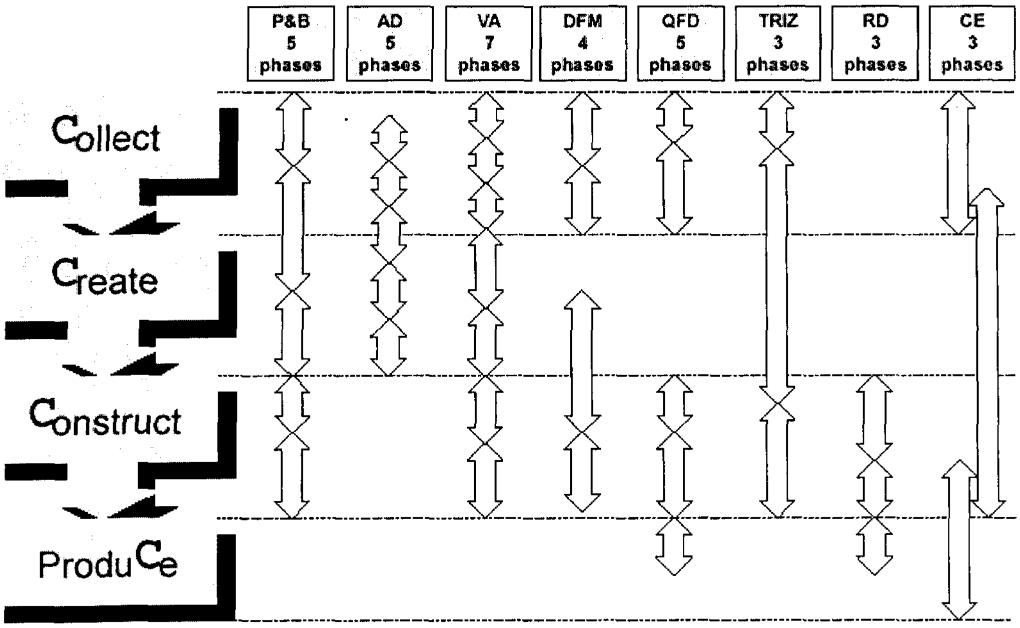
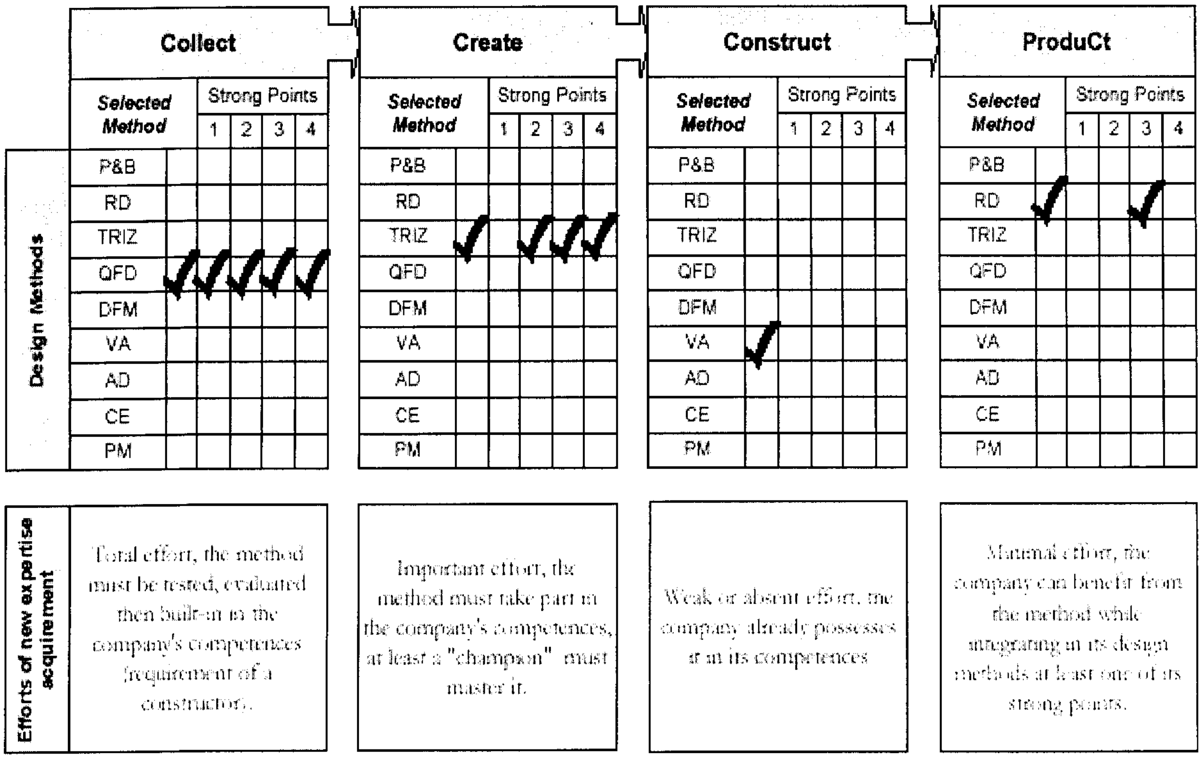


Figure 2.12 Parallel between Design Methods

The four phases clearly pinpoint the essential notions for all the methods. Since the methods are highly generic, they provide a structural approach to the project and in no way consist of a rigid, fixed structure. Through the comparative analysis, the method appears to be atypical in terms of its contribution to design methods. Indeed, its relevance and operational profile are fundamentally different from those of other methods studied. This is particularly true for the creativity phase which, although its is barely relevant in other methods, is the strong point of TRIZ, since the methodological effort of a company wishing to improve its design process will no doubt occur with TRIZ.

From the strong points which have arisen from the design methods, an intuitive design method process has been built. Initially, the different phases were formalized. The aim is to apply all the tools best adapted to the project. Figure 2.13 gives a summary of these steps and the expected objectives. [26]



Collect

Design Methods	Selected Method	Strong Points 1	2	3	4
P&B					
RD					
TRIZ					
QFD	✓	✓	✓	✓	✓
DFM					
VA					
AD					
CE					
PM					

Create

Design Methods	Selected Method	Strong Points 1	2	3	4
P&B					
RD					
TRIZ	✓		✓	✓	✓
QFD					
DFM					
VA					
AD					
CE					
PM					

Construct

Design Methods	Selected Method	Strong Points 1	2	3	4
P&B					
RD					
TRIZ					
QFD					
DFM					
VA	✓				
AD					
CE					
PM					

ProduCt

Design Methods	Selected Method	Strong Points 1	2	3	4
P&B					
RD	✓			✓	
TRIZ					
QFD					
DFM					
VA					
AD					
CE					
PM					

Efforts of new expertise acquirement	Collect	Create	Construct	ProduCt
	Total effort, the method must be tested, evaluated then built-in to the company's competences (requirement of a constructor).	Important effort, the method must take part in the company's competences, at least a "champion" must master it.	Weak or absent effort, the company already possesses it in its competences	Minimal effort, the company can benefit from the method while integrating in its design methods at least one of its strong points.

Figure 2.13 Intuitive Design Process

2.6 The Development of CAE Technology [38]

2.6.1 Introduction of CAE

Computer aided engineering is concerned with the application of computerized equipment to the engineering function. The aim of CAE is to have an open and homogeneous flow of technical information; integration between the various computerized, automated and networked units within the product development function and between this and the rest of the organization. CAE can be regarded as a key link and source to a common product database, on the technical engineering development side. It is much more than a CAD suite or a CAD CAM set up, it's a melding of not just these, but other systems too.

Computer Aided Engineering not only supports other concepts such as design for manufacture (DFM), but it also broadens the possibilities of what could be produced from the product architecture to materials, allowing the team to evaluate rival possibilities to enable the best product and strategic product goals. It also augments the management role and allows other functions, such as manufacturing engineering, closer access to design and allows for greater input and greater power to manipulate that information to complete tasks and reduce development time.

Computer simulations aim to imitate the behavior of a given system or situation. It allows for a partially, or suggested product design to be evaluated in a given situation - such as its own manufacture at an intended production facility. This, along with many of the other CAE tools can greatly aid design for manufacturability. It can be taken further, and compared against the real-life results when the product is manufactured for real which in turn will help in validating the simulation model which could be of further use in other project developments. The system most likely to be of use to a product delivery team is discrete event simulation using a next event system, commonly used to study queuing problems. As such it can model a pilot build through to full production build and may even be able to handle layout changes and part changes. This again will aid the process writing and layout design in the manufacturing shop floor area, before any real work is done - this then would not only save money, but also time, as an optimum layout could be ready as the product is ready to go into production.

2.6.2 Computer Aided Design [CAD] and Computer Aided Manufacture [CAM]

CAD

Most companies involved in design work today have at least a basic CAD set-up. In larger organizations this extends to CAD/CAM integrated systems and beyond - but the basic principles of CAD are always present - the ability to draw a part by computer (with all the flexibility that offers over a drafting board) and store it in an electronic format; many primarily being used without integration, to store, retrieve and print copies off of a particular drawing. Popular CAD based packages include AutoCAD from Autodesk and TurboCAD, through to more expensive packages such as Unigraphics. As computer aided design has evolved, it has come beyond a 2-D representation on a screen to incorporate 3-D drawings and on to solid modeling, i.e. although on screen the component would appear as a surface model, it would actually be a solid, representing a parts volume, its occupation of space, its centre of gravity. This allows a model to be spun and viewed in virtually any axis or angle, and then color rendered to appear as a solid, even with its final color and material texture. This is not merely a 'pretty picture'; it can give valuable information about a component or product's finished appearance, and may be of particular value to field and marketing representatives. Systems which excel in generating this 'virtual' product include IBM/Dassault's CATIA system, as used on the Boeing 777.

CAM

These types of features allow CAD to integrate further with other tools such as expert systems, since a line on a screen is no longer simply a reference point, but also a representation of a slot etc. From these models, many CADCAM systems can generate suggested tool paths, and even complete CNC code with the correct post-processing software, to facilitate DNC (Distributed, or Direct, Numerical Control) and other functions that require a representation of a part in real 3-D rather than a schematic in third or first person perspective, such as rapid prototyping tools e.g. stereo lithography. Examples of modern CADCAM systems which can integrate with several CAE tools are Pro\Engineer and ICAD. The latter of these is currently in use all over the world in companies such as Jaguar and British Aerospace and is fundamentally based on object oriented technology. It incorporates many facets of CAE such as knowledge systems and the ability to endow CAD representations with product structure and part dependency information as well as being able to incorporate manufacturing rules. Once these are set and the part model is complete, then various factors can be changed in one area of a part, and the ICAD system will automatically alter the rest of the part to suit in accordance with its rule base - with the effect of reducing modification times. It is also able to interface with parts databases and other knowledge bases. This means it can output not just drawings, but machine code, paths and even bills of materials [BOM] for a product.

2.6.3 FEA Analysis

Finite Element Analysis is a very powerful engineering design tool that enables engineers and designers to simulate structural behavior, make design changes, and see the effects of these changes. The finite element method works by breaking the geometry of a real object down into a large number (1000's or 100,000's) of elements (e.g. cubes). These elements form the mesh and the connecting points are the nodes. The behavior of each little element, which is regular in shape, is readily predicted by set mathematical equations. The summation of the individual element behavior produces the expected behavior of the actual object.

The mesh contains the material and structural properties that define how the part reacts to certain load conditions. In essence, FEA is a numerical method used to solve a variety of engineering problems that involve stress analysis, heat transfer, electromagnetism, and fluid flow. FEA is in effect a computer simulation of the whole process in which a physical prototype is built and tested, and then rebuilt and retested until an acceptable design is created.

Clearly, testing physical prototypes can be costly and time consuming when compared with running a computer simulation. However, FEA is not meant to replace prototype testing, merely to complement it. Testing is a means of validating the computer model. In certain cases it is impossible to accurately model a complex real life situation. Thankfully, with the constant improvements in today's finite element software, such situations are becoming more and more infrequent.

2.6.4 Virtual Manufacture

Manufacturing is a dynamic, exciting, and critical industry. A rapidly shrinking world is changing at an increasingly frantic rate. Manufacturing systems and processes are being combined with simulation technology, computer hardware, and operating systems to reduce costs and increase company profitability. [39]

Perhaps one of the most interesting and important of these recent developments is called "Virtual Manufacturing." Often termed "The Next Revolution in Global Manufacturing," virtual manufacturing involves the simulation of a product and the processes involved in its fabrication. Simulation technology enables companies to optimize key factors directly affecting the profitability of their manufactured products. These include manufacturability, final shape, residual stress levels, and product durability. They directly affect profitability by reducing the cost of production, material usage, and warranty liabilities. In addition, virtual manufacturing also reduces the cost of tooling, eliminates the need for multiple physical prototypes, and reduces material waste. This allows everyone to "get it right the first time." It provides manufacturers with the confidence of knowing that they can deliver quality products to market on time and within budget.

Small improvements in manufacturing have dramatic and profound effects in terms of cost and quality

Return on Investment calculations have shown that small savings in material usage deliver enormous returns in a manufacturing environment. For example, an automotive customer found that each ounce of material saved in a forged car engine component saved many hundreds of thousands of dollars of material costs each year. He calculated the impact on customer satisfaction, from the extra power available to the engine, to the reduced running costs of the final vehicle. These calculations are simple thanks to the large manufacturing runs.

2.6.5 Benefit of CAE

Fewer prototypes

The more trials you can simulate in a virtual environment, the less physical prototypes you need to perfect your design. This means you spend more time up front in engineering and design, and less resources running physical trials. Virtual prototyping is cheaper than building physical models and optimizing your design by trial-and-error. It is not a complete replacement for physical testing, but it can minimize the effort and enable the resulting physical tests to be more successful.

Less material waste

If you build fewer physical models, you waste less material in the form of prototypes as well as the tooling used to create them.

Reduced cost of tooling

Again, it follows that if you build fewer prototypes, then you develop fewer tools, which are typically very expensive. Furthermore, by modeling the tools, you can reduce the tool wear, thus increasing tool life.

Confidence in manufacturing process

Even if the tools are properly designed, the control of the tools may affect the quality of the part produced. Virtual manufacturing allows you to simulate the part, the tools, and their control. This simulation can let you optimize your tool control before building prototypes, again letting you "get it right the first time."

Improved quality

We have repeatedly seen our customers improve their part quality by utilizing virtual manufacturing techniques. There are numerous examples throughout this paper, and almost all of them result in a part with quality produced at lower cost than previously attained through traditional prototyping techniques.

Reduced time to market

Time to market is becoming increasingly critical in an age where information can be transmitted and shared readily. Although virtual manufacturing may translate into spending more resources in the design and engineering phases, the resulting product will need much less rework downstream. This saves enormously in unforeseen redesign and reengineering efforts.

Lower overall manufacturing cost

The bottom line is that our customers have had success incorporating virtual manufacturing techniques into their processes, and none have gone back to the traditional product design cycle. We are confident that you will also share in this success.

Chapter 3 TRIZ Methodology and Literature Review

3.1 Instruction of TRIZ Methodology

TRIZ is Russian acronym for The Theory of Inventive Problem Solving that originated from extensive studies of technical and patent information. TRIZ is the result of more than 45 years of research by Genrich Altshuller and colleagues. In 1946, Altshuller decided that he must create a new science for the theory of invention. By 1985, Altshuller had written over 14 books. Only two of Altshuller's books have been translated into English. Altshuller's key findings are explained in these books, which reflect his study of over 200,000 patents, focusing on 40,000 identified as containing the most innovative solutions. [40]

Studies of patent collections by Altshuller, the founder of TRIZ, indicated that only one per cent of solutions were truly pioneering inventions, the rest represented the use of previously known idea or concept but in a novel way [34]. Thus, the conclusion was that an idea of a design solution to new problem might be already known. But where this idea could be found?

The pillar of the Theory of Inventive Problem Solving (TRIZ) is the realization that contradictions can be methodically resolved through the application of innovative solutions. This is one of three premises upon which the theory is built: 1) the ideal design is a goal, 2) contradictions help solve problems, and 3) the innovative process can be structured systematically. [40]

Altshuller hated compromise. He called the situation where functions oppose each other contradictions and developed a methodology in which design teams could systematically innovate and find design parameters that resolved contradictions, creating win-win functional situations. The methodology began by identifying all possible contradictions that existed in patent databases and identifying how these contradictions were resolved. Altshuller found that only a few particular principles of resolution have ever been used in the history of mankind to resolve certain pairs of functional contradictions.

The general knowledge generated by solutions in TRIZ can be organized and used as shown in Figure 3.1. Inventors should match their problems to similar standard problems. Then possible standard solutions associated with the standard problem can be applied to the specific problem. Via this process, TRIZ accumulates innovative experience and provides access to the most effective solutions independent of industry. The traditional approach to creativity is to try to jump from "my problem" to "my solution". But there is no repeatable path from "my problem" to "my solution", and any attempt to follow that route could result in never ending random trials.

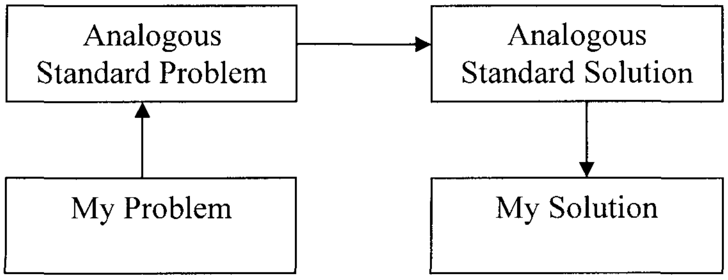


Figure 3.1 General Problem Solving Model [41]

3.2 TRIZ and Brainstorming

In the most simplistic terms, an actual problem with a solution hidden by the wall. [42]

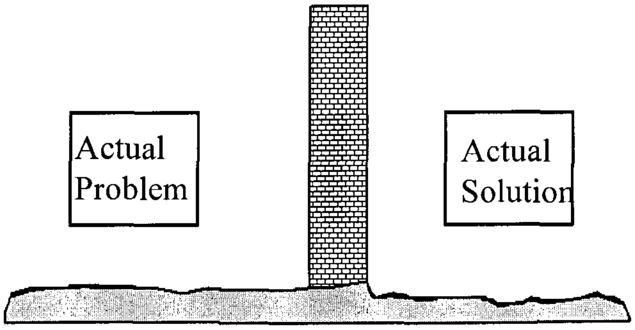


Figure 3.2 Actual Problems with a Solution Hidden by the Wall

In brainstorming, we set to and chip away at the wall hoping that one idea will lead to another and eventually the brick drops to make a hole big enough to reveal a solution.

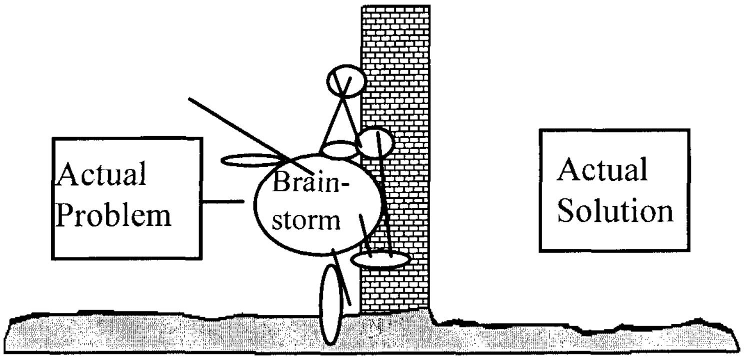


Figure 3.3 Brainstorming Problems Solution

Altshuller's conviction was that, instead of this 'psychological' method, it must be possible to put the problem into an abstract statement that could then be subjected to certain definable processes.

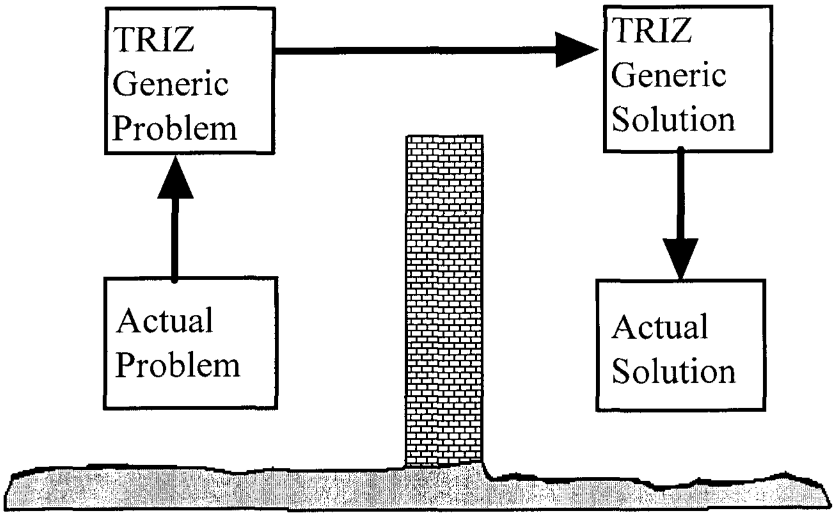


Figure 3.4 TRIZ Solution

3.3 TRIZ Tools and Application

There are many important principles (theories) and methods in TRIZ, such as:

- Innovation Situation Questionnaire (ISQ)
- Problem Formulation
- Contradiction Table
    - Contradiction Matrix
    - 39 Parameters
    - 40 Inventive Principles
    - 76 Standard Inventive Solutions
- The Ideal Design
- System Modeling, Substance-Field Analysis (Su-Field)
- Patterns of Evolution (S-curve)

The Figure 5.3 shown below was used to select the appropriate tools, depending on the type of problem statement (in terms of parameter, functions, contradictions, etc.). [43]

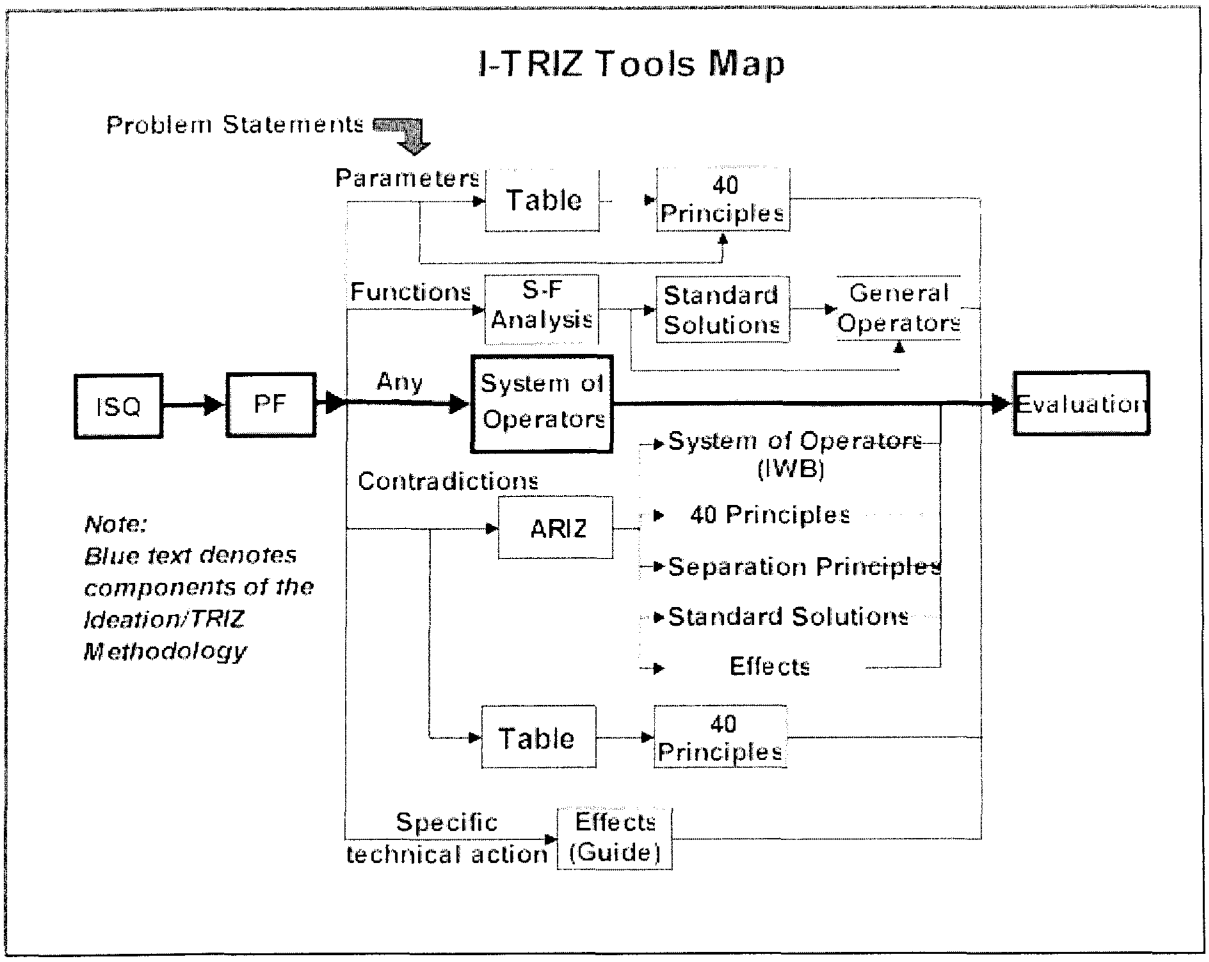


Figure 3.5 Structure of TRIZ

ARIZ refers to Algorithm for Inventive Problem Solving, a set of successive logical procedures directed at reinterpretation of a given problem. In TRIZ standpoint, a technological problem becomes an invention one when a contradiction is overcome. However, "real world" problems do not always appear as contradictions. Furthermore, Su-field analysis and required function analysis may not be applied directly in some situations. Thus it is not obvious how or where to apply TRIZ knowledge base tools to aid the problem solving. ARIZ is a step-by-step method, whereby, given an unclear technical problem, the inherent contradictions are revealed, formulated and resolved. [44].

3.4 Contradiction Analysis

Contradiction Analysis is a powerful tool of looking problem with the new perspective. Once the designers have gained this fresh perspective, the Contradiction Table becomes their tool for generating numerous solution concepts. [45]. If the problem fits into the parameters outlined, designers may be well on their way to finding an even greater variety of solutions that are both creative and effective.

There are two types of contradictions: Physical Contradictions and Technical Contradictions. In TRIZ standpoint, a challenging problem can be expressed as either a technical contradiction or a physical contradiction. TRIZ formulates and explores contradictions to develop accurate problem statements.

Technical Contradictions are identified first. They take the form:

If an action is taken (+X), there is a positive effect (+Y), but also negative effects (-Z). Also, if the action is not taken (-X), there is a positive effect (+Z), but also negative (-Y). Physical Contradictions are often defined as the result of this process. Physical contradictions describe antipodal property requirements for the problem. For instance, a substance may have to be hard to eliminate the initial problem, but must also be soft to satisfy other requirements of the problem.

A technical contradiction might be solved by using contradiction table that identifies 39 characteristics most frequently involved in design process. A physical contradiction might be solved by separation principles. Contradiction analysis is the fundamental step to apply 40 inventive principles, one of the knowledge base tools.

Table 3.1 39 Factors in the Contradiction Matrix

1. Weight of moving object
2. Weights of non-moving object
3. Lengths of moving object
4. Lengths of non-moving object
5. Areas of moving object
6. Areas of non-moving object
7. Volumes of moving object
8. Volumes of non-moving object
9. Speed
10. Force
11. Tension, pressure
12. Shape
13. Stability of moving objects
14. Strength
15. Durability of moving object
16. Durability of non-moving object
17. Temperature
18. Brightness
19. Energy spent by moving object
20. Energy spent by non-moving objects
21.Power
22. Waste of energy
23. Waste of substance
24. Loss of information
25. Waste of time
26. Amount of substance
27. Reality
28. Accuracy of measurement
29. Accuracy of manufacturing
30. Harmful factors acting on object
31. Harmful side effects
32. Manufacture ability
33. Convenience of use
34. Adaptability or versatility
35. Adaptability
36. Complexity of device
37. Complexity of control
38. Level of automation
39. Productivity

3.5 Comparisons of TRIZ and Traditional Design Strategies

Contradictions of this nature often lead to compromise solutions. TRIZ teaches that inventive solutions resolve contradictions without compromise. Tools guides ones imagination to resolve a physical contradiction inventively, and without compromise. A technical contradiction can be usefully drawn as a graph illustrated in Figure 3.6. [46]

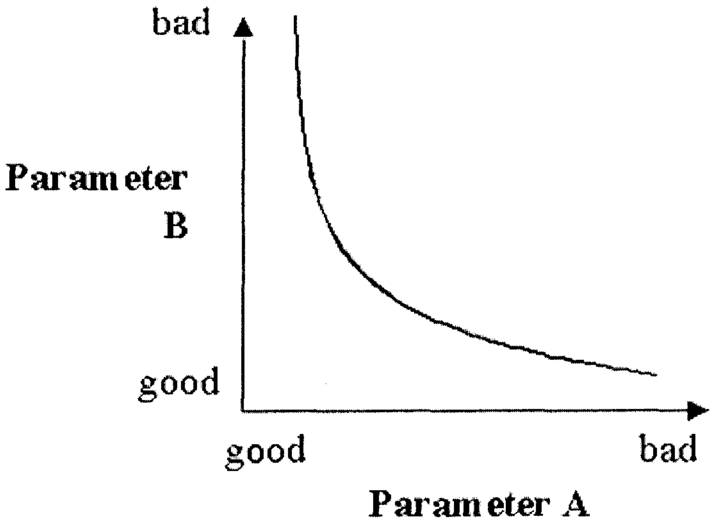


Figure 3.6 Graphical Representation of a Technical Contradiction

On the graph, the line may be seen as a 'line of constant design capability', or as a representation of the current design paradigm. For example, the design of flange joints, set Parameter A as 'leakage performance' of the flange, and Parameter B as the number of bolts around the flange joint. The designer is unconsciously following the graph, which is trying to find a balance between adequate leakage performance and minimum number of bolts. This generally means the flange is designed 'just' doesn't leak.

Using contradictions to assist in creating these paradigm shifts is one of the great strengths of the TRIZ methodology. The difference between the TRIZ Contradiction design philosophy and the traditional 'design is a trade-off' scenario may be illustrated by the graph shown in Figure 3.7.

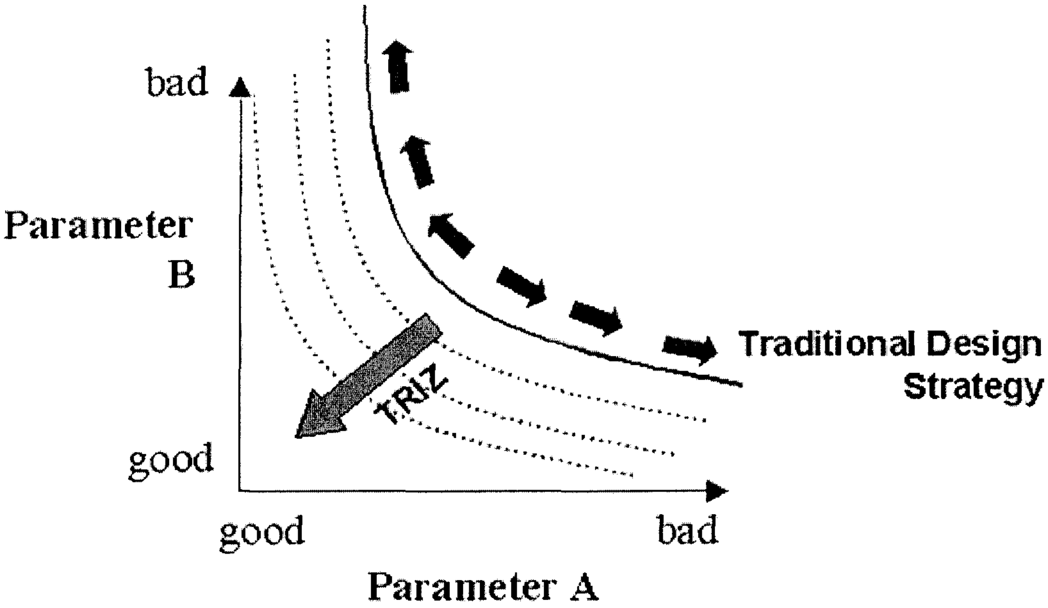


Figure 3.7 Comparisons of TRIZ and Traditional Design Strategies

Altshuller's recognition of generic problems in innovation and common trends in product evolution led to the development of a knowledge-based, systematic approach to innovation, namely TRIZ. Basic TRIZ concepts of ideality and contradiction resolution are discussed.

3.6 TRIZ is A Knowledge Base Tools

TRIZ knowledge base tools include 40 Inventive Principles, 76 Standard Solutions and Effect Database. These tools are developed based on the accumulated human innovation experience and the vast patent collection. The knowledge base tools are different from analytical tools in that they suggest the ways for transforming the system in the process of problem solving while analytical tools help change the problem statement [47].

Forty Inventive Principles are used to guide the TRIZ practitioner in developing useful "concepts of solution" for inventive situation. Each of solution is a recommendation to make a specific change to a system for the purpose of eliminating technical contradictions. Contradiction table recommends which principles should be considered in solving approximately 1250 contradictions.

Seventy-six Standard Solutions were developed for solving standard problems based on the Patterns of Evolution of Technological Systems. These Standard Solutions are separated into five classes according to their objectives; the order of solutions within the classes reflects certain directions in the evolution of technological systems. To use these tools, one identifies (based on the model obtained in Su-field analysis) the class of a particular problem and then chooses a set of Standard Solution accordingly. The standard solution is a recommendation as to what kind of system transformation should be made to eliminate the problem.

Effect Knowledge Base is probably the most easy to use tool in TRIZ. Very early in his research, Altshuller recognized that given a difficult problem, the ideality and ease of implementation of a particular solution could be substantially increased by utilizing various physical, chemical and geometric effects, thus a large vast of database has been developed. In applying Effect Knowledge Base tool, one has to select a appropriate function the system wants to perform (based on the required function analysis), then the knowledge base provides many alternatives for delivering the function.

3.7 Literature Review of TRIZ Methodology

3.7.1 TRIZ and Innovation Tools

A systematic programmed of research to compare and contrast different creativity tools, methods and philosophies in terms of their relevance to primarily scientific, engineering and business applications has concluded that TRIZ currently offers the most useful foundation for a higher order systematic creativity model and that given this foundation, the other available methods that are best able to complement and help deliver the higher order model are those shown in Figure 3.8. To varying degrees, all of these additional methods have already been the subject of some form of work to explore the benefits of integration with TRIZ. [48]

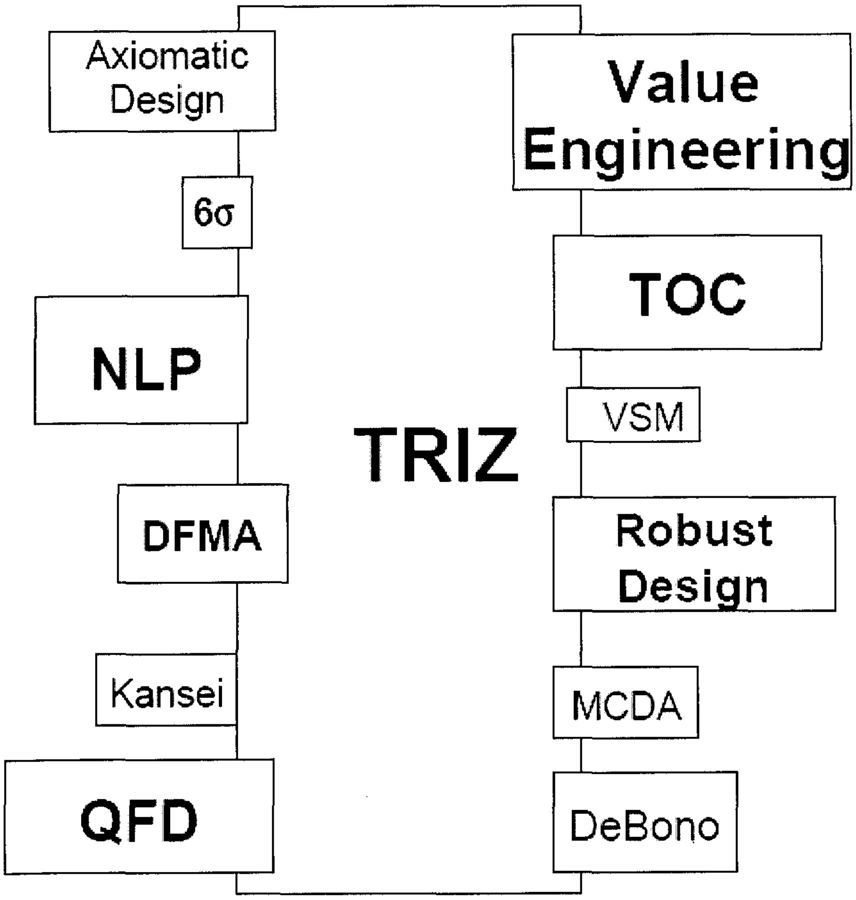


Figure 3.8: TRIZ and Innovation Tools

3.7.2 TRIZ and CAE

A paper continues a series about the research work that is being undertaken at the Center of Design and Product Innovation at the Monterrey Institute of Technology (Mexico), looking for the integration of different design tools and methodologies to increase design effectiveness and productivity. [49]

An integrated model of the Conceptual Design Process was presented at TRIZCON'99, which is based on integrating QFD, Functional Analysis and TRIZ. Now some theoretic reflections about the integration of TRIZ and CAD are presented with the objective to contribute to make this integration possible in a near future.

It is intended to contribute to a reduction in product development time and to an improvement in quality and performance by creating the groundwork for integrating interactions between product development tools and methods, thereby allowing the exploration of alternatives. Especially the integration between 3D Modeling CAD packages and TRIZ based Computer Aided Inventing Software could enhance the creativity needed for developing and improving products.

Synergies may be found among TRIZ tools and 3D-CAD-Systems, which allow improving the structure of the embodiment design process where inventive thinking is needed. Significant conceptual advances in the way this integration may be performed have been achieved as results of our research work that permits implementing a prototype in the near future.

George Hrydziuszko is Director of the EDS Detroit Virtual Reality Center. He presented an overview, "The Virtual Revolution in Design and Manufacturing" that predicted that extensive, integrated tools of virtual reality (VR) in the next decade will change design, manufacturing, and assembly radically. VR is now being used for visualization of design—in the future it will be used for production as techniques now used for rapid prototyping become the manufacturing tools for "mass customization." [50]

He noted 3 barriers to the implementation of the family of virtual reality tools::

1. *Cultural*: The comfort of the use of paper design, physical prototypes. Traditions of specific decision making authority based on models. The cultural impact of making mega-dollar decisions through the use of "toys."
2. *Organizational structure and antiquated methodologies.* Tools are enablers. Organizations can be enablers or roadblocks. Improvements tend to start in remote corners of the organization, protected from the roadblocks of the existing organizational infrastructure. Until the improvements are used organization-wide, only a small fraction of the benefits will be realized.
3. *Perception of cost:* There is always a cost of change, and benefits may not be immediate. Long-term rewards of change are priceless. Cost analysis frequently does not includes such issues as

- What is now being done that could stop being done with VR technology? (Physical prototypes, rework, redesign, etc.)
- What are the losses due to product introduction delay?
- Competitive advantage to early adopters.

Accounting for these factors will overcome any objections to the cost of VR systems. Bernie Nadel of IntelliGineering Corp. presented an excellent tutorial on knowledge-based engineering. He started with the history of expert systems. Since expert systems are computer programs that reason like the experts the benefit is the merged value of consulting with many experts. For creative situations, there is no deterministic algorithm, so the methods used combine knowledge with inference. This results in gigantic searches, and amplifies the trial-and-error opportunities many-fold. His example of a constraint satisfaction model for the design of a transmission using an expert system was an excellent teaching tool for demonstrating the method. Possible combined use of artificial intelligence techniques with virtual reality were discussed, and possible combined use with TRIZ became obvious—TRIZ analysis and concept development could limit the number of trial-and-error pathways that are explored by the artificial intelligence system, and make the results much more focused.

The conclusion was that VR may help you find problems, but TRIZ provides the means to develop innovative concepts that remove the problems, and that prevent future problems.

Kathleen L. Kitto1 presents the paper "USING TRIZ, PARAMETRIC MODELING, FEA SIMULATION, AND RAPID PROTOTYPING TO FOSTER CREATIVE DESIGN" [51]

Fostering creative design within the curriculum in engineering and engineering technology is often both daunting and time-consuming. This paper describes the efforts in the Engineering Technology Department at Western Washington University to foster creative design within the curriculum by using TRIZ, parametric modeling, finite element analysis (FEA) simulation, and rapid prototyping. First, the paper describes how assessment enabled the faculty to create a collaborative environment. Second, the introduction to the design process using parametric modeling and 3D printing rapid prototyping technology during the freshman experience is described. Next, the paper describes TRIZ, the Theory of Inventive Problem Solving, in detail and how that philosophy can be used within an academic setting to foster both creativity and efficient product and process design. Then the paper details how TRIZ, FEA simulation and Fused Deposition Modeling (FDM) are actually used in the senior year.

Chapter 4 Integration Design Models

4.1 The Robust Design

4.1.1 Two Powerful Early Design Methods, QFD and TRIZ

QFD helps TRIZ.

The power of TRIZ/Ideation Methodology is enhanced by using the voice of the customer to drive the design and innovation process. Quality Function Deployment (QFD) provides a process for identifying the needs of the customer and translating the language of the customer into the language of the engineer (design requirements.) The QFD process identifies design conflicts within existing systems and establishes criteria for evaluating design alternatives. Functional requirements and Failure modes are prioritized. Manufacturing deployment is included in comprehensive QFD. These all offer a different starting place for TRIZ than the Innovative Situation Questionnaire. [52]

TRIZ helps QFD.

QFD does not offer help in generating design alternatives. This has been left to brainstorming and the more effective Pugh concept of generation and evaluation. The QFD process does an excellent job of prioritizing problems to be solved or tasks to be performed. Modern TRIZ offers the most efficient means to generate creative/innovative solutions for the difficult problems prioritized in QFD. There is no universal "cure-all," but modern TRIZ comes very close to satisfying QFD's needs. Integrating TRIZ and QFD has resulted in Customer Driven Innovation. Just as QFD has applications in products and services, the regularities discovered by Henrich Altshuller apply to all systems including those of organizations and educational institutions.

4.1.2 Robust Design

According to Jack Hipple [Hipple, 2000], in the design stage one of the fatal mistakes that can be made was to attack those existing tools as inferior or useless. It is much better to take the time to understand how the existing tool is being used and then figure out how to complement and improved it. Offering to run an inexpensive experiment for a potential user can also help to overcome resistance. Collaboration rather than confrontation should be the rule. TRIZ can improve and complement Quality Function Deployment (QFD), Creative Problem Solving, Six Hats, Lateral Thinking, Taguchi Methods, Six Sigma, and other tools.

These new methods use the same fundamental research on the world collection of patents, which is the basis for TRIZ, but propose different methodologies for the use of the data. Each of these methods will need to be tested and validated. The methods of experimental science have been used to test each of the additions to TRIZ; that is the new method is proposed, a number of TRIZ practitioners test the new methods against a variety of case, and, if the new method proves better than the old, it is adopted. As any experimental science that relies on case studies, there is no one moment at which one can say that a new method has been proven, but as a preponderance of evidence accumulates, practitioners will move to using the new methods.

John Terninko, Alla Zusman and Boris Zlotin [Terninko, Zusman and Zlotin, 1998] introduced a significant innovation, Customer-Driven Robust Innovation, in the design area. There are three powerful Customer-Driven Robust design tools: Quality Function Deployment (QFD), Taguchi, and TRIZ. Taguchi's approach to robust designs has been introduced in North America since 1981. QFD arrived in 1984, and TRIZ arrived publicly in 1991. Each contributes to one aspect of the design process. Together they become an unbeatable form of Customer-Driven Robust Innovations.

QFD gathers customer requirements, and translates them into design requirements and technical specifications. The prioritized desired improvements in QFD become "initial useful functions" in TRIZ. The output of the QFD is used to rank the many innovative concepts generated by the TRIZ. The TRIZ methodology provides the concepts of a design -- not the design details. Taguchi's methodology determines the design specifications for a product to be insensitive to uncontrolled influences. The synergy formed the ideal design process.

QFD, TRIZ and Taguchi's methods fit together like a three-piece jigsaw puzzle (Figure 3.1) [Terninko, 1997] to form a complete picture of the design process. Missing from QFD is bottleneck engineering and optimization. Bottleneck engineering can be overcome with the solution concepts generated via TRIZ. TRIZ is weak, however, in the areas of customer-driven requirements and optimization. QFD provides the customer input and Taguchi provides the process for determining the best parameter values for a robust design. Taguchi's methods lack the customer-driven priorities and the tools required for system definition. These are provided by QFD and TRIZ, respectively.

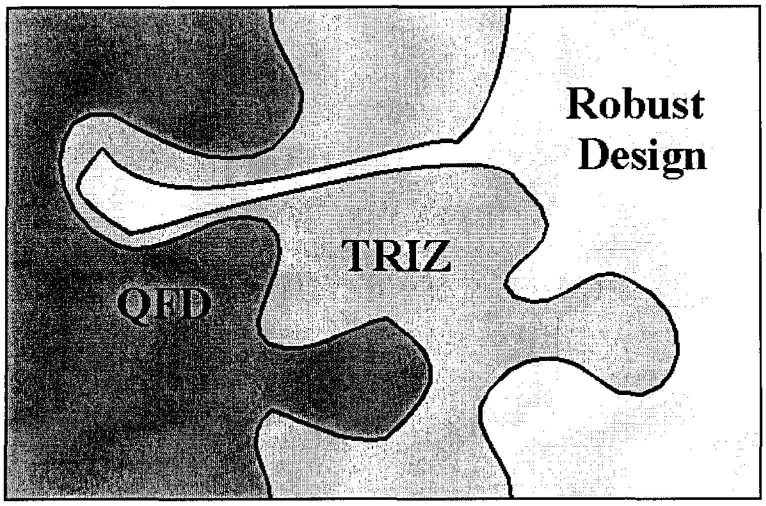


Figure 4.1 a Three-piece Jigsaw Puzzle

4.2 Design for Six Sigma

The process of design involves understanding what you want to achieve and then selecting a strategy that achieves that intent. To better understand the history of quality and the role of Six Sigma in product development, consider the domain model of product development shown in Figure 4.2. Nam Suh, chairman of the Mechanical Engineering Department at MIT, created this model, applicable to the development of either products or services, in the late 1970s. [17]

Suh believes the creation of great products or services involves selecting strategies associated with four primary activities or domains: customer domain, functional domain, physical domain and process domain. The customer domain consists of customer attributes—a characterization of needs,wants or delights that define a successful product or service from a customer perspective. The functional domain consists of functional requirements—a characterization of design goals or what the product or service must achieve to meet customer attributes from the viewpoint of the designer. The physical domain consists of design parameters—the collection of physical characteristics or activities that are selected to meet functional goals. The process domain consists of process variables—the collection of process characteristics or resources that create the design parameters.

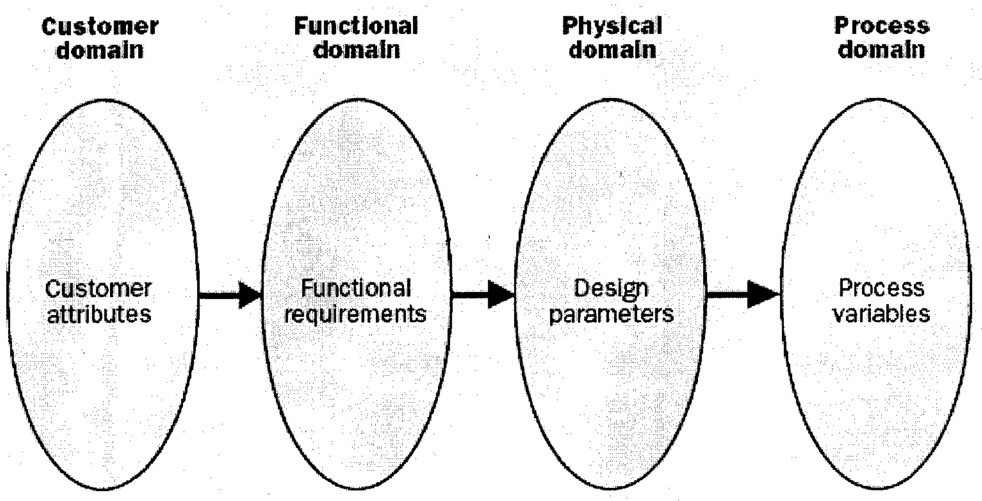


Figure 4.2 Nam Suh's Domain Model of Product Development

The evolution of design is correlated with the evolution of our thinking. Peter Senge, a professor at MIT's Sloan Management School, describes three levels of thinking: events, patterns, and structure. The event level is all too familiar. Something happens; we find out about it after the fact and are forced to react. Organizations typically react to significant short-term events in measures such as sales, profits, quality, etc.

Pattern thinking involves understanding longer-term trends and assessing implications. Structure thinking involves looking at the total system to understand how system elements relate to each other, and what in the system causes the patterns to behave the way they do. Figure 4.3 overlays Senge's levels of thinking onto Suh's domain model of product development.

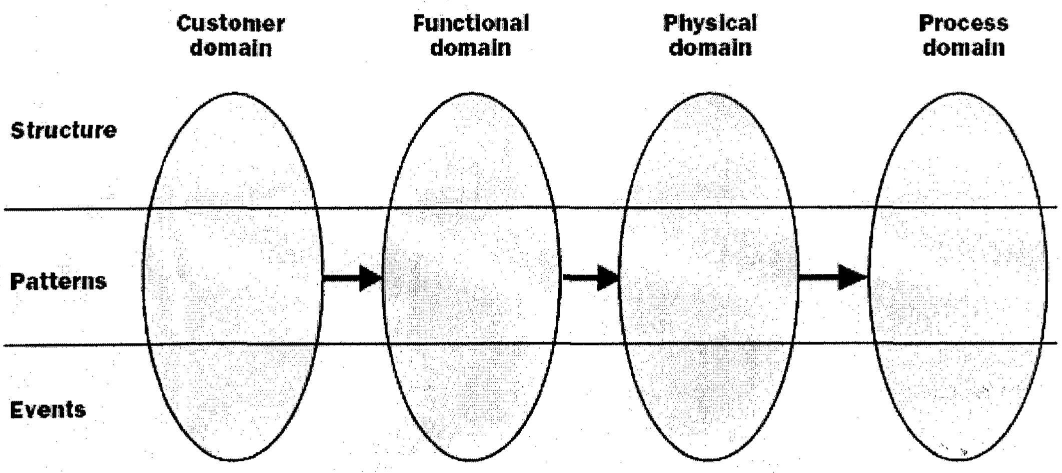


Figure 4.3 Senge's Levels of Thinking Overlaid on Suh's Domain Model of Product Development

In subsequent years, about 120 different quality tools and methods have been created at the pattern level for designers to manage product development process trends, making inspection events a nonevent. Some of the most popular and powerful methods are shown in Figure 4.4 and, in addition to SPC and QFD, include: failure mode and effects analysis (FMEA) for both the product and process domains, Genichi Taguchi's methods of parameter design (for the product and process domains) and tolerance design (for the product domain), design for assembly (DFA) and design for manufacturing (DFM), which improve the mapping from the product to the process domain, and system engineering, value analysis (VA) and value engineering (VE) in the functional domain.

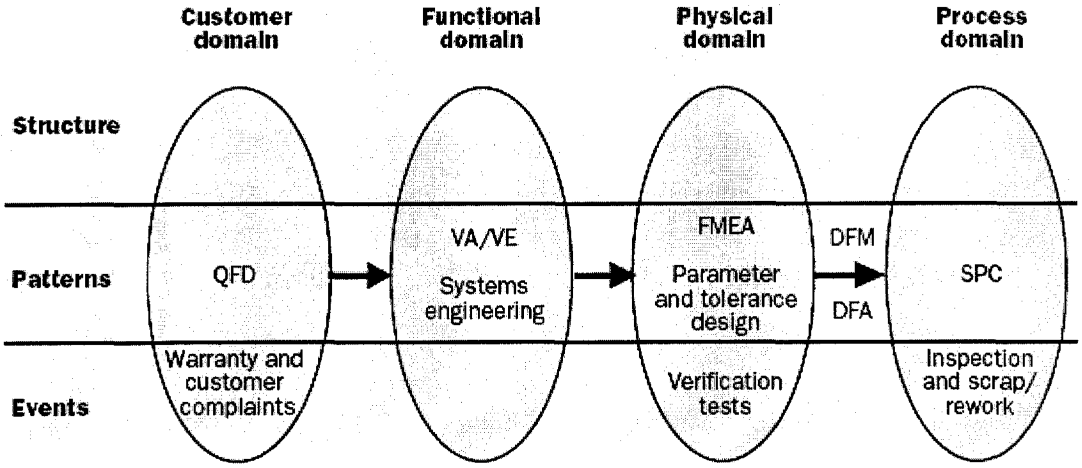


Figure 4.4 Pattern Thinking in the Various Design Domains

In the evolution of quality, two very powerful design methods have emerged at the structural level: axiomatic design and TRIZ. See Figure 4.5

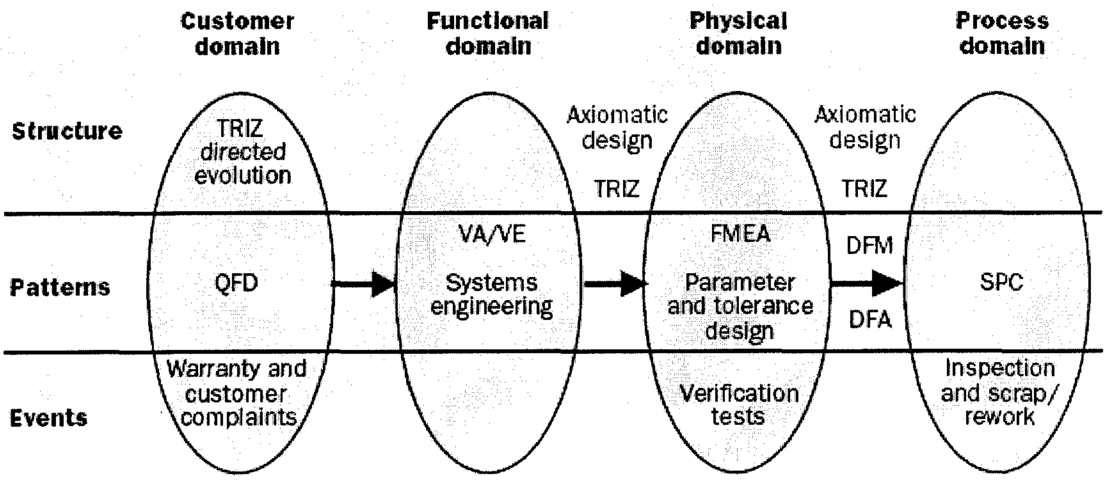


Figure 4.5 Quality Evolution in the Various Design Domains

Six Sigma is used to react to or fix unwanted events in the customer, design or process domains. DFSS is used to prevent problems by building quality into the design process across domains at the pattern level of thinking. Use of new structural tools such as TRIZ and axiomatic design provide a foundation for future enhancement of Six Sigma methodologies. The transition from event thinking to pattern thinking is the transition from find and fix to prevent. The transition from event thinking to pattern thinking is also the transition from Six Sigma to Design for Six Sigma (DFSS). (Figure 4.6)

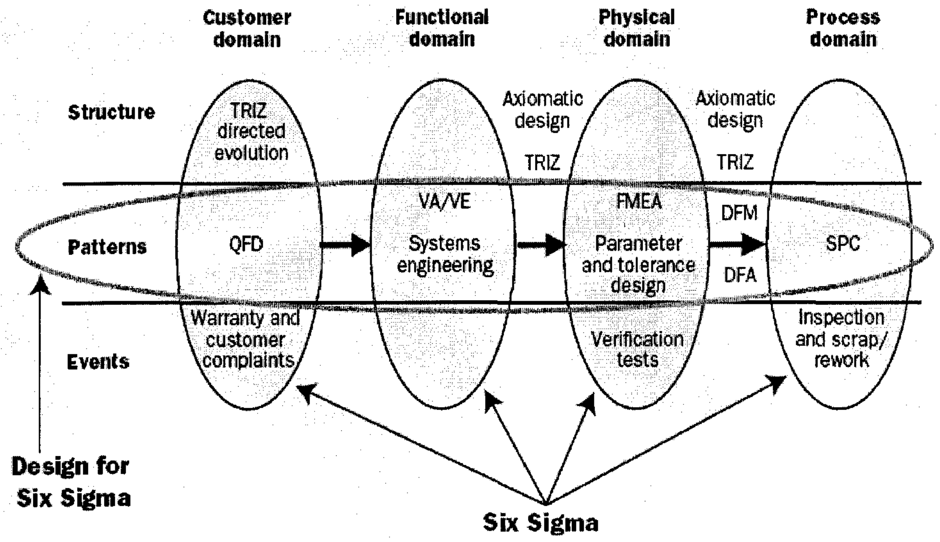


Figure 4.6 Design Process and Design Methods to Achieve Six Sigma

4.3 New Design Model

Developing new and innovative products and processes in today's fiercely competitive global marketplace is an immense challenge. Companies must meet that challenge with scarce resources, at the lowest cost, with higher quality and with shorter design cycle times.

4.3.1 Rapid Prototyping Techniques, CAE

Whilst many of the techniques in this sections deal with pseudo model, existing only in computers, there is often an inevitable requirement to have made a solid representation for various reasons from marketing and sales viewings to having models to use for preliminary testing such as in wind tunnels to test car aerodynamics. One method to achieve this real-life solid is to generate and then export solid model CAD data to a stereo lithography set-up which then can produce the part in resin; if after this a change is requested, the CAD model is changed and a new model can be produced. These models are often used to make moulds to make a further model which is useful if the models are to be used in potentially destructive tests. Another, broader field is that of metal tool production, still with the aim of producing tooling and parts quickly to reduce development time - even if the design requirements change and the tool has to be modified. Cast metal tooling, such as with Aluminum alloys are used in the rapid prototyping field using techniques such as investment casting and rubber/ plaster casting. These can produce master patterns quickly and can contain complex forms such cooling channels.

4.3.2 TRIZ Create Ideas for CAE

Conventional approaches simply will not get the job done. Techniques for solving routine engineering problems such as CAD, CAM, and FEA substantially facilitate development of the existing concepts, but do not generate novel breakthrough concepts. Systematic innovation in products and processes is an imperative for competitive leverage, but it is possible only if the approach to concept generation is equally unconventional. TRIZ is such an approach.

TRIZ saves time in idea generation by focusing on the fruitful areas of design space rather than randomly walking around design space as is done with brainstorming. Quality improves because better ideas are the result of TRIZ analysis -- not only for engineering innovation but for resolving management issues as well.

4.3.3 Increasing Simulation to Improve Quality

The continued trend toward improving product quality is best illustrated by the growing popularity of the Six Sigma management philosophy in the industrial manufacturing arena. Six Sigma strives to reduce the likelihood of defects or failure in a product to less than one-in-a-million. In an age when a manufacturing defect can cost manufacturers millions in recalled products and billions in lawsuits, pressure to produce quality products is higher than ever. [53]

Computer technology has significantly impacted product design and development, making it possible to do “virtual prototyping” of many new products. Traditionally, stylists would sketch ideas for a new concept and then pass their creations over to the CAD engineers, who then took those ideas and built models on their drafting tables along with associated design criteria and documentation. Next, CAE engineers took these blueprints and created physical models of the designs to be run through a barrage of live tests to assess flaws, structural defects, and accordance to manufacturing specifications. This process was long and error-prone.

Now advanced software and hardware tools allow the entire process to flow electronically from styling, to design, to analysis, to manufacturing, as well as looping back to improve the process. The key to all of this is the electronic design model that carries with it all the specifications and tolerances necessary to test and ultimately, manufacture the product. Flowing design models through the development process – with all the shared data – minimizes errors, speeds development and improves quality. This workflow process allows global design teams to collaborate around the clock on projects, sharing tools, workloads and critical knowledge.

Computer simulations offer additional benefits that are impossible with traditional techniques, such as just-in-time design modifications based on assembly problems or sharing of structural and fluid dynamics results with strategic partners who need to supply complete subsystems that operate flawlessly with a new vehicle. With computational fluid dynamic experiments, comprising more than a million elements – and growing – computers are the only solution.

4.3.4 New Design Model

Design for six sigma can be made more effective by CAE technology into the methodology. Use of CAE technology will make DFSS more effective and more productive with less effort. Because TRIZ and CAE address design foundation flaws, they will enhance every aspect of DFSS, making the process of problem solving and problem prevention much more insightful, productive and efficient than programs that do not utilize these methods. (Figure 4.7)

Companies that wish to accelerate development of their own quality programs can utilize the evolutionary trends explained in this paper to understand their current level of evolution and to implement focused actions that can quickly move them past their competition.

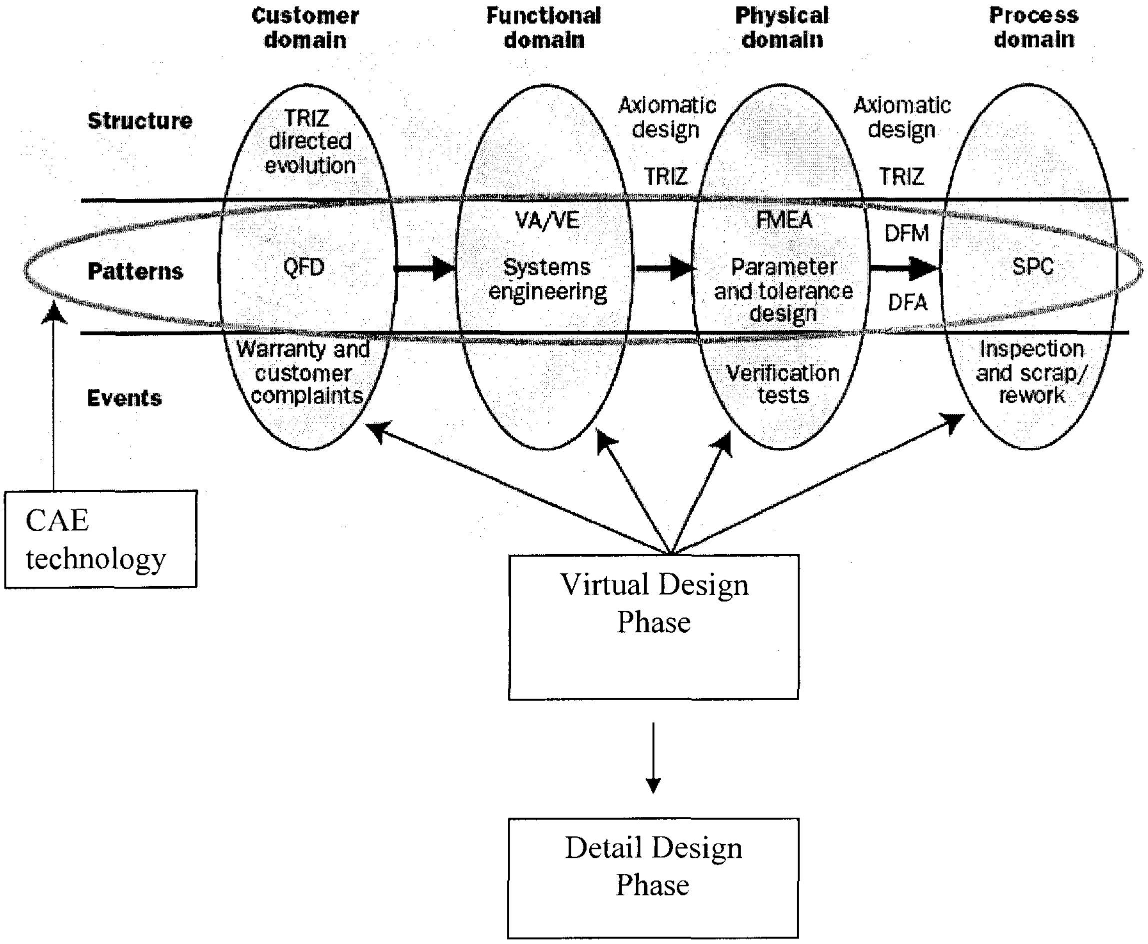


Figure 4.7 New Engineering Design Process

Chapter 5 Manufacturing Process Design with TRIZ Application

5.1 Introduction and Problem Definition

A truck is a motor vehicle for transporting goods. Unlike automobiles, which usually have a unibody construction, most trucks are built around a strong frame called a chassis.

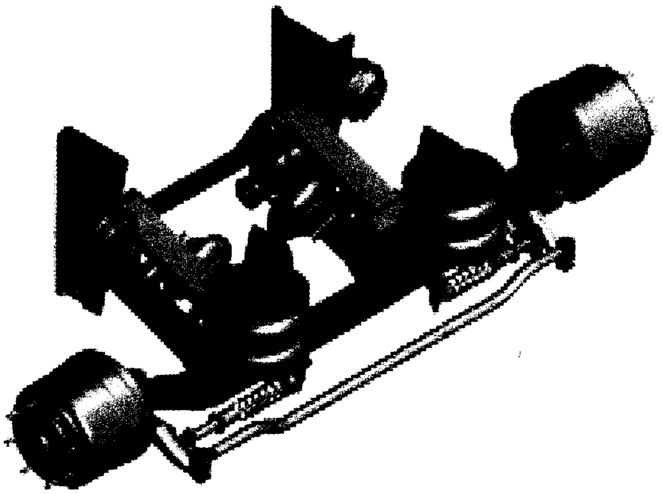


Figure 5.1 Truck Suspension Systems

The front axle beam of a truck is a major component of the suspension system. It requires very high quality of manufacture as this part experiences the worst load condition of the whole vehicle. (Figure 5.2)

Figure 5.2 Front Axle Beam

The rough part of this axle is made by forging. The traditional forging process of the front axle beam includes 2 pre-forming steps, and one refining forming step in the forging press machine. Due to the big size of the axle, one 3000 ton and one 12000 ton forging press are used to complete the three steps in a German company. The original investment of the forging production line with the traditional forging process was very high. In order to make the front axle beam in China as economic as possible, new forging process and forging production line need to be created. (Figure 5.3, Figure 5.4)

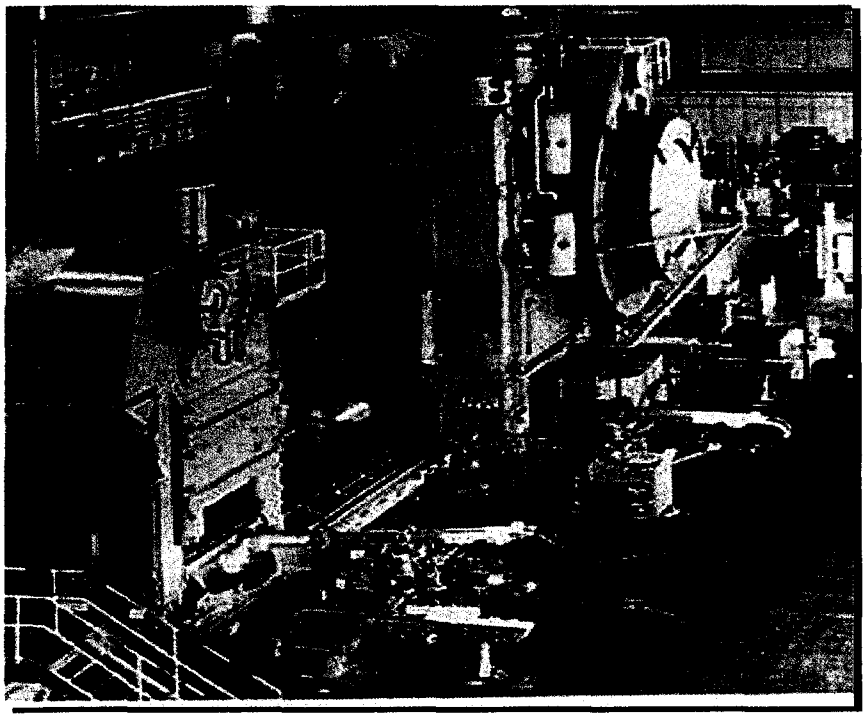


Figure 5.3 Traditional Axle Beam Forging Production Line

Pre-forming Make the curve of the Axle at the two ends	**Forging step 1** Make the rough shape of the Axle	**Forging step 2** Make the final shape of the axle
3000 ton press	12000 ton press	12000 ton press

Figure 5.4 Traditional Axle Forging Process

5.2 Forging Process

5.2.1 The Definition of Forging Process

Forging is a metal forming process used to produce large quantities of identical parts, as in the manufacture of automobiles, and to improve the mechanical properties of the metal being forged, as in aerospace parts or military equipment. The products of forging may be tiny or massive and can be made of steel (automobile axles), brass (water valves), tungsten (rocket nozzles), aluminum (aircraft structural members), or any other metal. More than two thirds of forging in the United States is concentrated in four general areas: 30 percent in the aerospace industry, 20 percent in automotive and truck manufacture, 10 percent in off-highway vehicles, and 10 percent in military equipment. [54]

Forging changes the size and shape, but not the volume, of a part. The change is made by force applied to the material so that it stretches beyond the yield point. The force must be strong enough to make the material deform.

In forging, a block of metal is deformed under impact or pressure to form the desired shape. Cold forging, in which the metal is not heated, is generally limited to relatively soft metals. Most metals are hot forged; for example, steel is forged at temperatures between 2,100°F and 2,300°F (1,150°C to 1,260°C). These temperatures cause deformation, in which the grains of the metal elongate and assume a fibrous structure of increased strength along the direction of flow.

Normally this results in metallurgical soundness and improved mechanical properties. Strength, toughness, and general durability depend upon the way the grain is placed. Forgings are somewhat stronger and more ductile along the grain structure than across it. The feature of greatest importance is that along the grain structure there is a greater ability to resist shock, wear, and impact than across the grain. Material properties also depend on the heat-treating process after forging. Slow cooling in air may normalize work pieces, or they can be quenched in oil and then tempered or reheated to achieve the desired mechanical properties and to relieve any internal stresses. Good forging practice makes it possible to control the flow pattern resulting in maximum strength of the material and the least chance of fatigue failure. These characteristics of forging, as well as fewer flaws and hidden defects, make it more desirable than some other operations (i.e. casting) for products that will undergo high stresses.

5.2.2 Types of Forging Process

Forging is divided into three main methods: hammer, press, and rolled types.

(1) *Hammer Forging (Flat Die)*: Preferred method for individual forgings. The shaping of a metal by an instantaneous application of pressure to a relatively small area. A hammer or ram, delivering intermittent blows to the section to be forged, applies this pressure. The hammer is dropped from its maximum height, usually raised by steam or air pressure. Hammer forging can produce a wide variety of shapes and sizes and, if sufficiently reduced, can create a high degree of grain refinement at the same time. The disadvantage to this process is that finish machining is often required, as close dimensional tolerances cannot be obtained.

(2) *Press Forging*: This process is similar to kneading, where a slow continuous pressure is applied to the area to be forged. The pressure will extend deep into the material and can be completed either cold or hot. A cold press forging is used on a thin, annealed material, and a hot press forging is done on large work such as armor plating, locomotives and heavy machinery. Press Forging is more economical than hammer forging (except when dealing with low production numbers), and closer tolerances can be obtained. A greater proportion of the work done is transmitted to the workpiece, differing from that of the hammer forging operation, where much of the work is absorbed by the machine and foundation. This method can also be used to produce larger forgings, as there is no limitation in the size of the machine.

(3) *Rolling Forging*: In roll forging, a bar stock, round or flat is placed between die rollers which reduces the cross-section and increases the length to form parts such as axles, leaf springs etc. This is essentially a form of *draw forging*.

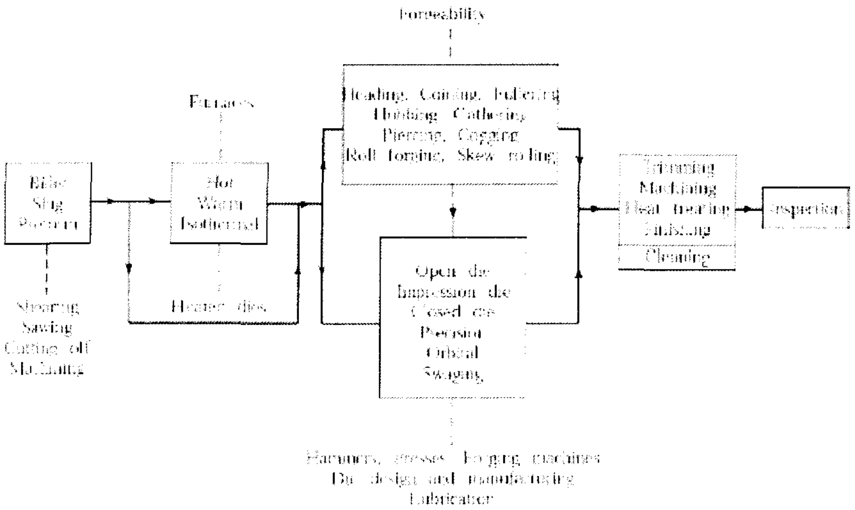


Figure 5.5 Forging and Related Operations [55]

5.2.3 Force Calculation

Press Forging

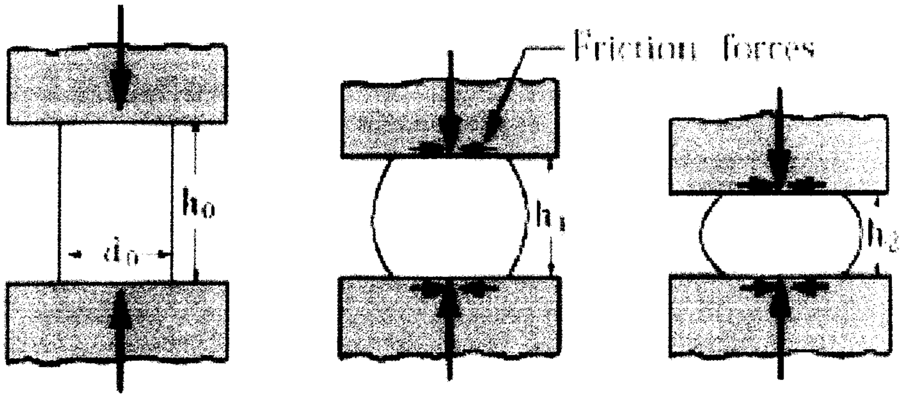


Figure 5.6 Deforming Force and Part Projection Area

P= (64-73) KF

P-Deforming force

K-Steel forming rate

F- Forging Objective (part) Projection Area

Forging load is related to the forging part projection area. If the forging part projection area is high, then the forging load is high. The flash increases the forging part projection area.

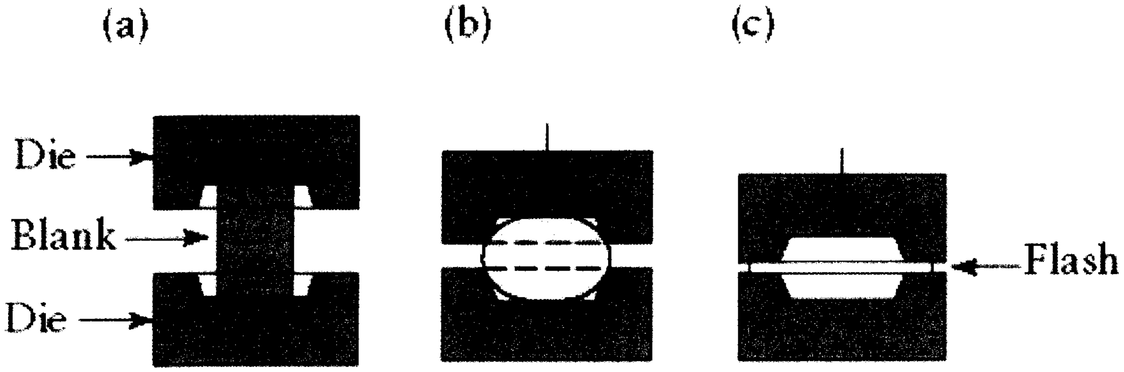


Figure 5.7 Deforming Force and Part Projection Area

A typical load-stroke curve for closed-die forging is shown in figure 5.8b. Note the sharp increase in load after the flash begins to form. In hot forging operations, the flash requires high levels of stress, because it is thin- that is, it has a small *h*-and cooler than the bulk of the forging. [56]

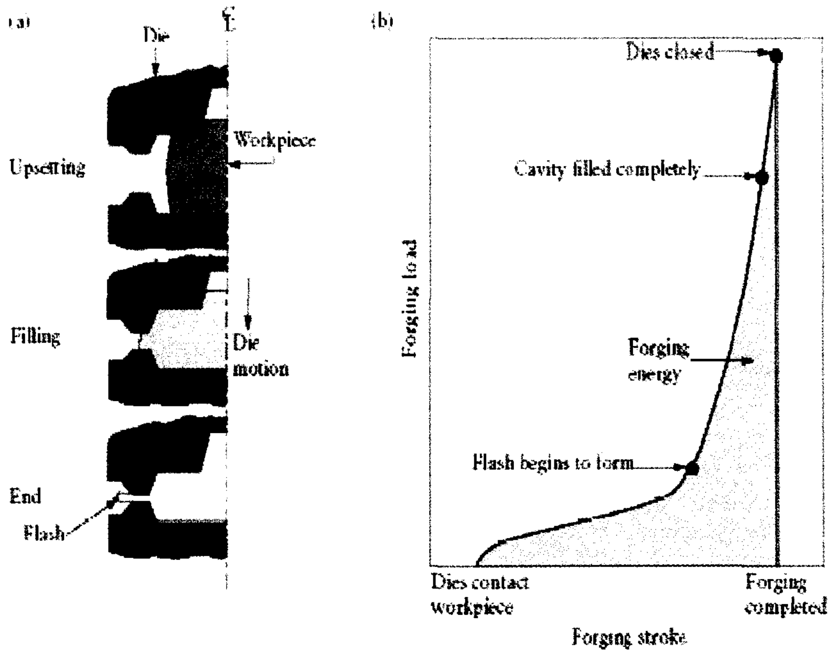


Figure 5.8 Forging Load and Flash

Rolling forging can arrange the material effectively and make the load lower.

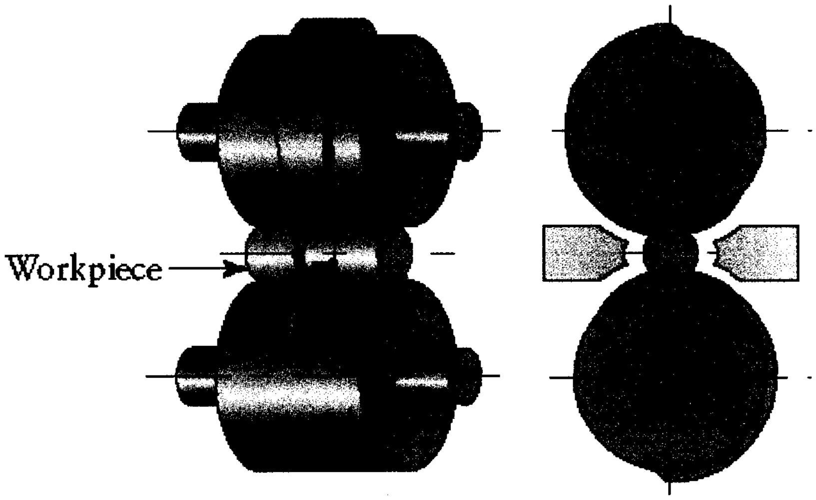


Figure 5.9 Rolling Forging

5.3 TRIZ Contradiction Analysis

Step 1. Identify and document the problem

Contradiction:

As we discussed before, the forging load is related to the forging part projection area. Flash is the excess metal that extends out from the body of the forging to ensure complete filling of the finishing impressions. However, the flash increases the forging part projection area, which makes the forging load high.

An axle is a big and complicated part. In the traditional forging press, a large flash is formed during the forging process. The large flash makes the forging load very high. Under this condition, only the large press machines can produce a high enough load. But larger press machines are very expensive.

The ideal forging process is axle deformation with a low load. Low load requires smaller flash and a smaller flash means fewer material of the bulk before the forging process. This makes a pair of contradiction. Searching the contradiction table, we come to the following two parameters.

Stress, pressure exerted upon the object (11)

Step 2 searching the contradiction table:

	Stress, pressure exerted upon the object (11)
Volume of stationary object (8)	24, 35

Figure 5.10 Contradiction Table

Step 3 Get the suggestion from the standard solution

24. Mediator

a. Use an intermediary object to transfer or carry out an action

b. Temporarily connect an object to another one that is easy to remove

Example:

- To reduce energy loss when applying current to a liquid metal, cooled electrodes and intermediate liquid metal with a lower melting temperature are used.

Idea: Use a pre-forming process to make the load that in the forging process low.

35. Transformation of the physical and chemical states of an object

Change an object's aggregate state, density distribution, degree of flexibility, temperature

Example:

- In a system for brittle friable materials, the surface of the spiral feed screw was made from an elastic material with two spiral springs. To control the process, the pitch of the screw could be changed remotely.

Idea: No suggestion

5.4 Simulation

The idea of using a rolling forging process was used for the pre-forming process. After the pre-forming, the axle beam would be final formed by the press machine. During the design process, CAE is used for a fast prototype.

In the field of hot forging technology, developments of new forming processes are difficult due to the large number of parameters constituting the process. In developing a process, the design engineer has to consider both the technical and economic limits in order to obtain competitive forgings. Forming an Axle Beam requires several single forming processes resulting in a precision forming operation.

During this multi-step process, the part must be matched after each forging step. Otherwise, there is the risk of gap formation between the forging steps. Gaps contain the danger of material flowing out of the next mold and making the forging useless. Other process goals include reducing the number of forging steps, minimizing tool abrasion, reducing the contribution of flash material, and ensuring the stability of the forming process with a minimum of rejects.

Experimental testing is one method of forging process development, but usually requires much time and money, especially during development of new processes. Time and costs of developing the axle beam forging process was reduced with the help of forging simulation. Simulation made it possible to vary many process parameters "virtually". The result was new process knowledge, which never would appear in such evident form during physical testing. These virtual methods allowed tuning of the forging process to avoid potential trouble areas, like gap formation, before the manufacturing of the tools took place.

Simulation of the metal forming process:

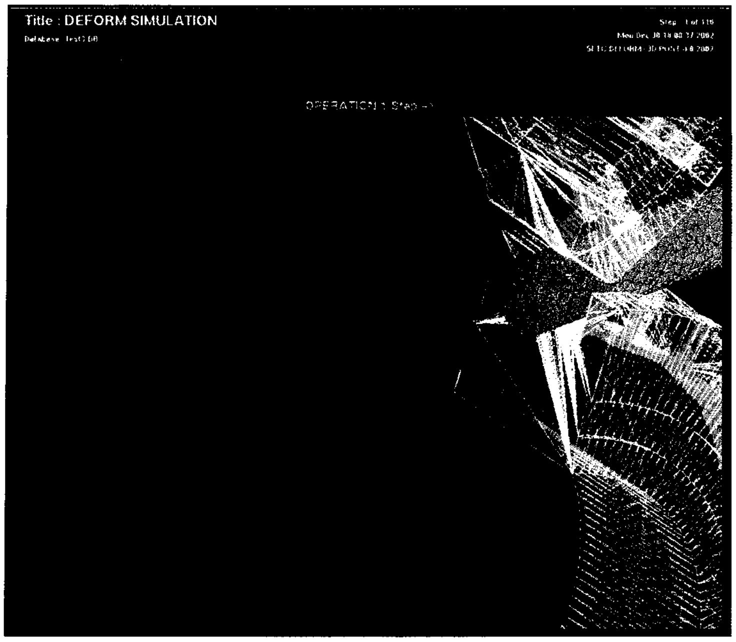


Figure 5.11 Rolling Forming Process Simulation

Figure 5.12 Rolling Forming Process Simulation

CAD/CAM designs rolling tooling and make a visual representation:

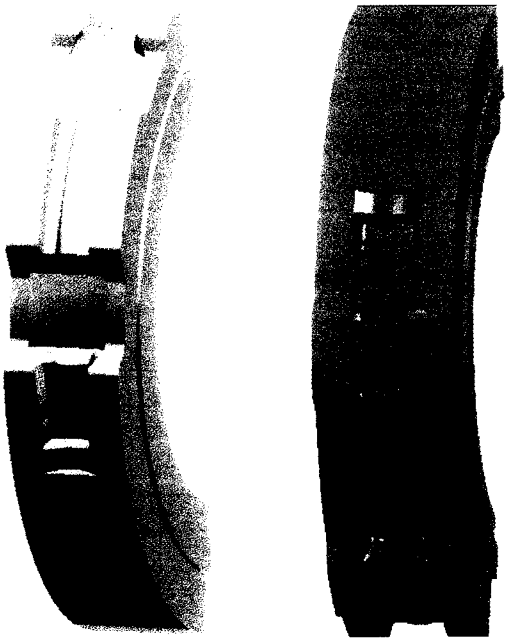


Figure 5.13 Tooling Simulation

5.5 New Forging Process

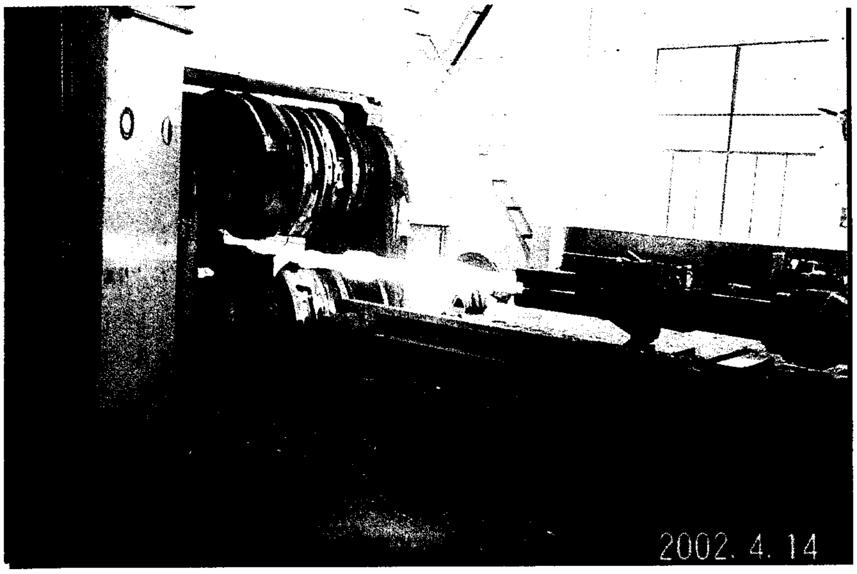


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Figure 5.14 Rolling Process for the Pre-Forming

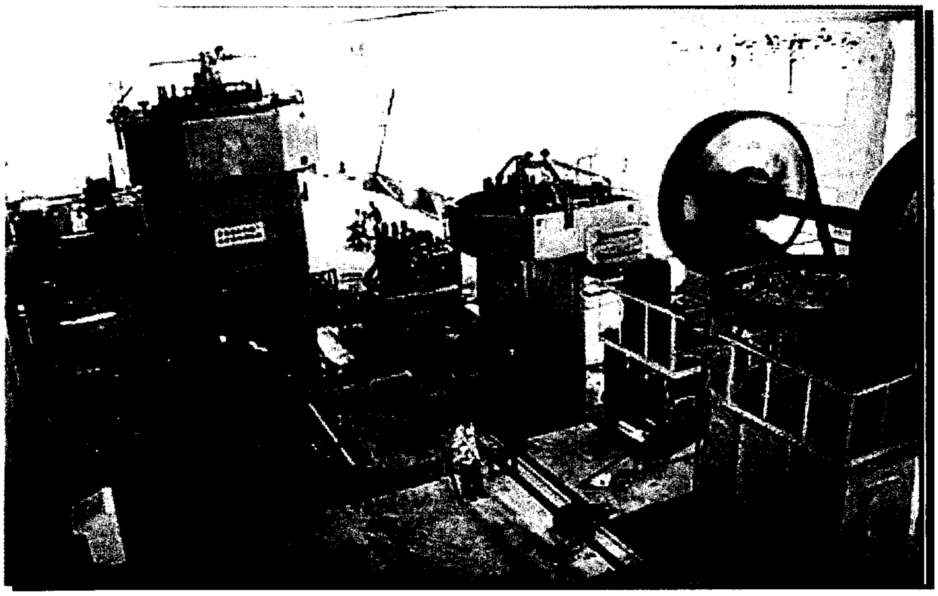


Figure 5.15 New Axle Forging Production Line

Pre-forming	**Forging step 1**	**Forging step 2**
Make the rough shape of the Axle	Make the curve of the Axle at the two ends	Make the final shape of the axle
Rolling Machine	3000 ton press	3000 ton press

Figure 5.16 New Axle Forging Process

Due to the price of the 3000 ton press machine is much lower than the price of the 12000 ton press machine, the investment of the new production line is as low as 3 million now.

Forging Process	Mechanical Press	Investment	Material Usage	Die Life	Cycle Time
Traditional	12500~16000	20 million	75%	5,000	3 yr
New	2500~4000	3 million	88%	10,000	1.5 yr

Figure 5.17 Comparisons between the Traditional Process and the New Process

Chapter 6 Product Design with TRIZ Application

6.1 Product Design Change

Localization is a hot topic in the process of international economic development. For example, during this localization process, China expected foreign enterprises to first transfer technology through semi knock down (SKD) and then through complete knock down (CKD). Then China hoped to develop a parts industry and finally cooperate in independent development through introducing technology for both production and development.

By shifting from simple assembly of imported auto parts to localization of auto production, the government of China made a series of announcements regarding a new automotive policy aimed at progressively increasing localization.

Local content policy is intended to increase local content rate on the basis of restricting import of complete cars. According to the State Planning Commission, the local content rate is calculated as below: [39]

$$\text{Local content rate (\%)} = \frac{\text{manufacturer's price} -- [\text{CKD price (CIF)} + \text{tariffs}]^{*}}{\text{manufacturer's price}} \times 100\%$$

The government links tariff on imported CKD parts with local content rate, and calls this "Classified Tariff". By doing this, the government intends to reward the automakers that increase their local content rate and penalize those that make little efforts.

During the localization process, engineering change requests were very frequent. An engineering change request is always required for changes to the following situations:

- Dimensions specified on the drawing
- Tolerances specified on the drawing (design tolerance)
- Material (including those not originally specified on the drawing
- Performance testing procedures or requirements.
- Localization of Tier 2 part
- Fastener sub-supplier source changes

6.2 Aluminum Wheel

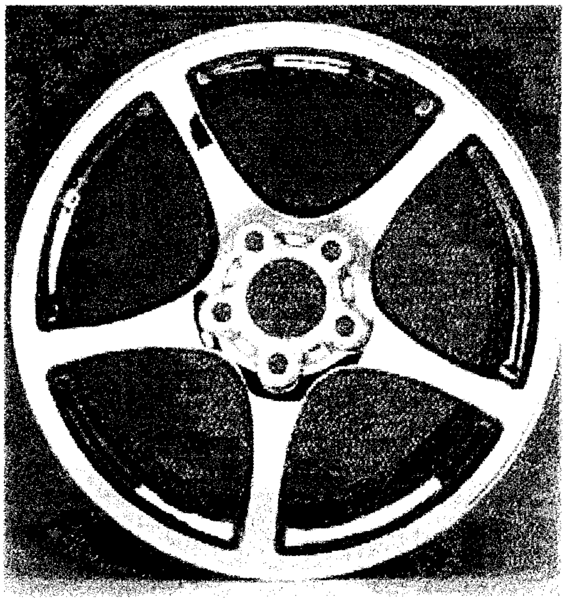


Figure 6.1 Aluminum Wheel

According to Stratecasts, Inc., Ft. Myers, Florida, aluminum casting shipments for automobiles and light trucks are expected to increase from 1.07 million tons in 2001 to 1.65 million tons in 2011, an increase of 4.4% per year. This translates to an increase from 185 lb of aluminum castings per automobile and light truck in 2001 to 270 lb/car by 2011. [57]

Aluminum has had mixed success in infiltrating vehicle areas that have traditionally belonged to steel, but one component for which it has become a clear winner is the wheel. In 1980 steel was the material of choice for 90% of wheel production, but by 2003 aluminum had surged to 60% of production, leaving steel with less than half of the market it had once practically owned. [58]

Alloy metals provide superior strength and dramatic weight reductions over ferrous metals such as steel, and as such they represent the ideal material from which to create a high performance wheel. In fact, today it is hard to imagine a world class racing car or high performance road vehicle that doesn't utilize the benefits of alloy wheels. The alloy used in the finest road wheels today is a blend of aluminum and other elements. [59]

While many people choose alloy wheels for their beauty, there are equally important performance benefits to be derived including:

1) **Reduced Un-sprung Weight:** Compared to Steel Wheels: This is one of the most critical factors affecting a vehicle's road holding ability. Unsprung weight is that portion of a vehicle that is not supported by the suspension (i.e. wheels, tires and brakes) and therefore most susceptible to road shock and cornering forces. By reducing unsprung weight, alloy wheels provide more precise steering input and improved "turning in" characteristics.

2) **Improved Acceleration and Braking:** By reducing the weight of the vehicle's rotational mass, alloy wheels provide more responsive acceleration and braking.

3) **Added Rigidity:** The added strength of a quality alloy wheel can significantly reduce wheel/tire deflection in cornering. This is particularly critical with an automobile equipped with high performance tires where lateral forces may approach 1.0g.

4) **Increased Brake Cooling:** The metals in alloy wheels are excellent conductors of heat - improving heat dissipation from the brakes - reducing risk of brake fade under demanding conditions. Additionally, alloy wheels can be designed to allow more cooling air to flow over the brakes.

A cast wheel is made by pouring molten aluminum into a mold. The metal then takes the mold's shape as it cools and hardens. There are three types of casting methods, low pressure/gravity, counter pressure, and high counter pressure molding (HCM); each method has its place in today's market. A wheel manufacturer will select a particular method according to the weight, strength and finish that they have specified for that design. Naturally, the more sophisticated and costly methods produce lighter and stronger wheels but at a higher price.

6.3 Problems of the Wheel in the Localization Process

Bolt Load Retention (BLR) is the amount of load (actually it is the tensile force in the male threaded fastener) retained in a clamped joint after some duration. Typically it is expressed as a percentage of the initial fastener preload, i.e. 75% BLR means that the joint has relaxed enough to reduce the tension in the male threaded fastener to 75% of its original value. Aluminum and magnesium are prone to reductions in BLR due to a combination of factors (creep, stiffness characteristics of the joint, etc.), especially if the service environment is characterized by variable amplitude loading and temperature fluctuations.

Due to the poor quality of aluminum in China, the area of the wheel around the lug nuts, which is under the stress of bolt loads retention, is often broken. (Figure 6.2)

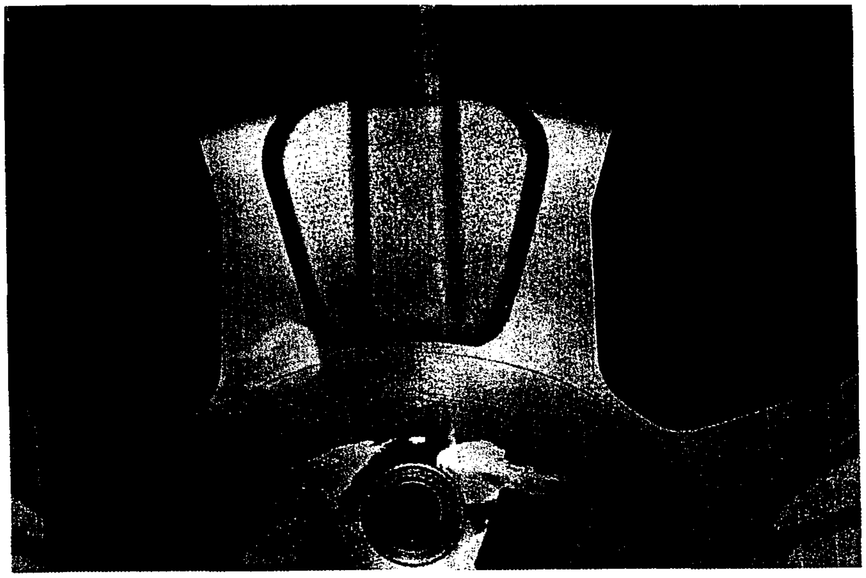


Figure 6.2 Broken in Lug Nuts Area

Considering the fairly short development period to solve this problem, it's not surprising that the engineering was basically unchanged with only minor changes in some areas.

6.4 Solving with TRIZ and CAE

6.4.1 Introduction

This section describes the solving idea creation process and a finite element analysis which is conducted to ensure efficiency in the application of TRIZ in the wheel.

The part analyzed is a bolt joint of wheel disc and rotor, as shown in figure 6.3. The rotor is made of steel while the disc of aluminum. When torque is applied on the bolt, clamp load will be generated in the joint, and both the disc and the rotor will be subject high stress around the bolt hole. Yielding, and sometimes cracking, consequently occurs on the disc around the bolt hole. This creates a critical engineering issue.

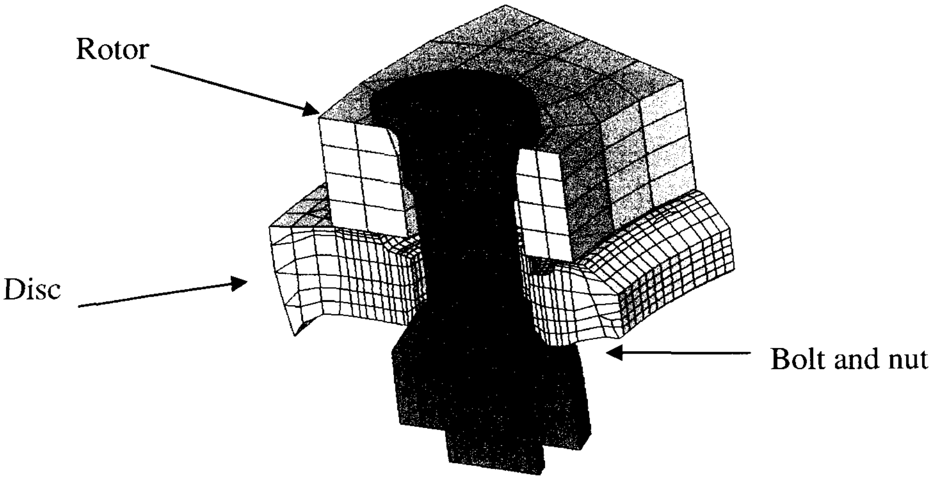


Figure 6.3 Bolted Disc and Rotor Joint

By applying the TRIZ method, one approach, reinforcing the bolt hole using higher strength material, comes up. The proposal is to add a steel ring around the bolt, Figure 6.4. This idea is simulated using finite element analyses.

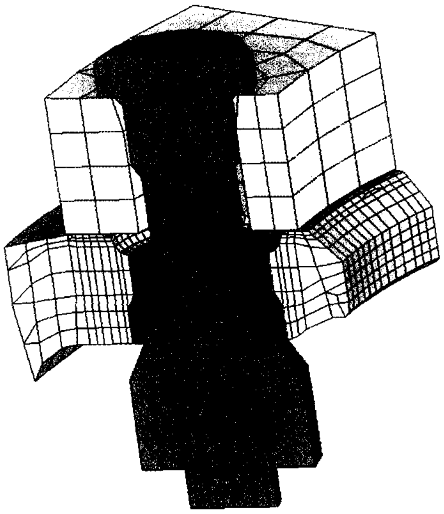


Figure 6.4 Bolted Disc and Rotor Joint with Steel Ring

6.4.2 TRIZ Analysis

Step 1. Identify and document the problem

Identify the Primary Useful Function (PUF) performed or implemented by the system.

PUF: The aluminum wheels support the tire and drive the car. Also, the aluminum wheel is attractive to the customer.

Indicate the negative effect or drawback.

Drawback: the aluminum wheel is not as strong as the steel wheel. The lug seat often cracks.

Contradiction:

A stronger wheel needs a stronger material, or a thicker aluminum wheel has to be designed. Both are rejected.

Reducing weight – Increasing mechanical strength

Step 2 Searching the contradiction table:

Selected feature to improve: *Weight of moving object*

Degraded attribute: *Strength*

The following Innovation Principles are recommended for trying to eliminate the above Technical Contradiction.

28. Replacement of a mechanical system
27. Inexpensive, short-lived object for expensive, durable one
18. Mechanical vibration
40. Composite materials

In addition, the following pairs of parameters can be considered:

Selected feature to improve: *Weight of moving object*

Degraded attribute: *Reliability*

Principles recommended:

3. Local conditions
11. Cushion in advance
1. Segmentation
27. Inexpensive, short-lived object for expensive, durable one

Selected feature to improve: *Weight of moving object*

Degraded attribute: *Harmful factors acting on object*

Principles recommended:

22. Convert harm into benefit

21. Rushing through

18. Mechanical vibration

27. Disposable object (substitute an inexpensive, short-lived object for an expensive, durable one)

Altogether we have obtained nine principles. Each has been considered in turn, yielding the following results:

28. Replacement of a mechanical system

a. Replace a mechanical system with an optical, acoustical or olfactory system

b. Use an electrical, magnetic or electromagnetic field for interaction with the object

c. Replace fields, for instance:

1. Stationary fields with moving fields

2. Fixed fields with those that change in time

3. Random fields with structured fields

d. Use a field in conjunction with ferromagnetic particles

IDEA #1: Use a disposable ring to protect the more expensive aluminum wheel.

27. Substitute an inexpensive, short-lived object for an expensive, durable one

Replace an expensive object by a collection of inexpensive ones, forgoing certain properties (e.g., longevity).

IDEA #2: Use a disposable ring that will be destroyed while absorbing the energy of the fragments.

18. Mechanical vibration

a. Set an object into oscillation

b. If oscillation exists, increase its frequency, even to ultrasonic

c. Use the resonant frequency

d. Instead of mechanical vibration, use piezo-vibrators

e. Use ultrasonic vibration in conjunction with an electromagnetic field

No ideas.

40. Composite materials

Replace a homogeneous material with a composite one

Example: Military aircraft wings are made of composites of plastics and carbon fibers for high strength and low weight.

IDEA #3: Make the ring from a stronger material.

3. Local conditions

a. Transition from a homogeneous structure of an object or outside environment/action to a heterogeneous structure

b. Have different parts of the object carry out different functions *c. Place each part of the object under conditions most favorable for its operation*

IDEA #4: Use a ring that has a heterogeneous structure.

11. Cushion in advance

Compensate for the relatively low reliability of an object by countermeasures taken in advance.

IDEA #5: Consider using additional protection from the cracking fragments

1. Segmentation

a. Divide an object into independent parts

b. Make an object sectional

c. Increase the degree of object segmentation

IDEA #6: Use a multi-layer ring containing additional strengthening rings of different hardness and elasticity.

22. Convert harm into benefit

a. Utilize harmful factors or environmental effects to obtain a positive effect

b. Remove a harmful factor by combining it with another harmful factor

c. Increase the amount of harmful action until it ceases to be harmful

Example: When using high-frequency current to heat metal, it was found that only the outer layer became hot. This negative effect was later used for surface heat-treating.

No ideas.

21. Rushing through

Perform harmful or hazardous operations at very high speed.

Example: A cutter for thin-walled plastic tubes prevents tube deformation during cutting by running at a very high speed (i.e., the cut is made before the tube has a chance to deform).

No ideas.

Results

The following ideas (shown in order of feasibility) resulted from considering the above Principles:

1. Use a disposable ring to protect the more expensive aluminum wheel.
2. Use a disposable ring that will be destroyed while absorbing the energy of the fragments.
3. Make the ring from a stronger material.
4. Use a ring that has a heterogeneous structure.
5. Consider additional protection from the cracking fragments
6. Use a multi-layer ring containing additional strengthening rings of different hardness and elasticity.

6.4.3 Using CAE to finish the primary design and detail design

Model and Set-up

The model set-up is illustrated in Figure 6.5. Only one bolted joint is included in the analysis. This joint consists of an M14 bolt, a portion of wheel disc and a portion of rotor. The model is built using hex dominated solid element. Fine mesh is generated around the bolt hole to represent the geometry details and to capture high stresses. Contacts between the bolt head and rotor, nut and disc as well as rotor and disc are simulated.

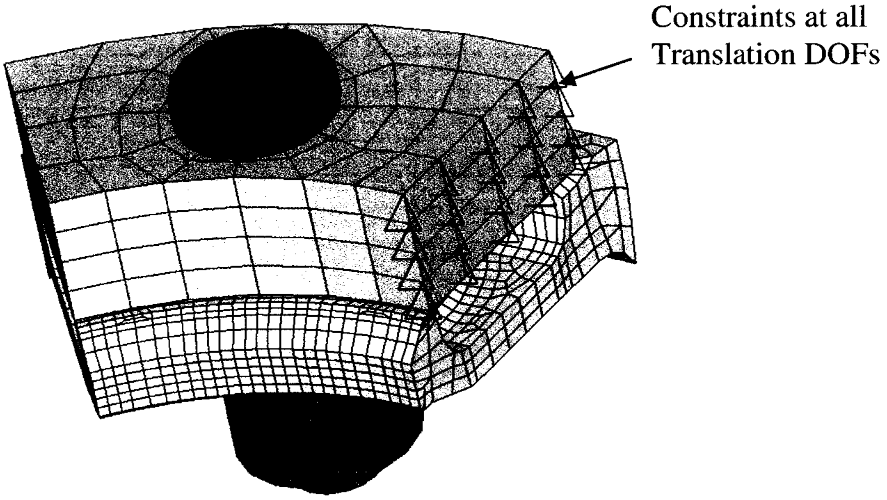


Figure 6.5 FEA Model of Part of an Aluminum Wheel

Material and properties

The wheel disc is made up of aluminum. The yield strength is 190 MPa, the tensile ultimate strength is 290 MPa, and the tensile elongation is 10%. The modulus of elasticity is 70,000 MPa, and Poisson's ratio is 0.33. Mass density is 2,800 kg/m3.

The rotor and bolt are made up of steel. The modulus of elasticity is 207,000 MPa, and Poisson's ratio is 0.30. Mass density is 7,800 kg/m3.

Boundary Conditions and Loading

The model is constrained at one cross section of the rotor, while the other cross section is free, Figure 6.3. If both the cross sections are constrained, additional stress will be generated as bolt load is applied and the disc and rotor deflect correspondently. The model is analyzed using ABAQUS/ Standard, which is a widely used FEA solver.

Bolt load, actually clamp load, is applied using a special function named PRETENSION SECTION in ABAQUS. The applied clamp load is 71.6 KN, which is determined based on the possible maximum applied torque on the M14 bolt.

Results and analysis

The stress and plastic strain on the disc around the bolt hole under the clamp load are shown in Figure 6.6 and Figure 6.7. The stress has reached the ultimate tensile strength of the material, 290 MPa with the maximum plastic strain 25%. This high stress will break the material as torque is applied to the bolt.

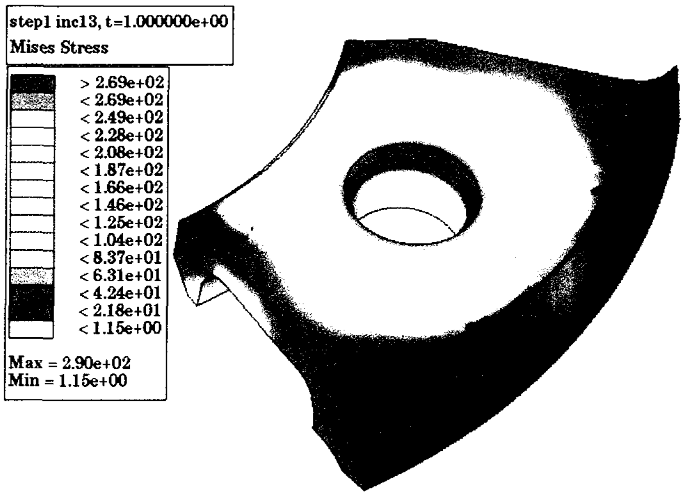


Figure 6.6 Stress on the Disc under Clamp Load without Steel Ring

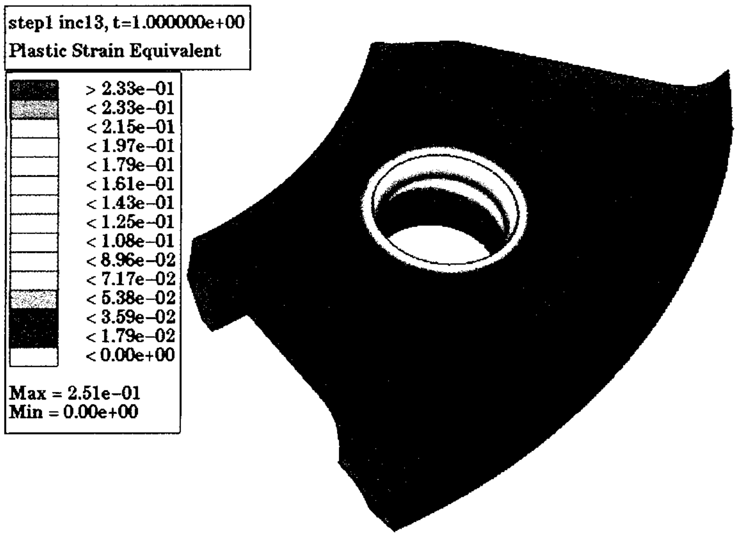


Figure 6.7 Plastic Strain under on the Disc Clamp Load without Steel Ring

For the case with steel ring added, the stress on aluminum material of the disc is reduced significantly. See Figure 6.8 for details.

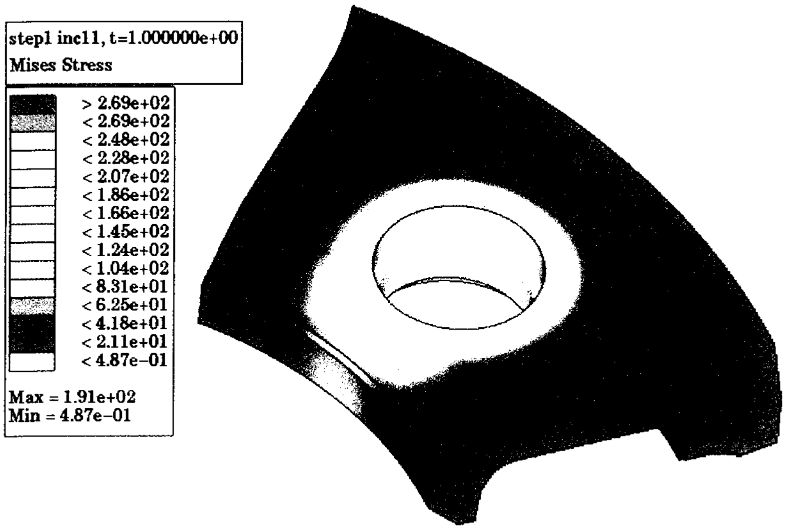


Figure 6.8 Stress on the Disc under Clamp Load with Steel Ring

The high stress is transferred to the steel ring, Figure 6.9. However it is easy to find a kind of high strength steel material for the ring.

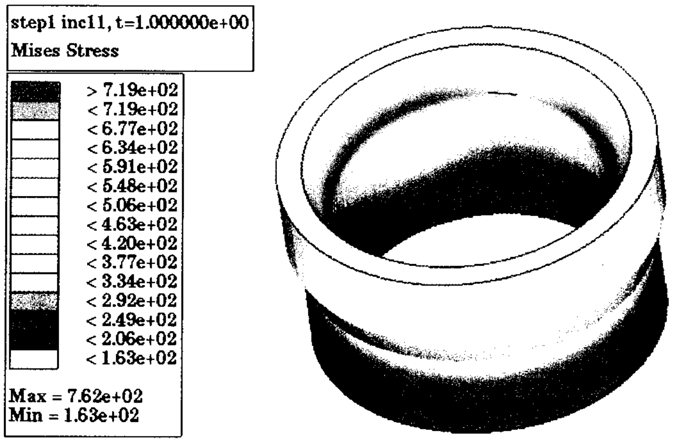
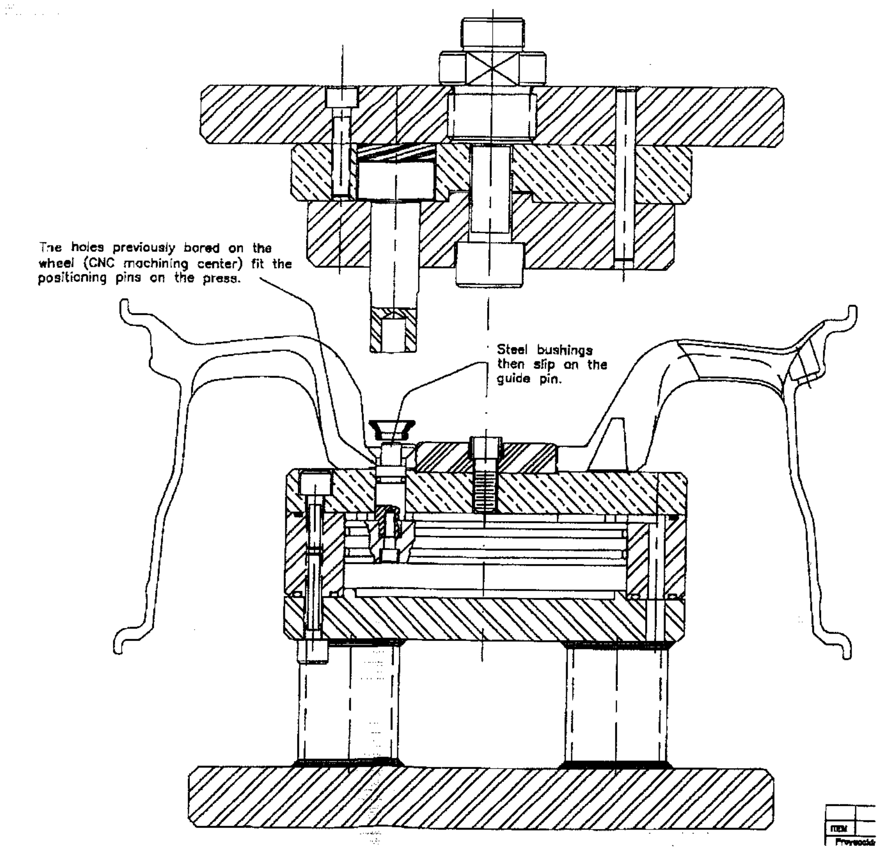


Figure 6.9 Stress on the Ring under Clamp Load

6.5 Solution

The simulations of the new design that push a steel ring into the aluminum wheel gives the engineer confidence. Thus, the design time was reduced.

Figure 6.10 show the steel ring is pushed in the lug seat by machine.



The holes previously bored on the wheel (CNC machining center) fit the positioning pins on the press.

Steel bushings then slip on the guide pin.

6.10 Steel Ring was pushed in the Lug Seat by Machine

Chapter 7 Conclusions and Future Work

7.1 Conclusions

This thesis provides a new design process of conceptual engineering design decision–making. The requirements of engineering conceptual design process are discussed and justified. The key issue that has to be addressed in developing a new design process is to find ways by which designers can be guided to generate valuable design concept in the shortest time. The fundamental challenges of the conceptual design process are illustrated and the difficulties which designers face while developing original alternative concepts are identified. At the conceptual design stage, the biggest challenge for designers is to generate and evaluate the alternative ideas. These problems are exemplified. The majority of the existing engineering design models that are less than successful in addressing the requirements of the conceptual stage of engineering design were found in the paper.

In the past, simulations such as these were limited to the major companies with large computers. That is no longer the case. Today, most of our analysis and graphical products operate on workstations that are readily available from a number of manufacturers running any of the popular operating systems. Increasingly, the single most important factor in determining which computer you choose is simply "How fast do you want your answers?"

Every simulation acts as the vantage point from which one can better view the possibilities and then ask the next question. That question generally requires one or more finer simulation. As soon as that is available, someone will ask for the "optimum" solution. The primary limitation today in reaching this optimum solution is the size of the problem. The needs by companies for faster solutions, for better and better simulations, for more refined and accurate simulations, and now for virtual manufacturing simulations lead to the unquenchable demand for more computational power. The computer industry is delivering on that demand.

Parallel Processing involves combining the resources of many creative design ideas generated using TRIZ and applying virtual manufacturing simulation to the solution of a best design. The appeal of parallel processing is that it offers a means of simultaneously capitalizing on the growth of engineering design performance and the potential performance benefits of multiple ideas.

I identify the contribution of this research work to address the discussed issues.

a. Understanding the engineering design

In order to realize the requirements of conceptual design process, I have studied the engineering design objectively, and identified three important characteristics of engineering design: engineering design process, engineering methods and new technology in engineering design.

b. Developing a systematic approach of integrating the three elements: design methods, design process and simulation in the early design phase to limit the design time and generate a valuable design.

c. Two engineering design case were studied with the new engineering design approach. These cases prove the new approach can be used in not only the product design, but also can be used in the manufacturing process design.

7.2 Future Work

In this section, several new research problems are identified as future work for this research topic:

Alternative Concept Generation:

Generation of design alternatives has been an active topic for research in the design modeling community. The process designers come up with new design concepts in situations that they have not encountered earlier, is one of the aspect of engineering design that is not well understood. Such understanding may assist researchers in developing models to support designers in generating new design concepts more effectively.

Behavior and structure modeling:

Modeling of manufacturing system structure and behavior is a primary focus of the research presented here. Many techniques exist for modeling system structure, including new design idea oriented methods, computer simulation, etc. This thesis presented two examples of how simulation analysis can be used to support the proposed process for trade-off analysis; other methods could be examined in a similar fashion to determine how such creative models can contribute to the creative engineering design process proposed here.

Performance evaluation under complex design problems:

We have evaluated our framework by applying it to two simplified conceptual design problems. The power of this framework can be illustrated better when it is applied to complex design problems. We have planned to apply this framework to several complex design problems that automotive manufacturing companies are dealing with, in order to evaluate the performance of our proposed model.

Extending the software to collaborative conceptual design and design-making:

Finally, the framework was planed to extend to others design collaboration. In order to achieve this goal, future researchers should look into conditions under which designers are able to share their design objectives and requirements that have to be meet in cases which, for example, a designer decides to modify or remove a design objective for a certain decision situation.

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APPENDIX A

TRIZ Contradiction Table

The parameter deteriorating as a result of the change / The parameter under change		1 Weight of mobile object	2 Weight of stationary object	3 Length of mobile object	4 Length of stationary object	5 Area of mobile object	6 Area of stationary object	7 Volume of mobile object	8 Volume of stationary object	9 Rate of change, speed	10 Force exerted by object	11 Stress, pressure exerted upon object	12 Shape of object	13 Stability of objects composition	
1	Weight of mobile object			15, 8, 29,34		29,17 38,34		29,2, 40,28		2,8, 15,38	8,10, 18,37	10,36 37,40	10,14 35,40	1,35, 19,39	1
2	Weight of stationary object				10,1, 29,35		35,30 13,2		5,35, 14,2		8,10, 19,35	13,29 10,18	13,10 29,14	26,39 1,40	2
3	Length of mobile object	8, 15, 29,34				15,17 4		7,17, 4,35		13,4, 8	17,10 4	1,8, 35	1,8, 10,29	1,8, 15,34	3
4	Length of stationary object		35,28 40,29				17,7, 10,40		35,8, 2,14		28,10	1,14, 35	13,14 15,7	39,37 35	4
5	Area of mobile object	2,17, 29,4		14,15 18,4				7,14, 17,4		29,30 4,34	19,30 35,2	10,15 36,28	5,34, 29,4	11,2, 13,39	5
6	Area of stationary object		30,2, 14,18		26,7, 9,39						1,18, 35,36	10,15 36,37		2,38	6
7	Volume of mobile object	2,26, 29,40		1,7, 4,35		1,7, 4,17				29,4, 38,34	15,35 36,37	6,35, 36,37	1,15, 29,4	28,10 1,39	7
8	Volume of stationary object		35,10 19,14	19,14	35,8, 2,14						2,18, 37	24,35	7,2, 35	34,28 35,40	8
9	Rate of change, speed	2,28, 13,38		13,14 8		29,30 34		7,29, 34			13,28 15,19	6,18, 38,40	35,15 18,34	28,33 1,18	9
10	Force exerted by object	8,1, 37,18	18,13 1,28	17,19 9,36	28,10	19,10 15	1,18, 36,37	15,9, 12,37	2,36, 18,37	13,28 15,12		18,21 11	10,35 40,34	35,10 21	10
11	Stress, pressure exerted upon object	10,36 37,40	13,29 10,18	35,10 36	35,1, 14,16	10,15 36,28	10,15 36,37	6,35, 10	35,24	6,35, 36	36,35 21		35,4, 15,10	35,33 2,40	11
12	Shape of object	8,10, 29,40	15,10 26,3	29,34 5,4	13,14 10,7	5,34, 4,10		14,4, 15,22	7,2, 35	35,15 34,18	35,10 37,40	34,15 10,14		33,1, 18,4	12
13	Stability of object's composition	21,35 2,39	26,39 1,40	13,15 1,28	37	2,11, 13	39	28,10 19,39	34,28 35,40	33,15 28,18	10,35 21,16	2,35, 40	22,1, 18,4		13
14	Strength of object	1,8, 40,15	40,26 27,1	1,15, 8,35	15,14 28,26	3,34, 40,29	9,40, 28	10,15 14,7	9,14, 17,15	8,13, 26,14	10,18 3,14	10,3, 18,40	10,30 35,40	13,17 35	14
15	Durability of mobile object	19,5, 34,31		2,19, 9		3,17, 19		10,2, 19,30		3,35, 5	19,2, 16	19,3, 27	14,26 28,25	13,3, 35	15
16	Durability of stationary object		6,27, 19,16		1,40, 35				35,34 38					39,3, 35,23	16
17	Temperature of object	36,22 6,38	22,35 32	15,19 9	15,19 9	3,35, 39,18	35,38	34,39 40,18	35,6, 4	2,28, 36,30	35,10 3,21	35,39 19,2	14,22 19,32	1,35, 32	17
18	Illumination of object	19,1, 32	2,35, 32	19,32 16		19,32 26		2,13, 10		10,13 19	26,19 6		32,30	32,3, 27	18
19	Energy consumption by mobile object	12,18 28,31		12,28		15,19 25		35,13 18		8,15, 35	16,26 21,2	23,14 25	12,2, 29	19,13 17,24	19
20	Energy consumption by stationary object		19,9, 6,27								36,37			27,4, 29,18	20
© Iouri Belski		1	2	3	4	5	6	7	8	9	10	11	12	13	CT-1

TRIZ Contradiction Table

The parameter under change	The parameter deteriorating as a result of the change	14 Strength of object	15 Durability of mobile object	16 Durability of stationary object	17 Temperature of object	18 Illumination of object	19 Energy consumption by mobile object	20 Energy consumption by stationary object	21 Power supplied or consumed by object	22 Energy loss by object	23 Substance loss by object	24 Information loss	25 Time loss	26 Quantity of matter	
1	Weight of mobile object	28,27 18,40	5,34, 31,35		6,29, 4,38	19,1, 32	35,12 34,31		12,36 18,31	6,2, 34,19	5,35, 3,31	10,24 35	10,35 20,28	3,26, 18,31	1
2	Weight of stationary object	28,2, 10,27		2,27, 19,6	28,19 32,22	19,32 35		18,19 28,1	15,19 18,22	18,19 28,15	5,8, 13,30	10,15 35	10,20 35,26	19,6, 18,26	2
3	Length of mobile object	8,35, 29,34	19		10,15 19	32	8,35, 24		1,35	7,2,3 5,39	4,29, 23,10	1,24	15,2, 29	29,35	3
4	Length of stationary object	15,14 28,26		1,40, 35	3,35, 38,18	3,25			12,8	6,28	10,28 24,35	24,26	30,29 14		4
5	Area of mobile object	3,15, 40,14	6, 3		2,15, 16	15,32 19,13	19,32		19,10 32,18	15,17 30,26	10,35 2,39	30,26	26,4	29,30 6,13	5
6	Area of stationary object	40		2,10, 19,30	35,39 38				17,32	17,7, 30	10,14 18,39	30,16	10,35 4,18	2,18, 40,4	6
7	Volume of mobile object	9,14, 15,7	6,35, 4		34,39 10,18	2,13, 10	35		35,6, 13,18	7,15, 13,16	36,39 34,10	2,22	2,6, 34,10	29,30 7	7
8	Volume of stationary object	9,14, 17,15		35,34 38	35,6, 4				30,6		10,39 35,34		35,16 32,18	35,3	8
9	Rate of change, speed	8,3, 26,14	3,19, 35,5		28,30 36,2	10,13 19	8,15, 35,38		19,35 38,2	14,20 19,35	10,13 28,38	13,26		10,19 29,38	9
10	Force exerted by object	35,10 14,27	19,2		35,10 21		19,17 10	1,16, 36,37	19,35 18,37	14,15	8,35, 40,5		10,37 36	14,29 18,36	10
11	Stress, pressure exerted upon object	9,18, 3,40	19,3, 27		35,39 19,2		14,24 10,37		10,53 14	2,36, 25	10,36 3,37		37,36 4	10,14 36	11
12	Shape of object	30,14 10,40	14,26 9,25		22,14 19,32	13,15 32	2,6, 34,14		4,6,2	14	35,29 3,5		14,10 34,17	36,22	12
13	Stability of object's composition	17,9, 15	13,27 10,35	39,3, 35,23	35,1, 32	32,3, 27,15	13,19	27,4, 29,18	32,35 27,31	14,2, 39,6	2,14, 30,40		35,27	15,32 35	13
14	Strength of object		27,3, 26		30,10 40	35,19	19,35 10	35	10,26 35,28	35	35,28 31,40		29,3, 28,10	29,10 27	14
15	Durability of mobile object	27,3, 10			19,35 39	2,19, 4,35	28,6, 35,18		19,10 35,38		28,27 3,18	10	20,10 28,18	3,35, 10,40	15
16	Durability of stationary object				19,18 36,40				16		27,16 18,38	10	28,20 10,16	3,35, 31	16
17	Temperature of object	10,30 22,40	19,13 39	19,18 36,40		32,30 21,16	19,15 3,17		2,14, 17,25	21,17 35,38	21,36 29,31		35,28 21,18	3,17, 30,39	17
18	Illumination of object	35,19	2,19, 6		32,35 19		32,1, 19	32,35 1,15	32	13,16 1,6	13,1	1,6	19,1, 26,17	1,19	18
19	Energy consumption by mobile object	5,19, 9,35	28,35 6,18		19,24 3,14	2,15, 19			6,19, 37,18	12,22 15,24	35,24 18,5		35,38 19,18	34,23 16,18	19
20	Energy consumption by stationary object	35				19,2, 35,32					28,27 18,31			3,35, 31	20
	© Iouri Belski	14	15	16	17	18	19	20	21	22	23	24	25	26	CT-2

TRIZ Contradiction Table

	The parameter deteriorating as a result of the change / The parameter under change	27	28	29	30	31	32	33	34	35	36	37	38	39	
		Reliability of object	Accuracy of measurement	Precision of production	Harmful influence of object's environment	Harmful effects caused by object	Ease of production	Convenience of use	Ease of repair and maintenance	Adaptability, versatility of object	Complexity of object	Difficulties in measuring, inspection	Level of automation	Production rate	
1	Weight of mobile object	3,11, 1,27	28,27 35,26	26,35 26,18	22,21 18,27	22,35 31,39	27,28 1,36	35,3, 2,24	2,27, 28,11	29,5, 15,8	26,30 36,34	28,29 26,32	26,35 18,19	35,3, 24,37	1
2	Weight of stationary object	10,28 8,3	18,26 28	10,1, 35,17	2,19, 22,37	35,22 1,39	28,1, 9	6,13, 1,32	2,27, 28,11	19,15 29	1,10, 26,39	26,26 17,15	2,26, 35	1,28, 15,35	2
3	Length of mobile object	10,14 29,40	28,32 4	10,28 29,37	1,15, 17,24	17,15	1,29, 17	15,29 35,4	1,28, 10	14,15 1,16	1,19, 26,24	35,1, 26,24	17,24 26,16	14,4, 28,29	3
4	Length of stationary object	15,29 28	32,28 3	2,32, 10	1,18		15,17 27	2,25	3	1,35	1,26	26		30,14 7,26	4
5	Area of mobile object	29,9	26,28 32,3	2,32	22,33 28,1	17,2, 18,39	13,1, 26,24	15,17 13,16	15,13 10,1	15,30	14,1, 13	2,36, 26,18	14,30 28,23	10,26 34,2	5
6	Area of stationary object	32,35 40,4	26,28 32,3	2,29, 18,36	27,2, 39,35	22,1, 40	40,16	16,4	16	15,16	1,18, 36	2,35, 30,18	23	10,15 17,7	6
7	Volume of mobile object	14,1, 40,11	25,26 28	25,28 2,16	22,21 27,35	17,2, 40,1	29,1, 40	15,13 30,12	10	15,29	26,1	29,26 4	35,34 16,24	10,6, 2,34	7
8	Volume of stationary object	2,35, 16		35,10 25	34,39 19,27	30,18 35,4	35		1		1,31	2,17, 26		35,37 10,2	8
9	Rate of change, speed	11,35 27,28	28,32 1,24	10,28 32,25	1,28, 35,23	2,24, 35,21	35,13 8,1	32,28 13,12	34,2, 28,27	15,10 26	10,28 4,34	3,34, 27,16	10,18		9
10	Force exerted by object	3,35, 13,21	36,10 23,24	28,29 37,36	1,35, 40,18	13,3, 36,24	15,37 18,1	1,28, 3,25	15,1, 11	15,17 18,20	26,35 10,18	36,37 10,19	2,35	3,28, 35,37	10
11	Stress, pressure exerted upon object	10,13 19,35	6,28, 25	3,35	22,2, 37	2,33, 27,18	1,35, 16	11	2	35	19,1, 35	2,36, 37	35,24	10,14 35,37	11
12	Shape of object	10,40 16	28,32 1	32,30 40	22,1, 2,35	35,1	1,32, 17,28	32,15 26	2,13, 1	1,15, 29	16,29 1,28	15,13 39	15,1, 32	17,26 34,10	12
13	Stability of object's composition		13	18	35,24 30,18	35,40 27,39	35,19	32,35 30	2,35, 10,16	35,30 34,2	2,35, 22,26	35,22 39,23	1,8, 35	23,35 40,3	13
14	Strength of object	11,3	3,27, 16	3,27	18,35 37,1	15,35 22,2	11,3, 10,32	32,40 28,2	27,11 3	15,3, 32	2,13, 28	27,3, 15,40	15	29,35 10,14	14
15	Durability of mobile object	11,2, 13	3	3,27, 16,40	22,15 33,28	21,39 16,22	27,1, 4	12,27	29,10 27	1,35, 13	10,4, 29,15	19,29 39,35	6,10	35,17 14,19	15
16	Durability of stationary object	34,27 6,40	10,26 24		17,1, 40,33	22	35,10	1	1	2		25,34 6,35	1	20,10 16,38	16
17	Temperature of object	19,35 3,10	32,19 24	24	22,33 35,2	22,35 2,24	26,27	26,27	4,10, 16	2,18, 27	2,17, 16	3,27, 35,31	26,2, 19,16	15,28 35	17
18	Illumination of object		11,15 32	3,32	15,19	35,19 32,39	19,35 28,26	28,26 19	15,17 13,16	15,10 1,19	6,32, 13	32,15	2,26, 10	2,25, 16	18
19	Energy consumption by mobile object	19,21 11,27	3,1, 32		1,35, 6,27	2,35, 6	28,26 30	19,35	1,15, 1728	15,17 13,16	2,29, 27,28	35,38	32,2	12,28 35	19
20	Energy consumption by stationary object	10,36 23			10,2, 22,37	19,22 18	1,4					19,35 16,25		1,6	20
	© Iouri Belski	27	28	29	30	31	32	33	34	35	36	37	38	39	CT-3

TRIZ Contradiction Table

The parameter deteriorating as a result of the change / The parameter under change		1	2	3	4	5	6	7	8	9	10	11	12	13	
		Weight of mobile object	Weight of stationary object	Length of mobile object	Length of stationary object	Area of mobile object	Area of stationary object	Volume of mobile object	Volume of stationary object	Rate of change, speed	Force exerted by object	Stress, pressure exerted upon object	Shape of object	Stability of objects composition	
21	Power supplied or consumed by object	8,36, 38,31	19,26 17,27	1,10, 35,37		19.38	17,32 13,38	35,6, 38	30,6, 25	15,35 2	26,2, 36,35	22,10 35	29,14 2,40	35,32 15,31	21
22	Energy loss by object	15,6, 19,28	19,6, 18,9	7,2, 6,13	6,38, 7	15,26 17,30	17,7, 30,18	7,18, 23	7	16,35 38	36,38			14,2, 39,6	22
23	Substance loss by object	35,6, 23,40	35,6, 22,32	14,29 10,39	10,28 24	35,2, 10,31	10,18 39,31	1,29, 30,36	3,39, 18,31	10,13 28,38	14,15 18,40	3,36, 37,10	29,35 3,5	2,14, 30,40	23
24	Information loss	10,24 35	10,35 5	1,26	26	30,26	30,16		22,2	26,32					24
25	Time loss	10,20 37,35	10,20 26,5	15,2, 29	30,24 14,5	26,4, 5,16	10,35 17,4	2,5, 34,10	35,16 32,18		10,37 36,5	37,36 4	4,10, 34,17	35,3, 22,5	25
26	Quantity of matter	35,6, 18,31	27,26 18,35	29,14 35,18		15,14 29	2,18, 40,4	15,20 29		35,29 34,28	35,14 3	10,36 14,3	35,14	15,2, 17,40	26
27	Reliability of object	3,8, 10,40	3,10, 8,28	15,9, 14,4	15,29 28,11	17,10 14,16	32,35 40,4	3,10, 14,24	2,35, 24	21,35 11,28	8,28, 10,3	10,24 35,19	35,1, 16,11		27
28	Accuracy of measurement	32,35 26,28	28,35 25,26	28,26 5,16	32,28 3,16	26,28 32,3	26,28 32,3	32,13 6		28,13 32,24	32,2	6,28, 32	6,28, 32	32,35 13	28
29	Precision of production	28,32 13,18	28,35 27,9	10,28 29,37	2,32, 10	28,33 29,32	2,29, 18,36	32,28 2	25,10 35	10,28 32	28,19 34,36	3,35	32,30 40	30,18	29
30	Harmful influence of object's environment	22,21 27,39	2,22, 13,24	17,1, 39,4	1,18	22,1, 33,28	27,2, 39,35	22,23 37,35	34,39 19,27	21,22 35,28	13,35 39,18	22,2, 37	22,1, 3,35	35,24 30,18	30
31	Harmful effects caused by object	19,22 15,39	35,22 1,39	17,15 16,22		17,2, 18,39	22,1, 40	17,2, 40	30,18 35,4	35,28 3,23	35,28 1,40	2,33, 27,18	35,1	35,40 27,39	31
32	Ease of production	28,29 15,16	1,27, 36,13	1,29, 13,17	15,17 27	13,1, 26,12	16,40	13,29 1,40	35	35,13 8,1	35,12	35,19 1,37	1,28, 13,27	11,13 1	32
33	Convenience of use	25,2, 13,15	6,13, 1,25	1,17, 13,12		1,17, 13,16	18,16 15,39	1,16, 35,15	4,18, 39,31	18,13 34	28,13 35	2,32, 12	15,34 29,28	32,35 30	33
34	Ease of repair and maintenance	2,27, 35,11	2,27, 35,11	1,28, 10,25	3,18, 31	15,13 32	16,25	25,2, 35,11	1	34,9	1,11, 10	13	1,13, 2,4	2,35	34
35	Adaptability, versatility of object	1,6, 15,8	19,15 29,16	35,1, 29,2	1,35, 16	35,30 29,7	15,16	15,35 29		35,10 14	15,17 20	35,16	15,37 1,8	35,30 14	35
36	Complexity of object	26,30 34,36	2,26, 35,39	1,19, 26,24	26	14,1, 13,16	6,36	34,26 6	1,16	34,10 28	26,16	19,1, 35	29,13 28,15	2,22, 17,19	36
37	Difficulties in measuring, inspection	27,26 28,13	6,13, 28,1	16,17 26,24	26	2,13, 18,17	2,39, 30,16	29,1, 4,16	2,18, 26,31	3,4, 16,35	36,28 40,19	35,36 37,32	27,13 1,39	11,22 39,30	37
38	Level of automation	28,26 18,35	28,26 35,10	14,13 17,28	23	17,14 13		35,13 16		28,10	2,35	13,35	15,32 1,13	18,1	38
39	Production rate	35,26 24,37	28,27 15,3	18,4, 28,38	30,7, 14,26	10,26 34,31	10,35 17,7	2,6, 34,10	35,37 10,2		28,15 10,36	10,37 14	14,10 34,40	35,3, 22,39	39
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TRIZ Contradiction Table

The parameter deteriorating as a result of the change / The parameter under change		14	15	16	17	18	19	20	21	22	23	24	25	26	
		Strength of object	Durability of mobile object	Durability of stationary object	Temperature of object	Illumination of object	Energy consumption by mobile object	Energy consumption by stationary object	Power supplied or consumed by object	Energy loss by object	Substance loss by object	Information loss	Time loss	Quantity of matter	
21	Power supplied or consumed by object	26,10 28	19,35 10,38	16	2,14, 17,25	16,6, 19	16,6, 19,37			10,35 38	28,27 18,38	10,19	35,20 10,6	4,34, 19	21
22	Energy loss by object	26			19,38 7	1,13, 32,15			3,38		35,27 2,37	19,10	10,18 32,7	7,18, 25	22
23	Substance loss by object	35,28 31,40	28,27 3,18	27,16 18,38	21,36 39,31	1,6, 13	35,18 24,5	28,27 12,31	28,27 18,38	35,27 2,31			15,18 35,10	6,3, 10,24	23
24	Information loss		10	10		19			10,19	19,10			24,26 28,32	24,28 35	24
25	Time loss	29,3, 28,18	20,10 28,18	28,20 10,16	35,29 21,18	1,19, 26,17	35,38 19,18	1	35,20 10,6	10,5, 18,32	35,18 10,39	24,26 28,32		35,38 18,16	25
26	Quantity of matter	14,35 34,10	3,35, 10,40	3,35, 31	3,17, 39		34,29 16,18	3,35, 31	35	7,18, 25	6,3, 10,24	24,28 35	35,38 18,16		26
27	Reliability of object	11,28	2,35, 3,25	34,27 6,40	3,35, 10	11,32 13	21,11 27,19	36,23	21,11 26,31	10,11 35	10,35 29,39	10,28	10,30 4	21,28 40,3	27
28	Accuracy of measurement	28,6, 32	28,6, 32	10,26 24	6,19, 28,24	6,1, 32	3,6, 32		3,6, 32	26,32 27	10,16 31,28		24,34 28,32	2,6, 32	28
29	Precision of production	3,27	3,27, 40		19,26	3,32	32,2		32,2	13,32 2	35,31 10,24		32,26 28,18	32,30	29
30	Harmful influence of object's environment	18,35 37,1	22,15 33,28	17,1, 40,33	22,33 35,2	1,19, 32,13	1,24, 6,27	10,2, 22,37	19,22 31,2	21,22 35,2	33,22 19,40	22,10 2	35,18 34	35,33 29,31	30
31	Harmful effects caused by object	15,35 22,2	15,22 33,31	21,39 16,22	22,35 2,24	19,24 39,32	2,35, 6	19,22 18	2,35, 18	21,35 2,22	10,1, 34	10,21 29	1,22	3,24, 39,1	31
32	Ease of production	1,3, 10,32	27,1, 4	35,16	27,26 18	28,24 27,1	28,26 27,1	1,4	27,1, 12,24	19,35	15,34 33	32,24 18,16	35,28 34,4	35,23 1,24	32
33	Convenience of use	32,40 3,28	29,3, 8,25	1,16, 25	26,27 13	13,17 1,24	1,13, 24		35,34 2,10	2,19, 13	28,32 2,24	4,10, 27,22	4,28, 10,34	12,35	33
34	Ease of repair and maintenance	11,1, 2,9	11,29 28,27	1	4,10	15,1, 13	15,1, 28,16		15,10 32,2	15,1, 32,19	2,35, 34,27		32,1, 10,25	2,28, 10,25	34
35	Adaptability, versatility of object	35,3, 32,6	13,1, 35	2,16	27,2, 3,35	6,22, 26,1	19,35 29,13		19,1, 29	18,15 1	15,10 2,13		35,28	3,35, 15	35
36	Complexity of object	2,13, 28	10,4, 28,15		2,17, 13	24,17 13	27,2, 29,28		20,19 30,34	10,35 13,2	35,10 28,29		6,29	13,3, 27,10	36
37	Difficulties in measuring, inspection	27,3, 15,28	19,29 39,25	25,34 6,35	3,27, 35,16	2,24, 26	35,38	19,35 16	19,1, 16,10	35,3, 15,19	1,18, 10,24	35,33 27,22	18,28 32,9	3,27, 29,18	37
38	Level of automation	25,13	6,9		26,2, 19	8,32, 19	2,32, 13		28,2, 27	23,28	35,10 18,5	35,33	24,28 35,30	35,13	38
39	Production rate	29,28 10,18	35,10 2,18	20,10 16,38	35,21 28,10	26,17 19,1	35,10 38,19	1	35,20 10	28,10 29,35	28,10 35,23	13,15 23		35,38	39
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TRIZ Contradiction Table

	The parameter deteriorating as a result of the change The parameter under change	27 Reliability of object	28 Accuracy of measurement	29 Precision of production	30 Harmful influence of object's environment	31 Harmful effects caused by object	32 Ease of production	33 Convenience of use	34 Ease of repair and maintenance	35 Adaptability, versatility of object	36 Complexity of object	37 Difficulties in measuring, inspection	38 Level of automation	39 Production rate	
21	Power supplied or consumed by object	19,24 26,31	32,15 2	32,2	19,22 31,2	2,35, 18	26,10 34	26,35 10	35,2, 10,34	19,17 34	20,19 30,34	19,35 16	28,2, 17	28,35 34	21
22	Energy loss by object	11,10 35	32		21,22 35,2	21,35 2,22		35,32 1	2,19		7,23	35,3, 15,23	2	28,10 29,35	22
23	Substance loss by object	10,29 39,35	16,34 31,28	35,10 24,31	33,22 30,40	10,1, 34,29	15,34 33	32,28 2,24	2,35, 34,27	15,10 2	35,10 28,24	35,18 10,13	35,10 18	28,35 10,23	23
24	Information loss	10,28 23			22,10 1	10,21 22	32	27,22				35,33	35	13,23 15	24
25	Time loss	10,30 4	24,34 28,32	24,26 28,18	35,18 34	35,22 18,39	35,28 34,4	4,28, 10,34	32,1, 10	35,28	6,29	18,28 32,10	24,28 35,30		25
26	Quantity of matter	18,3, 28,40	3,2, 28	33,30	35,33 29,31	3,35, 40,39	29,1, 35,27	35,29 25,10	2,32, 10,25	15,3, 29	3,13, 27,10	3,27, 29,18	8,35	13,29 3,27	26
27	Reliability of object		32,3, 11,23	11,32 1	27,35 2,40	35,2, 40,26		27,17 40	1,11	13,35 8,24	13,35 1	27,40 28	11,13 27	1,35, 29,38	27
28	Accuracy of measurement	5,11, 1,23			28,24 22,26	3,33, 39,10	6,35, 25,18	1,13, 17,34	1,32, 13,11	13,35 2	27,35 10,34	26,24 32,28	28,2, 10,34	10,34 28,32	28
29	Precision of production	11,32 1			26,28 10,36	4,17, 34,26		1,32, 35,23	25,10		26,2, 18		26,28 18,23	10,18 32,39	29
30	Harmful influence of object's environment	27,24 2,40	28,33 23,26	26,28 10,18			24,35 2	2,25, 28,39	35,10 2	35,11 22,31	22,19 29,40	22,19 29,40	33,3, 34	22,35 13,24	30
31	Harmful effects caused by object	24,2, 40,39	3,33, 26	4,17, 34,26							19,1, 31	2,21, 27,1	2	22,35 18,39	31
32	Ease of production		1,35, 12,18		24,2			2,5, 13,16	35,1, 11,9	2,13, 15	27,26 1	6,28, 11,1	8,28, 1	35,1, 10,28	32
33	Convenience of use	17,27 8,40	25,13 2,34	1,32, 35,23	2,25, 28,39		2,5, 12		12,26 1,32	15,34 1,16	32,26 12,17		1,34, 12,3	15,1, 28	33
34	Ease of repair and maintenance	11,10 1,16	10,2, 13	25,10	35,10 2,16		1,35, 11,10	1,12, 26,15		7,1, 4,16	35,1, 13,11		34,35 7,13	1,32, 10	34
35	Adaptability, versatility of object	35,13 8,24	35,5, 1,10		35,11 32,31		1,13, 31	15,34 1,16	1,16, 7,4		15,19 37,28	1	27,34 35	35,28 6,37	35
36	Complexity of an object	13,35 1	2,26, 10,34	26,24 32	22,19 29,40	19,1	27,26 1,13	27,9, 26,24	1,13	29,15 28,37		15,10 37,28	15,1, 24	12,17 28	36
37	Difficulties in measuring, inspection	27,40 28,8	26,24 32,28		22,19 29,28	2,21	5,28, 11,29	2,5	12,26	1,15	15,10 37,28		34,21	35,18	37
38	Level of automation	11,27 32	28,26 10,34	28,26 18,23	2,33	2	1,26, 13	1,12, 34,3	1,35, 13	27,4, 1,35	15,24 10	34,27 25		5,12, 35,26	38
39	Production rate	1,35, 10,38	1,10, 34,28	18,10 32,1	22,35 13,24	35,22 18,39	35,28 2,24	1,28, 7,19	1,32, 10,25	1,35, 28,37	12,17 28,24	35,18 27,2	5,12, 35,26		39
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APPENDIX B

The 40 Inventive Principles

1. Segmentation

a. Divide an object into independent parts

b. Make an object sectional

c. Increase the degree of an object's segmentation

Examples:

- Sectional furniture, modular computer components, folding wooden ruler
- Garden hoses can be joined together to form any length needed

2. Extraction

a. Extract (remove or separate) a "disturbing" part or property from an object, or

b. Extract only the necessary part or property

Example:

- To frighten birds away from the airport, use a tape recorder to reproduce the sound known to excite birds. (The sound is thus separated from the birds.)

3. Local Quality

a. Transition from a homogeneous structure of an object or outside environment/action to a heterogeneous structure

b. Have different parts of the object carry out different functions

c. Place each part of the object under conditions most favorable for its operation

Examples:

- To combat dust in coal mines, a fine mist of water in a conical form is applied to working parts of the drilling and loading machinery. The smaller the droplets, the greater the effect in combating dust, but fine mist hinders the work. The solution is to develop a layer of coarse mist around the cone of fine mist.
- A pencil and eraser in one unit.

4. Asymmetry

a. Replace a symmetrical form with an asymmetrical form.

b. If an object is already asymmetrical, increase the degree of asymmetry

Examples:

- Make one side of a tire stronger than the other to withstand impact with the curb
- While discharging wet sand through a symmetrical funnel, the sand forms an arch above the opening, causing irregular flow. A funnel of asymmetrical shape eliminates the arching effect.

5. Combining

a. Combine in space homogeneous objects or objects destined for contiguous operations

b. Combine in time homogeneous or contiguous operations

Example:

- The working element of a rotary excavator has special steam nozzles to defrost and soften the frozen ground

6. Universality

Have the object perform multiple functions, thereby eliminating the need for some other object(s)

Examples:

- Sofa which converts into a bed
- Minivan seat which adjusts to accommodate seating, sleeping or carrying cargo

7. Nesting

a. Contain the object inside another which, in turn, is placed inside a third object

b. Pass an object through a cavity of another object

Examples:

- Telescoping antenna
- Chairs which stack on top of each other for storage
- Mechanical pencil with lead stored inside

8. Counterweight

a. Compensate for the object's weight by joining with another object that has a lifting force

b. Compensate for the weight of an object by interaction with an environment providing aerodynamic or hydrodynamic forces

Examples:

- Boat with hydrofoils
- A rear wing in racing cars which increases pressure from the car to the ground

9. Prior counter-action

a. Perform a counter-action in advance

b. If the object is (or will be) under tension, provide anti-tension in advance

Examples:

- Reinforced concrete column or floor
- Reinforced shaft made from several pipes which have been previously twisted to some specified angle

10. Prior action

a. Carry out all or part of the required action in advance

b. Arrange objects so they can go into action in a timely matter and from a convenient position

Examples:

- Utility knife blade made with a groove allowing the dull part of the blade to be broken off, restoring sharpness
- Rubber cement in a bottle is difficult to apply neatly and uniformly. Instead, it is formed into a tape so that the proper amount can be more easily applied.

11. Cushion in advance

Compensate for the relatively low reliability of an object by countermeasures taken in advance

Example:

- Merchandise is magnetized to deter shoplifting.

12. Equipotentiality

Change the working conditions so that an object need not be raised or lowered.

Example:

- Automobile engine oil is changed by workers in a pit to avoid using expensive lifting equipment

13. Inversion

a. Instead of an action dictated by the specifications of the problem, implement an opposite action

b. Make a moving part of the object or the outside environment immovable and the non-moving part movable

c. Turn the object upside-down

Example:

- Abrasively cleaning parts by vibrating the parts instead of the abrasive

14. Spheroidality

a. Replace linear parts or flat surfaces with curved ones; replace cubical shapes with spherical shapes

b. Use rollers, balls spirals

c. Replace a linear motion with rotating movement; utilize a centrifugal force

Example:

- Computer mouse utilized ball construction to transfer linear two-axis motion into vector motion

15. Dynamism

a. Make an object or its environment automatically adjust for optimal performance at each stage of operation

b. Divide an object into elements which can change position relative to each other

c. If an object is immovable, make it movable or interchangeable

Examples:

- A flashlight with a flexible gooseneck between the body and the lamp head
- A transport vessel with a cylindrical-shaped body. To reduce the draft or a vessel under full load, the body is comprised of two hinged, half-cylindrical parts which can be opened.

16. Partial or overdone action

If it is difficult to obtain 100% of a desired effect, achieve somewhat more or less to greatly simplify the problem

Examples:

- A cylinder is painted by dipping into paint, but contains more paint than desired. Excess paint is then removed by rapidly rotating the cylinder.
- To obtain uniform discharge of a metallic powder from a bin, the hopper has a special internal funnel which is continually overfilled to provide nearly constant pressure.

17. Moving to a new dimension

a. Remove problems with moving an object in a line by two-dimensional movement (i.e. along a plane)

b. Use a multi-layered assembly of objects instead of a single layer

c. Incline the object or turn it on its side

Example:

- A greenhouse which has a concave reflector on the northern part of the house to improve illumination of that part of the house by reflecting sunlight during the day.

18. Mechanical vibration

a. Set an object into oscillation

b. If oscillation exists, increase its frequency, even as far as ultrasonic

c. Use the resonant frequency

d. Instead of mechanical vibrations, use piezovibrators

e. Use ultrasonic vibrations in conjunction with an electromagnetic field

Examples:

- To remove a cast from the body without injuring the skin, a conventional hand saw was replaced with a vibrating knife
- Vibrate a casting mold while it is being filled to improve flow and structural properties

19. Periodic action

a. Replace a continuous action with a periodic (pulsed) one

b. If an action is already periodic, change its frequency

c. Use pulsed between impulses to provide additional action

Examples:

- An impact wrench loosens corroded nuts using impulses rather than continuous force

- A warning lamp flashes so that it is even more noticeable than when continuously lit

20. Continuity of a useful action

a. Carry out an action continuously (i.e. without pauses), where all parts of an object operate at full capacity

b. Remove idle and intermediate motions

Example:

- A drill with cutting edges which permit cutting in forward and reverse directions

21. Rushing through

Perform harmful or hazardous operations at very high speed

Example:

- A cutter for thin-walled plastic tubes prevents tube deformation during cutting by running at a very high speed (i.e. cuts before the tube has a chance to deform)

22. Convert harm into benefit

a. Utilize harmful factors or environmental effects to obtain a positive effect

b. Remove a harmful factor by combining it with another harmful factor

c. Increase the amount of harmful action until it ceases to be harmful

Examples:

- Sand or gravel freezes solid when transported through cold climates. Over-freezing (using liquid nitrogen) makes the ice brittle, permitting pouring.

- When using high frequency current to heat metal, only the outer layer became hot. This negative effect was later used for surface heat-treating.

23. Feedback

a. Introduce feedback

b. If feedback already exists, reverse it

Examples:

- Water pressure from a well is maintained by sensing output pressure and turning on a pump if pressure is too low
- Ice and water are measured separately but must combine to total a specific weight. Because ice is difficult to dispense precisely, it is measured first. The weight is then fed to the water control device, which precisely dispenses the needed amount.

24. Mediator

a. Use an intermediary object to transfer or carry out an action

b. Temporarily connect an object to another one that is easy to remove

Example:

- To reduce energy loss when applying current to a liquid metal, cooled electrodes and intermediate liquid metal with a lower melting temperature are used.

25. Self-service

a. Make the object service itself and carry out supplementary and repair operations

b. Make use of wasted material and energy

Examples:

- To prevent wear in a feeder which distributes an abrasive material, its surface is made from the abrasive material
- In an electric welding gun, the rod is advanced by a special device. To simplify the system, the rod is advanced by a solenoid controlled by the welding current.

26. Copying

a. Use a simple and inexpensive copy instead of an object which is complex, expensive, fragile or inconvenient to operate.

b. Replace an object by its optical copy or image. A scale can be used to reduce or enlarge the image.

c. If visible optical copies are used, replace them with infrared or ultraviolet copies

Example:

- The height of tall objects can be determined by measuring their shadows.

27. Inexpensive, short-lived object for expensive, durable one

Replace an expensive object by a collection of inexpensive ones, forgoing properties (e.g. longevity)

Examples:

- Disposable diapers

28. Replacement of a mechanical system

a. Replace a mechanical system by an optical, acoustical or olfactory (odor) system

b. Use an electrical, magnetic or electromagnetic field for interaction with the object

c. Replace fields

1. Stationary fields with moving fields

2. Fixed fields with those which change in time

3. Random fields with structured fields

d. Use a field in conjunction with ferromagnetic particles

Example:

- To increase the bond between metal coating and a thermoplastic material, the process is carried out inside an electromagnetic field which applies force to the metal

29. Pneumatic or hydraulic construction

Replace solid parts of an object by gas or liquid. These parts can use air or water for inflation, or use air or hydrostatic cushions

Examples:

- To increase the draft of an industrial chimney, a spiral pipe with nozzles was installed. When air flows through the nozzles, it creates an air-like wall, reducing drag.
- For shipping fragile products, air bubble envelopes or foam-like materials are used.

30. Flexible membranes or thin film

a. Replace traditional constructions with those made from flexible membranes or thin film

b. Isolate an object from its environment using flexible membranes or thin film

Example:

- To prevent water evaporation from plant leaves, polyethylene spray was applied. After a while, the polyethylene hardened and plant growth improved, because polyethylene film passes oxygen better than water vapor.

31. Use of porous material

a. Make an object porous or add porous elements (inserts, covers, etc.)

b. If an object is already porous, fill the pores in advance with some substance

Example:

- To avoid pumping coolant to a machine, some of its parts are filled with a porous material soaked in coolant liquid. The coolant evaporates when the machine is working, providing short-term uniform cooling.

32. Changing the color

a. Change the color of an object or its surroundings

b. Change the degree of translucency of an object or processes which are difficult to see

c. Use colored additives to observe objects or processes which are difficult to see

d. If such additives are already used, employ luminescent traces or tracer elements

Examples:

- A transparent bandage enabling a wound to be inspected without removing the dressing
- A water curtain used to protect steel mill workers from overheating blocked infrared rays but not the bright light from the melted steel. A coloring was added to the water to create a filter effect while preserving the transparency of the water.

33. Homogeneity

Make those objects which interact with a primary object out of the same material or material that is close to it in behavior.

Example:

- The surface of a feeder for abrasive grain is made of the same material that runs through the feeder, allowing a continuous restoration of the surface.

34. Rejecting and regenerating parts

a. After it has completed its function or become useless, reject or modify (e.g. discard, dissolve, evaporate) an element of an object

b. Immediately restore any part of an object which is exhausted or depleted

Examples:

- Bullet casings are ejected after the gun fires
- Rocket boosters separate after serving their function

35. Transformation of the physical and chemical states of an object

Change an object's aggregate state, density distribution, degree of flexibility, temperature

Example:

- In a system for brittle friable materials, the surface of the spiral feedscrew was made from an elastic material with two spiral springs. To control the process, the pitch of the screw could be changed remotely.

36. Phase transformation

Implement an effect developed during the phase transition of a substance. For instance, during the change of volume, liberation or absorption of heat.

Example:

- To control the expansion of ribbed pipes, they are filled with water and cooled to a freezing temperature

37. Thermal expansion

a. Use a material which expands or contracts with heat

b. Use various materials with different coefficients of heat expansion

Example:

- To control the opening of roof windows in a greenhouse, bimetallic plates are connected to the windows. A change in temperature bends the plates, causing the window to open or close.

38. Use strong oxidizers

a. Replace normal air with enriched air

b. Replace enriched air with oxygen

c. Treat an object in air or in oxygen with ionizing radiation

d. Use ionized oxygen

Example:

- To obtain more heat from a torch, oxygen is fed to the torch instead of atmospheric air

39. Inert environment

a. Replace the normal environment with an inert one

b. Carry out the process in a vacuum

Example:

- To prevent cotton from catching fire in a warehouse, it is treated with inert gas while being transported to the storage area.

40. Composite materials

Replace a homogeneous material with a composite one

Example:

- Military aircraft wings are made of composites of plastics and carbon fibers for high strength and low weight

VITA AUCTORIS

Nathan Yu was born in Beijing, P.R. China on the 30th of October 1970.

He attended TaiYuan Heavy Machinery Institute from 1989 to 1993, graduating with a B. Eng in Mechanical Engineering. Since September 1997, he had attended Master and PhD program in Mechanical Engineering at China Agricultural University. Since May 2002, he has been studying towards a M.A. Sc. in Industrial Engineering at the University of Windsor.