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A Conceptual Design Tool for Engineers: An Amalgamation of Theory of Constraints, Theory of Inventive Problem Solving and Logic

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A CONCEPTUAL DESIGN TOOL FOR ENGINEERS: AN AMALGAMATION OF THEORY OF CONSTRAINTS, THEORY OF INVENTIVE PROBLEM SOLVING AND LOGIC

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ABSTRACT

A CONCEPTUAL DESIGN TOOL FOR ENGINEERS: AN AMALGAMATION OF THEORY OF CONSTRAINTS, THEORY OF INVENTIVE PROBLEM SOLVING AND LOGIC

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This research creates a design methodology by synthesizing three different design tools, the Theory of Inventive Problem Solving (TRIZ), the Theory of Constraints (TOC) and Logic. The basic approach of this design method is to:

- Reduce a design problem to a logic diagram,
- Code the inputs and outputs to determine desirability and degree of control,
- Identify the best inputs to manipulate in order to obtain the desired outputs and
- Exploit innovative algorithms developed in TRIZ to find the best ways to manipulate the chosen inputs.

This research integrates and expands the methods of TRIZ and TOC. It expands TOC by:

- Expanding the levels of control from three to five,
- Adding additional logical operators to the toolset and
- Allowing for quantitative and qualitative variables to be treated as analog circuitry.

It expands TRIZ by:

- Allowing for three levels of desirability (desirable, neutral and undesirable) instead of only two (useful and harmful),
- Focusing the design area to keep the number of design solutions from increasing exponentially and
- Allowing for logical operators to be used with the TRIZ toolset.

This dissertation integrates the strength of TRIZ (powerful innovative idea generation) with the strength of TOC (focused design) along with the strength of logical operators. In addition to providing a method, this research also provides a questionnaire to guide the designer through the methodology. This dissertation brings the power of focused innovation to early design stages.

This dissertation is dedicated to the memory of my beloved father, Frank Luke, who went to be with the Lord on September 30, 2001, and to the honor and glory of my Lord and Savior, Jesus Christ, who resolved the technical contradiction between God's love and justice by satisfying both in dying for me on the cross.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

1.1.1 The first problem: Design innovation

It can be frustrating to try to come up with an innovative design solution. Inventors seem to be a breed apart from engineers; inventors are both creative and technical and who see strange approaches to problems that technical people (like engineers) miss. Moreover, they often receive their inspiration in the form of a flash of insight. This "flash of insight" or idea cannot be studied because it is totally creative in nature and seems to come out of thin air. Neither the inventor nor the engineer can reproduce it and use it on another problem at another time.

On the other hand, practically everything else in the engineering and design world can be studied and understood and described by rules, theories, methods, algorithms, equations and physical relationships. Engineers are highly trained in refining problem solutions and in specifying parameters, while they can be very weak in identifying the best conceptual approach to begin with.

Genrich Altshuller[1] identified the above problem many years ago and set out to solve it by studying patents and inventions, then codifying the approaches used and abstracting these methods for application to other problems. In essence, he created a new engineering discipline governed by rules, theories, methods, algorithms, equations and physical relationships. He called his method the Theory of Inventive Problem Solving, or TRIZ (the Russian acronym for "Theory of Inventive Problem Solving").

Although TRIZ is a very powerful innovation tool, it has some flaws. The engineering community has never fully embraced it for several reasons:

- It was developed in the Soviet Union during the Cold War and was not available to the West until very recently[2].
- Its practitioners view it as a competitive advantage and have been slow to share their knowledge with industry, except in a consulting capacity[2,3].
- The methods are slow and abstract. Understanding TRIZ takes a great deal of time and disciplined study; applying it takes even more[2,4].
- Large numbers of abstract solution approaches are generated from even simple problems with TRIZ software[2,5-7]. Analysis of each approach takes a great deal of time.

The first three problems listed above are being overcome with time and education; the last remains an area of difficulty. If an engineer were able to identify one or two key weak points in a system, then he could apply TRIZ solutions to the identified weak areas only. With this focus, the amount of time spent on developing the abstract solution method would be dramatically reduced and TRIZ would be of practical use to the engineer. This leads to a second problem.

1.1.2 The second problem: Design focus

Eliyahu Goldratt noted that every system has many constituent parts that are integrally linked together[8]. The success of the system, whether it is a business model or a design, ultimately depends on the weakest link in that

The reference model used for this work is *Quality Engineering* chain of constituent parts[9]. He therefore posited that any design effort or improvement on any area other than the weakest link is useless. He called this weakest link "the chief constraint," and developed a theory around locating the weakest link and strengthening it. That theory is called the Theory of Constraints[10] (TOC).

The engineering community has never fully embraced TOC for several reasons:

- It is based on a business model and has not fully transitioned into the engineering community.
- It identifies problem locations, but not problem solutions, except in very vague terms.
- Engineering problems often have many quantitative variables that are not easily expressed using Goldratt's logic diagrams.
- Logical breakdowns do not go far enough; they are basically only able to handle a few logical operators.

Goldratt's ideas present a good foundation on which to build. The basic logical approach of Goldratt must be modified to accept quantitative values and more complex operators. After that, TOC can be used as a front-end to identify the major constraint(s) to be designed/redesigned/innovated/solved to TRIZ. TRIZ, in turn, can use the focusing power of TOC to only apply its innovations to the areas of the design that need it the most.

1.2 RESEARCH OBJECTIVES

The objectives of this research are to:

- Develop a design methodology that identifies the best areas to apply design solutions and suggests the best innovative methods to accomplish those solutions.
- Develop a new logical diagram to look at an entire system and quickly identify the design opportunities.
- Synthesize the strengths of TRIZ's innovations and TOC's focus using a Logical, repeatable approach.

1.3 OVERVIEW OF METHOD

The method proposed in this dissertation uses a logic diagram to establish and meet design objectives. It uses four steps that are summarized below:

Step 1. GATHER INFORMATION ABOUT THE PROBLEM AND DEFINE IT

The goal of this step is to gather all relevant facts on existing problem:

- Step 1.1. Describe the **problem** in non-technical terms
- Step 1.2. Define and describe the **system**
- Step 1.3. Refine the definition of the **problem**
- Step 1.4. Define the **solution** space
- Step 1.5. Define available **resources**
- Step 1.6. Consider allowable changes to the **system**
- Step 1.7. Further refine **solution** space

When Step 1 begins, all that is known is a vague description of a perceived problem. When Step 1 is completed, a fairly complete picture of the problem has been established, along with an idea of what constitutes an acceptable solution.

It is very important that the solution is not defined at the onset of this process. It is typical to have a solution in mind when first describing the problem in non-technical terms. Often the wording of the problem will suggest a particular solution or solution form. The discipline of developing the problem definition and the solution space is intended to identify the best solution. A solution offered too quickly is often sub-optimal.

In developing the problem statement and the solution space, several solution forms may become evident to the designer. Since these ideas may be in the form of the final solution, the designer should keep a log of ideas along with the file where the problem is described. Later, these ideas can be investigated in detail. This is described in more detail in Chapter 3, Methodology.

Step 2. CONSTRUCT A LOGIC DIAGRAM

This is the most crucial step of this approach and does not follow either a pure TRIZ Problem formulation or the TOC's Current Reality Tree. Instead, it uses a logic diagram that incorporates ideas from both, as well as using basic Boolean algebra. The logic diagram looks similar to an electrical schematic, but it is not intended to be one. The electrical schematic look is intended to get the designer/engineer to think of ways to "turn on" desirable signals and "turn off" undesirable signals. Unlike an electrical schematic, this model only reflects the designer's perception of what already exists and cannot be designed.

In this step, entities are defined. Entities are states of the system or its components. They can be either inputs to the system or outputs of the system. Since the method of this dissertation is used to control the value of outputs by the manipulation of inputs, there are several things about these entities that must be known, namely:

- Is the entity desirable, undesirable or neutral?
- Is the entity quantitative or qualitative?
- Can the entity be controlled?
- How is the entity related to other entities? Which entities does it cause? Which other entities cause it to occur?

Every entity is coded for the above characteristics:

- For desirability, it is given the code D, U or N for "Desirable," "Undesirable" and "Neutral."
- For Quantitative/Qualitative, it is given the code "Q" for Quantitative and "L" for Qualitative or Logical.
- For control, it is given a code of C1 through C5, defined as follows:
    - "-C1" for entities under *direct* control: this is the highest level of items in our span of control. In these, we can *directly control* their value.
    - "-C2" for entities under *indirect* control: like C1, these are in our span of control, but only through manipulation of other entities or the logic of the system can we change them. Still, we do not need to get authority from an outside agency to change their value.
    - "-C3" for entities that are controlled by an outside source or agency: Since someone controls these, they are by definition under our *sphere of influence*. All we need to do is influence the person or agency controlling these entities. Policies often fall into this group.
    - "-C4" for entities that are controlled by nature or are "given" for the problem: These are outside of our sphere of influence, unless we are allowed to redefine the problem. For instance, in the airbag example (Chapter 4), the existence of a driver who is less than 5 feet

tall is given. We cannot allow the to design exclude these people, although we may be able to compensate for their height (if necessary) by changing the system in some way that negates the danger of short drivers in an accident.

- "-C5" for entities completely outside our sphere of influence: In some cases, we can still ignore them, but it is even more difficult than for C4 entities. In the airbag example, "an accident occurs" is such an entity. We cannot remove it from the problem because it is the reason for having an airbag in the first place. If we could redesign the safety system of an automobile to make an accident impossible, then we could circumvent even this problem. From a creative thinking standpoint, solutions that address the C5 control level are exciting because they will by definition change the entire complexion of both the problem and the solution.

- To show relationships, a hierarchical numbering system is established with terminal entities coded with values in the 100s, their causes coded with values in the 200s and so on.

The greatest difficulty experienced with this approach was to code entities that are not Boolean in nature but are quantitative. To address this problem, variables are allowed to be either quantitative or Boolean and are transformed from one type to the other using amplifiers to convert signals from logical to quantitative. Special operators are defined to convert quantitative relationships to Boolean logic.

Step 3. ANALYZE THE LOGIC DIAGRAM

There are two goals of this step: to ensure that the logic diagram is correct and to identify the areas of the system to be redesigned. The sub-steps are as follows:

- Step 3.1. Find the switches for the system.
- Step 3.2. For each Desirable Entity, seek to ensure the logical value of the entity is = 1.
- Step 3.3. For each Undesirable Entity, seek to ensure the logical value of the entity is = 0.
- Step 3.4. Identify any trade-offs in the design.
- Step 3.5. Review total system.

Analysis of the logic diagram is the step where the design solution is given its proper focus. First, the developer identifies the "switches" in the system. A "switch" is an input in the design that can be easily controlled and has the maximum effect on the desired outputs of the design. Once these switches are found, the logic of the solution is tested to ensure that desired events will occur with the proposed design change (step 3.2) and that undesirable events will be stopped from occurring with the proposed design change (step 3.3).

Another area that is very useful in TRIZ theory is the establishment of design trade-offs and contradictions. To Altshuller, the goal of design was to resolve trade-offs, not to make compromises between them. In step 3.4, these trade-offs and contradictions are identified so that they can be resolved in the solution generation step (step 4). Finally, the entire logic diagram must be checked to ensure that it doesn't violate any rules of logic. This is accomplished in step 3.5.

Step 4. GENERATE SOLUTION

A critical entity is an entity found in step 3 to be a switch that can control the final outcome of the design. At this point, there is enough information to focus on where the best application of the final solution should be and apply the principles of TRIZ to it.

The foundation of Ideation TRIZ[11-14] is the simple, profound notion that the objective of design and innovation is to increase Ideality. If entities can be described as either "useful" (desirable) or "harmful" (undesirable), then to increase ideality, one merely has to increase the beneficial effects of desirable entities and decrease the detrimental effects of the undesirable entities. At the onset, this sounds exactly like the Classical TRIZ contradiction resolution, but in fact it goes much further. Where Classical TRIZ only tries to eliminate trades between harmful and useful events, Ideation TRIZ goes further because it seeks to increase benefits and decrease detriments regardless of the presence of limiting factors.

For consistency, let us define the two different kinds of events, Harmful Events (HE) and Useful Events (UE), as Undesirable Entities (UDEs) and Desirable Entities (DEs), respectively. The relationship between entities may either be causal (→) or counteractive (↛). Therefore, in a system with two or more entities, the smallest component of relationships between events can be manifested in eight configurations:

1. DE → DE. A Desirable Entity causes another Desirable Entity. For example, pressing the accelerator causes a car to move forward.
2. DE → UDE. A Desirable Entity Causes an Undesirable Entity (Contradiction). For example, shipping containers are too expensive to reuse and are stacked in junkyards.
3. DE ↛ DE. An Undesirable Entity Causes a Desirable Entity (Contradiction). For example, carbon Dioxide exhaled by animals is food for plants.
4. DE ↛ UDE. An Undesirable Entity Causes an Undesirable Entity. For example, electrostatic discharge causes equipment damage.
5. UDE → DE. A Desirable Entity counteracts another Desirable Entity (Contradiction). For example, strengthening of aircraft decreases speed.
6. UDE → UDE. A Desirable Entity counteracts an Undesirable Entity. For example, putting on mosquito repellant keeps mosquitoes away.
7. UDE ↛ DE. An Undesirable Entity counteracts a Desirable Entity. For example, procrastination keeps work from being completed.
8. UDE↛UDE. An Undesirable Entity counteracts an Undesirable Entity (Contradiction). For example, addition of zinc in a car frame diminishes corrosion.

A system then can be drawn for any problem that consists of these eight building blocks.

The Ideation Software Tool, Innovation Workbench 2000[7] (IWB2000) from Ideation International, has a Problem Formulator Module to analyze systems. To use this module, an inventor first converts a system to a diagram consisting of events coded as harmful or useful and relationships between these events that are either causal or counteractive. After completing the diagram, the inventor selects the "formulate" icon and solution types for relationships between the blocks are generated. Problem formulator offers four solution types:

- Solution types that target an undesirable entity.
- Solution types that target a desirable entity.

- Solution types aimed at resolving contradictions.
- Solution types aimed at increasing the level of ideality of the system.

Each of these four solution types, which are called "parent relations" in this dissertation, can be further expanded to general forms of solutions, which are called "child relations." Each child relation can be broken down into 1 to 13 different forms of solutions, which are called "grandchild relations." Each grandchild relation, in turn, can be decomposed into 1 to 40 different solution types called "operators." Some operators are further broken down into sub-operators. At the lowest level of operator or sub-operator, IWB2000[7] offers examples of the application of the particular principle.

With a defined system of even a relatively small size, IWB2000[7] defines:

- One parent relationship for every desirable cause or effect entity (1, 2, 3, 4, 5 and 7 from the list above),
- One parent relationship for every undesirable cause or effect entity (2, 4, 5, 6, 7 and 8),
- One parent relationship for every contradiction (2, 3, 5 and 8) and
- One parent relationship for each *terminal* desirable effect (1, 3, 5 and 7) (A terminal effect is not modeled as a cause of any other entity).

For a system of even a relatively small size, IWB2000[7] creates a large number of possible solutions, especially considering that each parent relationship has as many as 211 operators associated with it. With the proposed method, we use the coding of entities to determine which relationships we can ignore before generating relations and operators, making a more manageable design space to work with.

1.4 CASE STUDY RESULTS

1.4.1 Airbag Case Study

Automobile Airbags are designed to save lives by deploying rapidly enough during an accident to provide a buffer between the occupants of the front seat of a vehicle and any hard surface. They deploy so rapidly that they present a deadly force if encountered before full deployment. There have been documented cases of people being killed by airbags because of this phenomenon.

The airbag case study in chapter 4 defines the problem, the logic diagram and the solution using the methodology proposed in Chapter 3 of this dissertation. The results were not expected. Once the system, along with the problem, was properly defined, it was evident that the problem was due to the relative distance between the occupant and the airbag before deployment. The only failsafe way the problem could be solved for the driver's side was to remove the airbag from the steering column. Several suggestions are presented on how to approach this problem as well as a strategy to solve airbag fatality mechanisms on the passenger side of the car. The case study is found in chapter four.

1.4.2 Airlift Loading System Case Study

Large Cargo Planes are being used to transport material across large distances. Because the material is not stackable, it is being placed one-box high on pallets. It was noted that a great deal of volumetric capacity of the airplane was being wasted. This case study uses the methods developed in this dissertation to define and solve this problem. The solution is simple and seems intuitive: create a loading system with removable shelves for greatest flexibility.

This study also exemplifies the need for a disciplined approach because it can be compared to an identical design effort that was based on the traditional "flash of insight" undisciplined approach. The group that solved the original problem had a brilliant idea to increase the volumetric capacity by adding a second pallet position to the loading system. Immediately, a study ensued because the design was considered a great idea, born in a flash of insight. The study that ensued did not define the problem or the system that it was in, but rather immediately started on the development of a solution.

The designers generated hundreds of drawings. They also created prototypes and tested them destructively. Millions of research dollars were spent over a two to three year period. A cost study comparing the new 2-level solution with the old method of loading pallets was conducted, and this study demonstrated substantial savings.

Had the developers defined the problem with the method described in this dissertation, they would have saved a great deal more with virtually no additional development costs by realizing that they could have added many more loading options by creating multiple pallet positions that can be reconfigured as necessary.

The solution to this problem is shown is found in Chapter 5. A detailed cost analysis is performed in Appendix C.

1.4.3 Truck Bed Cover Case Study

Pick-up trucks have coverings that stretch across the truck bed can be purchased can be purchased after-market. There are a number of problems encountered in handling these covers, including:

- Installing the cover requires adding a permanent fastener or hold-down to the truck, which is unattractive and becomes a site for corrosion.
- The covers have great localized stress and can tear if they are used to carry large loads.
- The covers are difficult to align and attach if there is a large load.

A case study of a new truck bed cover design is found in chapter 6. The truck bed cover design developed arrives at the same approach as a recent new design found in the US Patent database and currently sold in the United States.

1.4.4 Shuttle Bike Case Study

Bicyclers would like to travel through the woods and over small streams and lakes with their bicycles, but they are constrained to only travel over dry land because bicycles are constrained to only travel over land. Shuttle boats travel on water but not on dry land. Some shuttle boats have been designed with bicycle parts, but these are bulky and generally require one-time conversion. This case study creates a new bi-system that incorporates a bicycle and a shuttle boat into a single design that can be easily converted from one mode to the other and back while hiking is presented in chapter 6. The solution developed using this dissertation methodology closely parallels a design currently being marketed throughout the world.

1.5 RESEARCH CONTRIBUTIONS

There are six contributions that are established in this research:

1. This research presents a new method to identify and solve design problems in the conceptual stage.
2. This research integrates and expands the disciplines of TRIZ, TOC and logic.
3. This research creates a new logic diagram that can be used in the solution of a design concept.

4. This research improves upon a problem solving worksheet that is useful in guiding the designer through the design process (see Appendix B).
5. This research establishes codes for design entities that are useful in analyzing designs, including 3 degrees of Desirability and 5 levels of Control.
6. This research provides a bridge between qualitative and quantitative design elements such that one diagram and method can be used in the presence of both factors.

CHAPTER 2. LITERATURE REVIEW

The Literature is divided into three parts. The first part is a review and discussion of the various methodologies in use today that are proposed to optimize the conception, design and manufacture of parts. The second part is a review and discussion of various works that either propose combining one or more of the methods together or present a comparison/contrast of one or more of these methods. The third part is a literature review of the airbag case study problem. The airbag case study problem is solved in chapter 4.

2.1 REVIEW AND DISCUSSION OF VARIOUS METHODOLOGIES

The design phase can be divided into three sub-phases:

- Configuration Design
- Parameter Design
- Tolerance Design

The activities regarding quality during the design phase are sometimes called "off-line quality control." The activities that take place during manufacture are sometimes called "on-line quality control."

Likewise, on-line quality control can be subdivided into the following sub-phases:

- Diagnosis and Adjustment
- Prediction and Correction
- Measurement and Disposition

In the design phase, there is considerable feed-forward consideration of on-line quality control. For instance, it is necessary to consider the acceptable disposition of defective units and the expected defects and defective rates of the process. Additionally, it is necessary to understand and consider the constraints of manufacture. Likewise, on-line quality control is a necessary feedback to the design phase.

There are many ideas and techniques to optimize design and manufacture of products; some are centered in one of the sub-phases of off-line quality control, while others are centered in the sub-phases of on-line quality control. Additionally, some are qualitative, others are quantitative, but most have both qualitative and quantitative elements. These ideas and techniques have been developed in different times and different places, and each has its own disciples and followers. Each of these ideas and techniques has its own rationale, method and case study history. Each one has merit and value in its own rite.

Modern manufacturers cannot support using all of the techniques espoused by all of the different disciplines. There are simply too many philosophies available. Each one requires training, changes in corporate structure, changes in thought process and (possibly) consultants. An ideal solution for a manufacturer is one that can be deployed by indigenous people with minimal disruption to daily operations. An ideal solution would incorporate the ideals and rationales of all valid methods, but not necessarily all of the many tools used by each method. The solution, once implemented, would require a minimal amount of consultant help.

The literature review considers all three sub-phases of design and explores the eleven disciplines below for optimization of the design process. In performing this review, I discovered that it is not possible to integrate all of these design methods and present a unified process in the time constraints of this dissertation. Instead, I chose to focus on integration of TRIZ with TOC in the Configuration/concept development sub-phase of design. The other design methods and ideas provide a fertile ground for further research and development and are included in the literature review.

The following methodologies for their application into a holistic design process have been reviewed:

1. Axiomatic Design (AD) as proposed by Nam Suh of MIT and his followers[15-17]
2. Cost as an Independent Variable (CAIV)[18-26]
3. Design for Manufacturing/Assembly as proposed by Boothroyd, Dixon, Poli and their followers
4. ISO-9000
5. Zero Quality Control[50-62] as proposed by Shigeo Shingo, Taiichi Ohno and their followers (Includes Poka Yoke, JIT, Lean manufacturing, Affinity diagrams and Kanban)
6. Quality Function Deployment[63-70] as proposed by Yoji Akao and his followers
7. Robust Engineering[71-74] applications as proposed by Taguchi, Phadke and their followers and Robust Engineering applications as proposed by Box, Hunter and their followers (Includes discussion of Quality Loss Function[75-80])
8. Theory of Constraints[4-10, 81-86] (TOC) as proposed by Goldratt and his followers
9. Total Quality Management[87] (TQM)- Qualitative and Quantitative methods as proposed by Shewhart, Deming, Crosby, Juran and their followers
10. Theory of Inventive Problem Solving[1, 2, 3, 88-134] (TRIZ) as proposed by Altshuller and his followers (Classical TRIZ) and Theory of Inventive Problem Solving (TRIZ) as advanced by Ideation International and their followers (Ideation/TRIZ or I-TRIZ)
11. Failure Modes, Effects and Criticality Analysis[135] (Sometimes called "Failure Modes and Effects Analysis)

2.1.1 Axiomatic Design (AD) [15-17]

AD[15-17] is a design methodology that posits that the design process should be based on generalizable principles that govern underlying behavior[15-17]. Suh proves this by establishing two axioms of design and then developing a number of techniques, rules and corollaries that support these two axioms. The two axioms are as follows:

1. The independence axiom: the independence of Functional requirements must always be maintained, i.e. design decisions must always be made without violating the independence of each functional requirement from other functional requirements and
2. The information axiom: minimize the information content, i.e. among those designs that satisfy the independence axiom; the design that has the highest probability of success is the best design.

Suh[17] has defined four domains for his axiomatic design framework, they are:

1. The customer domain,
2. The functional domain,
3. The physical domain and
4. The process domain.

Each domain has a characteristic vector. The characteristic vectors provide a link between the different domains. The characteristic vectors are as follows:

1. For the customer domain, customer attributes (CAs)
2. For the functional domain, functional requirements (FRs)
3. For the physical domain, design parameters (DPs)
4. For the process domain, process variables (PVs)

If the characteristic vectors are linearly related to each other, then they can be mapped using a series of matrix equations, found below. Note that [DM] denotes a design matrix used to link domains through their characteristic vectors:

$$\mathbf{CA} = [DM_1] \times \mathbf{FR} \tag{1}$$

$$FR = [DM_2] \times DP \tag{2}$$

$$DP = [DM_3] \times PV \tag{3}$$

In order to avoid redundancy, there should be the same number of CAs, FRs, DPs and PVs. The best possible solution is one in which a one-to-one relationship exists between each set of domains. To find a one-to-one relationship, the design matrix should be manipulated until it yields values only on the diagonal.

Leaving Suh's discussion for a moment, it is easy to see a link between AD and QFD. QFD is used to link "customer needs and wants" to "technical requirements," to produce "manufacturing specifications." AD links customer attributes to functional requirements to produce design parameters. These are essentially the same inputs and outputs, but they use different methods to link the two together. QFD also seeks uncoupled matching and one-to-one mapping whenever possible. Another similarity with QFD is in the process of the approach to begin with customer requirements then proceed to technical requirements, finally ending on process specifications. The journey is the same, but the mode of transportation is different.

Another interesting idea is that AD is not a substitute for TRIZ because their objectives are very different. Both methods desire to make a rigorous process out of what is often ad hoc, but AD is working on design refinement and optimization and TRIZ seeks innovative solutions. AD can recognize a superior solution when it meets AD criteria, but it does little to help find an innovation.

AD is at odds with robust engineering, despite the efforts of many to rectify the differences between the two. AD cannot handle interactions between design requirements. Whether the relationships between variables contained in a matrix are considered absolute mathematical relations (which presupposes linearity) or a kind of figurative relationship, it still cannot account for interactions. Taguchi methods ignore interactions to reduce the number of experiments necessary for design and in doing so have met with harsh criticism from statisticians and other designers who regularly find intense interactions in many designs.

Returning to a discussion of Suh, the second axiom of AD is the information axiom. Information content, IC, must be minimized. Using Shannon's mathematical theory of communication, Suh defines IC as:

$$IC = \sum_{i=1}^{n} -\ln(p_i) \tag{5}$$

where p_i is the probability of DP_i meeting FR_i. Note: Suh calls information content "I," not "IC." I chose to use IC to avoid confusion with TOC's "I" for inventory or investment.

Here there is an obvious connection between AD, SPC and the Quality Loss Function. SPC defines process capability (C_{pk}) as the probability that a process can meet its specification limits. AD demonstrates the benefit of defining a process in quantifiable terms. QLF is the best of all three methods because it demonstrates mathematically that there is a loss to the customer whenever a target is not met and that loss is dependent on the amount of deviation from the target value. QLF is the easiest to understand, the most intuitive to apply and the clearest model of observed phenomenon.

2.1.2 Cost as an Independent Variable[18-26] (CAIV)

Cost as an Independent Variable[18-26] is an acquisition process used by the buyer of a large acquisition (generally the United States Government) to attempt to buy a system at the right price with the right performance capabilities. Since CAIV is a buyer's tool, it becomes a constraint for sellers wishing to deal with a particular buyer. Most of the other methods are developer's tools and can either be used or not depending on whether the developer has the skill to use them and the need for their technology.

From a developer's perspective, CAIV may seem like an unnecessary constraint on his or her ability to build the best product and to price that product according to the best business practices. Also, the presupposition of CAIV that one must make trade-offs between performance, cost and schedule is especially troubling to a designer who can find ways to increase ideality. An increased ideality solution may very well increase performance while holding to schedule and lowering cost.

Another potential issue with CAIV is that it is a bureaucratic solution to a design problem. A designer may try to circumvent the CAIV process by satisfying its requirements without really seriously considering its underlying tenets. In this case, a developer could hire an expert to write a CAIV trade-off analysis that is slanted to produce whatever the results the developer wishes.

CAIV does not solve any design problems. Instead it mandates that design problems are solved as trade-offs between cost, schedule and performance characteristics. In this regard, it becomes a design constraint and inhibits certain design scenarios from contention early because of perception of impact on Life Cycle Cost (LCC).

CAIV discourages the use of innovations and inventions to solve problems. From the buyer's perspective, innovations and inventions need to be established before the agreement to purchase a product is consummated. Otherwise, the buyer may have to absorb the inherent risk of the design not being able to perform as advertised or absorb increased costs due to schedule overruns while the designer waits for inspiration.

Another issue with CAIV is that it relies heavily on predictions, probabilities and uncertain forecasts of future events. If the probabilities and risk factors are estimated improperly, then the decision is flawed. Since the same assumptions are used to evaluate each alternative, CAIV proponents argue that it is not intended to give an accurate answer, but rather it produces a "best choice" from a decision-making perspective. Still, there is a risk of gross inaccuracy that could be magnified by the desires of the seller or developer to select a predetermined alternative.

All of the above points being considered, it may be argued that CAIV is incompatible with many of the other methods considered in this dissertation, especially TRIZ. It must be pointed out that the TRIZ methodology is an attempt to overcome the constraint of making abhorrent trade-offs by resolving conflicts. CAIV and TRIZ can be said to be in technical conflict with one another leading one to believe that TRIZ methods could be used to resolve the contradiction between TRIZ and CAIV.

The CAIV method recognizes the following tenets:

1. Place cost on an equal footing with performance and schedule and search for the 'best value' solutions, not the 'greatest performance' or the 'lowest cost.'
2. There are trade-offs made between cost, schedule and performance.
3. Cost can best be effectively controlled in the earliest stages of acquisition, such as the concept design stage, before the design is established.

Some other characteristics of CAIV are as follows:

- CAIV is a buyer's tool to try to control the cost, performance and schedule of a new system, but it requires the seller to participate in the decisions.
- CAIV is profoundly different than Design to Cost (DTC), a previous government initiative. DTC set a cost goal and forced the design within that goal, while CAIV seeks an optimal solution taking cost, schedule and performance into account.
- CAIV decisions are not made by an individual, but in a group called the Cost-Performance Integrated Process Team, or CPIPT. The CPIPT is comprised of government and contractor personnel.
- CAIV attempts to control Life Cycle Cost (LCC), not just purchase price.
- CAIV uses the cost-risk identification and management system (CRIMS).

CAIV has the following objectives:

- Set realistic but aggressive cost objectives early in each acquisition process.
- Manage risks to achieve cost, schedule and performance objectives.
- Devise appropriate metrics for tracking progress in setting and achieving cost objectives.
- Motivate and incentivize government and industry managers to achieve program incentives.
- Put in place for fielded systems additional incentives to reduce operating and support costs.

A few observations about the practice of CAIV:

1. CAIV forces the contractor and the government into making trade-offs instead of finding a better solution that avoids trade-offs.
2. CAIV, as a buyer's tool, only has limited incentive for the seller to create the best system at the lowest cost.
3. CAIV is fundamentally based on estimates, probabilities and best guesses. (For instance: LCC is an unknowable figure.)
4. CAIV allows an additional level of freedom from earlier DTC methods and is thus a natural evolution from DTC.
5. CAIV discourages innovation and encourages reuse of existing design.
6. CAIV and TRIZ appear to be fundamentally incompatible because CAIV is a method that encourages making trade-offs and TRIZ seeks to resolve trade-offs.
7. The contractor or designer does not necessarily have a choice regarding whether or not they wish to use CAIV. The buyer mandates CAIV and its application is presided over by the buyer.

2.1.3 Design for Manufacture and Assembly[27-40] (DFMA)

Design for Manufacture and Assembly[27-40] is a disciplined approach to create designs that take into account manufacturing and assembling concerns.

Product Design and Assembly[29] lays out the mechanics of DFMA. Especially useful is the extensive information on Design for Assembly and the chapter on Injection Molding DFM considerations.

Engineering Design and Analysis[33] has several useful resources. Its discussion of DFA is relatively weak, but it provides an extensive algorithm and approach for DFM for injection molding complete with several charts and tables. One major weakness is that the authors do not establish why certain design features may be desirable nor does it discuss how to decide which features to use and which to avoid in each given design problem.

Chapter 1[7] provides an approach to solving generic design problems by guided iteration. The guided iteration method entails using a decision matrix to map the relationships between Design Variables (DV) and Problem Definition Parameters (PDPs). Two examples are given, one with an I-beam design and another with a belt-pulley system.

Maheux's short article[35] is a testimony of Nortel's success using DFMA tactics to reduce the cost of an electronic module by almost $300 per unit by reducing the number of parts from 59 to 32. Maheux also redesigned a cover for a sheet metal box by eliminating fasteners and incorporating snaps and manufacturing the part out of plastic. The new part cost 1/3 of the original part (from $78 to $26 per unit).

Design for manufacture - guidelines[27] is a table from the Internet that summarizes the guidelines for DFM:

- Minimize total number of parts
- Develop a modular design
- Use standard components
- Ensure adequate access and unrestricted vision
- Design parts with multiple functions
- Design parts with multiple uses
- Design parts for ease of fabrication
- Avoid separate fasteners
- Minimize assembly directions
- Maximize compliance
- Minimize handling

Design for manufacturability imperative[31] is a nice overview of DFM concepts. The author points out that decisions made during design account for 70% of the product's cost, while decisions made during production only account for 20% of the cost. The author demonstrates that savings may be available through simplification and standardization and that retrieval of standardized parts may be possible using group technology. He also provides the following familiar product design guidelines:

- Reduce the number of parts to minimize the opportunity for a defective part or an assembly error, to decrease the total cost of fabricating and assembling the product and to improve the chance to automate the process

- Foolproof the assembly design (Poka-yoke) so that the assembly process is unambiguous
- Design verifiability into the product and its components to provide a natural test or inspection of the item
- Avoid tight tolerances beyond the natural capability of the manufacturing processes and design in the middle of a part's tolerance range
- Design "robustness" into products to compensate for uncertainty in the product's manufacturing, testing and use
- Design for parts orientation and handling to minimize non-value-added manual effort, to avoid ambiguity in orienting and merging parts and to facilitate automation
- Design for ease of assembly by utilizing simple patterns of movement and minimizing fastening steps
- Utilize common parts and materials to facilitate design activities, to minimize the amount of inventory in the system and to standardize handling and assembly operations
- Design modular products to facilitate assembly with building block components and sub-assemblies
- Design for ease of servicing the product

Crow[12] refines his guidelines in "Design for manufacturability/assembly guidelines" and expounds on them as well. The new guidelines are reproduced below:

- Simplify the design and reduce the number of parts
- Standardize and use common parts and materials
- Design for ease of fabrication
- Design within process capabilities and avoid unneeded surface finish requirements
- Mistake-proof product design and assembly (Poka-yoke)
- Design for parts orientation and handling
- Minimize flexible parts and interconnections
- Design for ease of assembly
- Design for efficient joining and fastening
- Design modular products
- Design for automated production
- Design printed circuit boards for assembly

Capron® Nylon Product Selection Guide[30] provides physical properties of various thermoplastic nylons, resins for injection molding, blow molding, profile extrusion and rotational molding. No cost data or cost modeling data is found here.

Product Reference Guide: Capron®, Petra®, Nypel®[38] is a very short, high-level description of a number of AlliedSignal Plastics products. It can be used in conjunction with the more specific product guides. No prices, cost data or cost modeling data is found here.

Injection Molding Processing Guide for Capron® Nylon[34] contains very specific information regarding how to use Capron ® nylon in injection molding applications. It includes part design, machine considerations, mold and tooling considerations, auxiliary equipment, processing information and a troubleshooting guide. There is a great deal of design for manufacturability information that appears to go beyond recommendations in DFM/DFMA texts.

Petra® PET Product Selection Guide- Recycled PET (Thermoplastic Polyester) Resin for Injection Molding[37] is a reference of physical and other properties of AlliedSignal Plastics' Thermoplastic Polyester product.

Modulus® Design Solutions Guide[36] is the British version of AlliedSignal's design guidebook. This has everything from equations to advice on DFM/DFMA. This text explains a great deal that is left out of the DFM/DFMA texts. For instance, it explains when and where ribs, inserts and bosses are used in parts.

Snaps are extensively used in DFA applications. *Snap-Fit Design Manual*[40] explains how to select and design built-in snaps for plastic parts.

2.1.4 ISO-9000[41-49]

ISO 9000[41-49] is the parent standard for a series of international standards regarding quality systems. ISO 9000 and its associated standards are international and are recognized all over the world. If a company wishes to do business in multiple countries, registration to an ISO 9000 standard will be recognized in all countries that perform ISO 9000 registration.

In most of the world, ISO standardization can be traced to governmental control, and each country regulates its own standard in its own language. In the United States, the applicable standard is ANSI/ASQ 90 and it is regulated by the American Society for Quality (ASQ) and the American National Standards Institute (ANSI).

ISO 9000 is similar to CAIV in that it does not help the designer at all; it is supported by an immense bureaucratic structure; it is imposed by the customer; it doesn't make money (or avoid spending it) and it is effectively a constraint of the designer.

ISO 9000 forces its user to keep very good records and define their processes well enough to satisfy an outside auditor. Keeping better records may indirectly improve the process. But since there was nothing to prevent the designer from keeping good records and defined features in the first place, the contribution of ISO 9000 is dubious at best.

Having an ISO 9000 registration does not assure anyone that a company is an innovator or an industry leader in quality. Instead, it assures that a company has met minimum standards of compliance.

Implementing ISO 9000 can be very costly. It requires expense to bring a system up to standard, expense in training company representatives to perform an internal audit and the expense of hiring an outside auditor to register a company. Auditing companies generally send teams to perform audits that can last up to two weeks while the company pays for their *per diem* expenses, daily meetings, interruption of work and schedules and management and departmental support. Since companies rarely pass the ISO 9000 audit on the first try, there are additional expenses of the implementation of audit findings and subsequent follow-up visits from the audit team.

ISO 9000 is not relegated to one aspect of the design and manufacturing process. Rather, it is pervasive throughout the entire product life cycle.

Compliance with ISO 9000 is neither necessary nor sufficient for satisfaction of TQM objectives, although many try to equate the two. ISO 9000 is rarely imposed concurrently with CAIV because CAIV is a governmental initiative and ISO 9000 is an industrial standard (although the government has, on occasion, stipulated ISO 9000 registration in consideration for contractual approval).

Note that the discussions that follow use the older versions of ISO 9000 standards. There is a newer standard, published in 2000, called ISO 9000:2000. For the purposes of this discussion, there is little difference between the new and old standard, and the discussion of the older standard has been retained in the literature search. The newer standard makes the following changes:

- It reorders the quality elements into 5 subtypes (instead of 20 elements). The 20 elements are still in the standard, but they are incorporated into the 5 sections. The 5 sections are
  1. The Quality Management System
  2. Management Responsibility
  3. Resource Management
  4. Product Realization
  5. Measurement, Analysis and Improvement
- ISO-9001:2000 includes an appendix that maps the 20 quality elements of the earlier versions to the current version.
- It incorporates the 3 types of registration (9001, 9002 and 9003) into one (9001). In the new ISO-9001:2000 registration schema, the company being certified simply opts out of the clauses that do not apply.

2.1.4.1.1. The ISO 9000 Family of Standards

There are basically five standards in the ISO 9000 family.

- ISO 9000 *Quality management and quality assurance standards- guidelines for selection and use*: contains guidelines for use of the other four standards in the ISO 9000 series.
- ISO 9001 Quality systems: model for quality assurance in design/development, production, installation and servicing.
- ISO 9002 Quality systems: model for quality assurance in production and installation
- ISO 9003 Quality systems: model for quality assurance in final inspection and test
- ISO 9004 Quality management and quality system elements: guidelines

ISO 9000 is used to determine which of the next three requirements should be used. Depending on the work of the system being certified, either ISO 9001, 9002 or 9003 is selected. ISO 9004 helps managers in building their quality systems and is not a quality requirement, but rather gives suggestions for effective quality management so that the companies can then be qualified to meet the ISO 9001, 9002 or 9003 requirements.

There are 20 different quality system elements referenced in ISO 9001. ISO 9002 has the 15 clauses that are identical to ISO 9001 and 3 clauses that are less stringent versions of their ISO 9001 counterparts. ISO 9003 has only twelve clauses, nine of which are less stringent versions of their ISO 9001 counterparts and the other three of which are less stringent versions of their ISO 9002 counterparts. The following table is taken from *ISO 9000: Preparing for registration*.

Title	Corresponding paragraph number in		
	9001	9002	9003
Management responsibility	4.1	4.1[a]	4.1[b]
Quality system principles	4.2	4.2	4.2[a]
Contract review	4.3	4.3	
Design control	4.4		
Document control	4.5	4.4	4.3[a]
Purchasing	4.6	4.5	
Purchaser supplier product	4.7	4.6	
Product identification and traceability	4.8	4.7	4.4[a]
Control of production	4.9	4.8	
Inspection and testing	4.10	4.9	4.5[a]
Inspection, measuring and test equipment	4.11	4.10	4.6[a]
Inspection and test status	4.12	4.11	4.7[a]
Control of nonconforming product	4.13	4.12	4.8[a]
Corrective action	4.14	4.13	
Handling, storage, packaging and delivery	4.15	4.14	4.9[a]
Quality records	4.16	4.15	4.10[a]
Internal audits	4.17	4.16[a]	
Training	4.18	4.17[a]	4.11[b]
After-sales servicing	4.19		
Statistical techniques	4.20	4.18	4.12[a]
a- less stringent than 9001 b- less stringent than 9002			

Table 1. Clauses of ISO 9001 through 9003

2.1.4.1.2. The clauses of ISO 9001 through 9003

CLAUSE 4.1 MANAGEMENT RESPONSIBILITY

Clause 4.1 deals with Quality policy, quality organization and management review. Bearing in mind that ISO 9000 is intended to assure that the minimum of acceptable quality standards are followed, clause 4.1 ensures:

- There is an active quality policy,
- There are individuals who have responsibility for the quality function and for verification,
- There is a management tie to quality and
- Management reviews quality on a regular basis.

Clause 4.2 Quality System

"The supplier shall establish and maintain a documented quality system as a means of ensuring that product conforms to specified requirements."

The quality system clause is one of the most potentially damaging clauses in the standard, from the supplier's standpoint. With this clause, the supplier is required not only to have a quality system with its attendant policies, plans and procedures, but also requires that the quality system be documented. The supplier, therefore, must create a documented policy that becomes the standard by which he is judged from the date of inception. If the standard is too specific, then he may find himself spending an inordinate amount of time updating records and following procedures. If it is too general, then it may not pass audit scrutiny. It is a better idea to keep it as general as possible and only change it if the need arises. Unfortunately, in their zeal to be certified, many companies overspecify a quality policy that they do not always follow.

Note the definition of quality intrinsic in the quality system is "conformance to requirements," not "delighting the customer" or "continuous improvement." ISO 9000 does not deal with quality in the same way as TQM, which uses the latter two definitions. Again, ISO 9000 is about maintaining minimum standards and executing them flawlessly.

Clause 4.3 Contract Review

The contractor is required to establish and maintain procedures for contract review and coordination. The purpose of the contract review clause is to ensure that the contractor regularly reviews his customer's requirements. Along with this general requirement, the contractor must assure that he has the resources to perform the task, the task is defined and documented well enough for the contractor to perform and the requirements are the same as those that the contractor had bid.

Clause 4.4 Design Control

ISO 9000 does not have anything to say about how a design is conceived and how a solution is obtained. Instead, ISO 9000 establishes a link between customer requirements and proposed design assuring that the design is intended to conform to requirements. The standard also establishes that certain roles are identified and followed, that the design requirements are known (input), that the design output meets the requirements and that the design is verified. Finally, ISO 9000 checks that proposed changes to the design are also properly documented and reviewed.

Clause 4.5 Document control

ISO requires that a document control procedure is in place and is in use. An ISO 9000 auditor will check that the necessary documentation is ready and available for those who need it. The regular review of documentation, changes to documentation and purging of obsolete documentation are also regulated by this clause.

Clause 4.6 Purchasing

ISO 9000 seeks to establish that purchased product conforms to specification. The process also addresses verification of output quality of vendors.

Clause 4.7 Purchaser Supplied Product

Clauses 4.6 and 4.7 are very closely related. Clause 4.7 mandates that the purchaser establishes and maintains procedures for verification, storage and maintenance of purchaser supplied products. Also addressed is the disposition of nonconforming parts. ISO 9000 states that the purchaser is responsible for the quality of material he buys and is not absolved by source inspection provided by the supplier.

Clause 4.8 Product Identification and Traceability

Where required, the supplier shall establish and maintain procedures for identifying the product from applicable drawings, specifications or other documents during all stages of production, delivery and installation.

Clause 4.9 Process Control

"The supplier shall identify and plan the production and, where applicable, installation processes which directly affect quality and shall ensure that these processes are carried out under controlled conditions."[41]

Clause 4.10 Inspection and Testing

Inspection and testing is divided into four parts:

1. Receiving inspection and testing
2. In-process inspection and testing
3. Final inspection and testing
4. Inspection and test records

Clause 4.11 Inspection, Measuring and Test Equipment

"The supplier shall control, calibrate and maintain inspection, measuring and test equipment, whether owned by the supplier, on loan or provided by the purchaser, to demonstrate the conformance of product to the specified requirements. Equipment shall be used in a manner which ensures that measurement uncertainty is known and is consistent with the required measurement capability."[41]

Clause 4.12 Inspection and Test Status

"The inspection and test status of product shall be identified by using markings, authorized stamps, tags, labels, routing cards, inspection records, test software, physical location or other suitable means, which indicate the conformance or nonconformance of product with regard to inspection and tests performed."[41]

Clause 4.13 Control of Nonconforming Product

"The supplier shall establish and maintain procedures to ensure that product that does not conform to specified requirements is prevented from inadvertent use or installation." [41]

Clause 4.14 Corrective Action

The supplier shall establish, document and maintain procedures for

1. Investigation of nonconforming product;
2. Analysis of all processes, work operations, concessions, quality records, service reports and customer complaints to detect and eliminate potential causes of non-conforming product;

3. Initiation of preventive actions to deal with problems to a level corresponding to the risks encountered;
4. Application of controls to ensure that corrective actions are taken and are effective and
5. Implementation and recording of changes in procedures that result from corrective action.

Clause 4.15 Handling, Storage, Packaging and Delivery

"The supplier shall establish, document and maintain procedures for handling, storage, packaging and delivery of product."[41]

Clause 4.16 Quality Records

"The supplier shall establish and maintain procedures for identification, collection, indexing, filing, storage, maintenance and disposition of quality records."[41]

Clause 4.17 Internal Quality Audits

"The supplier shall carry out a comprehensive system of planned and documented internal quality audits to verify whether quality activities comply with planned arrangements and to determine the effectiveness of the quality system."[41]

Clause 4.18 Training

"The supplier shall establish and maintain procedures for identifying the training needs and provide for the training of all personnel performing activities affecting quality. Personnel performing specific assigned tasks shall be qualified on the basis of appropriate education, training and/or experience, as required."[41]

Clause 4.19 Servicing

"Where servicing is specified in the contract, the supplier shall establish and maintain procedures for performing and verifying that servicing meets the specified requirements."[41]

Clause 4.20 Statistical Techniques

"Where appropriate, the supplier shall establish procedures for identifying adequate statistical techniques required for verifying the acceptability of process capability and product characteristics."[41]

2.1.5 Zero Quality Control[51-62] (ZQC)

2.1.5.1. Poka Yoke[51-52]

The following is from the preface to Poka-yoke: Improving product quality by preventing defects[50]:

"There are three major inspection techniques in the field of quality control:

1. *Judgment inspection*- separates defective products from good ones after processing. It prevents defects but being delivered to customers, but does not decrease a company's defect rate.
2. *Informative inspection*- investigates the causes of defects and feeds back this information to the appropriate processes so that action can be taken to reduce the defect rate.

3. *Source inspection*- a defect is a result, or an *effect*, usually caused by a simple mistake. Through 100 percent inspection at the source, the mistake can be corrected before it becomes a defect. 'Defects = Zero' can be achieved."

Statistical process control (SPC) was developed in the United States. SPC activities are based on the premise that 100 percent inspection is burdensome and time consuming and can be adequately replaced by sampling inspection and statistics. According to Poka Yoke, the use of statistics is really no more than qualified guesswork. Because there is always some discrepancy with the reality, a certain level of defects is tolerated. In a zero quality control (ZQC) system, however, 100 percent inspection is achieved through Poka-yoke, an approach that is inexpensive and requires little effort.

ZQC has three components that lead to elimination of defects:

1. *Source inspection*- checks for factors that cause errors, not the resulting defect.
2. *100 percent inspection*- uses inexpensive Poka-yoke (mistake-proofing) devices to inspect automatically for errors or defective operating conditions.
3. *Immediate action*- operations are stopped instantly when a mistake is made and not resumed until it is corrected.

The underlying philosophy of ZQC is based on the following ideas:

1. Any kind of mistake people make can be reduced or eliminated.
2. 100 percent inspection makes more sense than sampling inspection.
3. The user is the best inspector. Therefore, if users test subsequent processes in manufacture, they can easily check the parts before they begin, thus eliminating defects before they occur.
4. There are three basic strategies for zero defects:
    - Don't make products you don't need (In this regard, ZQC is closely tied to JIT, which was also developed by Shigeo Shingo).
    - Make your products to withstand any use. Quality can be built into a product by implementing Poka-yoke, automation and work standardization.
    - Once you've made it, use it right away.
5. There are 10 different kinds of errors:
    - Forgetfulness
    - Errors due to misunderstanding
    - Errors in identification
    - Errors made by amateurs
    - Willful errors
    - Inadvertent errors
    - Errors due to slowness
    - Errors due to lack of standards
    - Surprise errors
    - Intentional errors

6. There are 10 different kinds of defects
   - Omitted processing
   - Processing errors
   - Errors setting up workpieces
   - Missing parts
   - Wrong parts
   - Processing wrong workpiece
   - Misoperation
   - Adjustment error
   - Equipment not set up properly
   - Tools and jigs improperly prepared
7. There are five elements of production. Defect free products are assured by control in each of these areas. (This is closely tied to the concepts behind the *Affinity Diagram.*)
   - Information
   - Material
   - Machinery
   - Me (worker)
   - Method
8. The five best Poka-yoke are:
   - Guide pins of different sizes
   - Error detection and alarms
   - Limit switches
   - Counters
   - Checklists
9. A defect exists in one of two states: it is either about to occur or it has already occurred. Poka yoke has three functions to use against defects- shutdown, control and warning.
10. Some hints for establishing Poka yoke:
    - Identify items by their characteristics.
    - Detect deviation from procedures or omitted processes.
    - Detect deviations from fixed values.
11. Detection devices used for Poka yoke:
    - Contact devices- microswitches, limit switches and mechanical devices
    - Non-contact devices- photoelectric switches for opaque, translucent or transparent objects, depending upon the need
12. The eight principles of basic improvement for Poka yoke and zero defects:
    - Build quality into processes.

- All inadvertent errors and defects can be eliminated.
- Stop doing it wrong and start doing it right- now.
- Don't think up excuses, think about how to do it right.
- A 60% chance of success is good enough- implement your idea now.
- Mistakes and defects can be reduced to zero when everyone works together to eliminate them.
- Ten heads are better than one.
- Seek out the true cause using the 5 W's and 1 H (who, what, when, where, why and how).

2.1.5.2. Just In Time Manufacturing[53-62]

JIT was developed by Shingo and Ohno. The thrust of JIT is to focus on the next step of the production process and what is needed there. JIT uses a "pull" philosophy of inventory where raw materials and parts are pulled from the back of the factory towards the front where they become finished goods.

2.1.5.2.1. Lean manufacturing philosophy

JIT is also often called a lean manufacturing philosophy. The lean manufacturing philosophy is based on the following[59]:

- Customers can have what they want, when they want it without a penalty.
- Improvement is always possible and necessary.
- Customers are the reason for existence and they must always have a perfect product or service.
- All buffers are wasteful and need to be eliminated.
- A career consists of solving more difficult problems in a multi-skilled, cross-functional team environment.

2.1.5.2.2. Lean Manufacturing Strategy[59]

- Know your customers and their needs.
- Identify value-added activities and functions.
- Focus all the businesses' processes around the value stream of activities.
- Align your company to the needs of your customers.
- Activities that take time, resources and space but do not address the customer's requirements are non-value added and must be reduced or eliminated.
- Establish performance measurements in all aspects of the value stream.

JIT influences ordering, scheduling and producing of parts and finished products.

From "Just In Time Production (JIT)"[58]:

"Just In Time (JIT) philosophy is a system focused on the factory: The smaller lot size, the better. And the system is focused on Group technology and the handling and transportation of (half)-products.

"JIT producing seeks to achieve the following goals:

- Zero Defects
- Zero Set-up Time
- Zero Inventories
- Zero Handling
- Zero Lead time
- Lot Size of one"

2.1.5.2.3. Zero Defects

From "Just In Time Production (JIT)"[58]:

"In manufacturing, traditionally people thought that zero defects producing was not possible and not necessary. Not possible because of the fact that people thought that at some level of production it would be no longer possible to produce without defects and not necessary because although there were defects, the product did reach customer expectations.

"It is the aim of JIT for there to be no longer any cause of a defect and therefore all products will meet (far more) than the expectations"

2.1.5.2.4. Zero Set-up Time

From "Just In Time Production (JIT)"[58]:

"Reducing the set up-times leads to a more predictable production. No set-up time also leads to a shorter production time/production cycle and less inventories"

2.1.5.2.5. Zero Inventories

From "Just In Time Production (JIT)"[58]:

"Inventories, including work-in-progress, finished goods and sub-assemblies, have to be reduced to **zero**. There will be no sub-assemblies, no work-in-progress and no finished goods.

"This means a different view than in traditional manufacturing, where inventories are seen as a buffer against a fluctuating demand or as a buffer against unreliable suppliers. Also, in traditional manufacturing, inventory was built up to make sure expensive machines were running for full capacity, because only then the hourly costs were as low as possible."

2.1.5.2.6. Zero Handling

From "Just In Time Production (JIT)"[58]:

"Zero handling in JIT means eliminating all non-value-adding activities."

2.1.5.2.7. Zero lead-time

From "Just In Time Production (JIT)"[58]:

"Zero lead times are a result of the usage of small lots and increase the flexibility of the system. When there are no lead-times, the possibility to plan without relying on forecasts becomes bigger and bigger.

"The JIT philosophy recognizes that in some markets it is impossible to have zero lead-times. But, it makes it clear that when a firm focuses on reducing lead-times, this firm can manufacture more flexibly, gaining a competitive advantage over other manufacturers in the same market."

2.1.5.2.8. Lot Size of one

From "Just In Time Production (JIT)"[58]:

"A lot size of one makes it possible to adapt when demand is changing. If lot-size is, for example 100 and demand is changing, the firm ends up with inventory (let's say 45 pieces) and there will be the possibility that this inventory-level will only slowly decrease. This is because when demand is increasing again a new batch will be produced, which is being sold. The inventory level is too low to sell and will only be sold by chance, when someone asks a lower amount of pieces."

2.1.5.2.9. Objectives of JIT[53]

"Many have the misconception that Just-in-Time (JIT) primarily concerns the reduction of inventory. "Fundamentally JIT have the following objectives:

- Produce What the Customer Wants
- When the Customer Wants It
- In Lot Sizes of One (produce one unit as efficiently as 1,000 units)
- With Prefect Quality (do it right the first time)

"While the above objectives are not about inventory, a measure of how well JIT has been implemented is the amount of inventory required to cover-up mistakes. The level of inventory is appropriately a measurement tool—the result of a successful JIT implementation will be a reduction of inventory. However, JIT cannot be implemented solely by reducing inventory. What it takes to accomplish this reduction in inventory involves the entire organization.

"JIT contains a broad philosophy of continuous improvement and includes the following major categories of effort that are interdependent:

1. JIT Manufacturing
2. Quality at the Source
3. Respect for People
4. Supplier & Customer Relations
5. Uniform Scheduling (Level Load, Communicate Cycle Times)

"Other concepts requires for effective implementation of JIT include:

1. Kanban
2. Electronic Data Interchange / Supply Chain Management

"The concept of JIT in distribution is called Rapid Response or Quick Response."

2.1.5.2.10. JIT Manufacturing

JIT Manufacturing Strategy: manufacturing of goods only when needed using as little inventory as possible, in the shortest time possible. With continuous advances in technology, there are always better ways to produce a product. If am manufacturer does not find a better way for production, his or her competition will.

Produce to Exact Demand: Tie into the customer's information system to anticipate product demand. The supply base must be able to react to customer demands.

Produce One-at-a-Time as a goal: Produce necessary units in the necessary quantities at the necessary times. This is impossible to do if machine setups take several hours to accomplish.

Minimize Set-up Time: Aim for less than 10-minute setup times for every machine in their factory.

The Economic Order Quantity formula (EOQ) is primarily used to determine optimum order sizes that will absorb the setup time.

Set-up Time can be looked at in two different categories: Internal - that part that must be done while the machine is stopped (ex. changing tools, setting tolerances) and External - that part that can be done while the machine is operating (ex. getting tools and dies for the next job while the current job is operating).

Electronic Data Interchange is essential in reducing order lead times

Produce with Zero Defects/Strive for no Contingencies - "Draw out human capabilities to the very limit by placing all people, equipment and materials involved under uniform stress."

Eliminate Waste- Anything other than the minimum amount of plant, equipment, materials and workers that are absolutely essential to the production process.

Overproduction is the greatest waste because excess inventory must be stored, and the manufacturer uses aw materials that could be better used in products that have higher demand.

Accountants view inventory as an asset. Manufacturers should view inventory as a liability.

Re-engineer the production process

2.1.5.2.11. Quality at the Source

- When producing goods only when needed and using goods with minimal inspection, any production problems become everyone's problem.
- Quality control is each employee's responsibility. Source of quality is at the operation level, anyone that adds value to the product.
- Inspectors inspecting after the fact can usually only find 80% of defects and inspectors tend to create an adversary "big brother" atmosphere.
- The way to reduce defects is to re-engineer the process.
- Every Employee should learn Statistical Process Control techniques as a tool to determine whether their mistakes are process oriented or just random variations.
- Practice Jidoka, which means, "Stop everything when something goes wrong." Plan on assembly line downtime of 15 to 30 minutes per day. (This is a brute force way to be sure that problems are fixed.)

- Output will be reduced initially.
- New Definition of a Customer - each operator must regard the next operation as the customer. Order entry's customer is the stock room.
- Visibility Management - use peer pressure to promote good performance. If everyone is involved, all can see how things should be done.
- Re-Engineer production processes to be fail-safe (parts are designed so that there is only one way that can be assembled).
- Machines must always be ready (Preventative Maintenance). Do not just fix a breakdown; find out why it broke and fix that problem.
- Schedule maintenance to anticipate problems and fix before they break.
- Rework costs more in the long term than a solution. In companies not practicing JIT manufacturing, the cost of poor quality is 15% to 25% of sales.

2.1.5.2.12. Respect for People

If accountants view employees as expenses, manufacturing companies should view employees as assets. For JIT to work (for continuous improvement to work), it is essential that employees feel secure in their jobs. An employee will be less likely to be innovative if he believes that the innovation may cost him his job. An investment in automation is also easier when employees feel secure in their jobs.

Quality Circles are also used as a means of communication and problem solving

Management by Consensus is a slow decision making process, but once the decision is made, everyone understands how to implement it.

The responsibility for decision-making must be at the line level and may also include such non-traditional players as suppliers. Production people are the source of quality improvement and the source of many ideas to improve production.

2.1.5.2.13. Supplier & Customer Relations

Communicate needs to suppliers. Allow suppliers to tie into your information system so they can anticipate your product demand. JIT supplier relations are in effect long-term partnerships: Ideally, there should be two (or so) suppliers per product family. With two suppliers, guarantee each 40% of the business, while reserving the remaining 20% for the better-performing supplier. JIT can be implemented in relative isolation by increasing WIP inventory buffers to account for unreliable supplier deliveries or quality.

2.1.5.2.14. Uniform Scheduling (Level Load, Communicate Cycle Times)

Traditionally, people have tended to combine the functions of authorizing a production schedule for immediate action and planning a production plan. Uniform Scheduling is defined to only include gathering the necessary resources to meet planned production. The authorization for immediate action is initiated by either the Final Assembly Schedule (not the Master Production Schedule) or a Pull (kanban) type system.

Develop a Level Load for the system to provide a smooth demand for manufacturing, thereby making it easier to schedule resources. Load Leveling strives to build the same product mix every day during a given month.

The alternative is to minimize change by scheduling a specific part to be run only once each month in large lot sizes. Using load leveling, smaller lot sizes are produced that tend to more closely match current customer demand, requiring less inventory.

For planning purposes, load leveling allows planners to think in terms of averages. It is easier to work with averages than with time-phased events. When you make some of everything every day, a customer can be furnished with at least a partial quantity of new product. Most "urgent" customer orders ask for more pieces than are needed immediately.

Communicate Cycle Times to all support functions in the network to tell all involved what has to be done to get ready to meet the planned demand. MRP, especially when using the Planning Bill of Material, can be very useful in uniform scheduling—A Planning Bill of Material identifies all the products that comprise a family of parts and forecasts the percentages that each product represents (the product mix).

2.1.5.2.15. Manufacturing Inventory

Inventory has several legitimate uses in business. Functionally, inventory may be of the following types:

- Buffering or Caching- When one machine at the beginning of a manufacturing sequence needs to be cleaned (for example) once per hour to keep the line running, an inventory of parts should be built up to feed the rest of the line when the machine is shut down.
- Transportation- When goods are transported from one point to another, they are usually transported in large lots, rather than one at a time.
- Cycle- To the extent that there is a processing delay from the time a customer decides the item is needed to the time the part is available for use, inventory is required to buffer the system for the length if time required to process, manufacture and distribute the item.
- Store of Value- In times of high inflation, one may make money by purchasing an item, storing it and later reselling it at a higher price. This type of inventory is kept for financial and not operational reasons.
- CYA (cover your assets)- just in case some one makes a mistake—forgets to place the order when required, places the wrong order, or the parts delivered are incorrect or of bad quality. CYA inventory may represent 2/3 of the inventory cost in an organization. To the extent that JIT is successfully implemented, all operational inventory types (except transportation) will be reduced.

2.1.5.2.16. Kanban[54]

The kanban production control system is a pull type inventory control system.

- Originated by Taiichi Ohno at Toyota Motor Company.
- Like uniform scheduling, the Pull system is based on the premise that there will be variable flow of materials through the plant.
- While high volume is not necessary, repetition is important.

In a kanban system, a card is used to signal when it is time for a batch of inventory at a workstation to be replaced.

- The batches are typically small (lasting a few hours). Such a system requires tight schedules and frequent set-up of machines. Small quantities of everything must be produced several times a day.
- The kanban system must run smoothly because any shortages have an almost immediate impact on the entire system.

2.1.6 Kanban Card Calculations

The amount of WIP inventory is controlled by the number of cards that are in the system. The number of Production Cards is given by the formula

Ad * (Wt + Pt) * (1 + SS) = CQ, where: (6)

- Ad = Average Daily Demand during the month for the part
- Wt = Waiting time at the work center for the card to be in a position for it to be produced (queue time).
- Pt = Processing time, including setup time for one container of parts
- SS = Safety stock (up to 10% of daily demand, or one container of parts)

CQ = Container Quantity Production Cards The formula can be modified for Cards for outside suppliers:

Ad * (2 + Td) * (1 + SS) = DD * CQ, where: (7)

- Td = Transit Delay, the number of additional scheduled trips that will take place between the time the card is picked up and the actual delivery of materials. It takes a minimum of two visits to complete the transaction (1 picks up card, 2 delivers materials). However, if the supplier is far away or cannot immediately comply with the instructions on the card, it introduces a delay reflected in the size of Td.
- DD = Deliveries per Day currently scheduled

2.1.7 QFD[63-71]

Quality function deployment (QFD) was developed in Japan in the 1970s, primarily by Akao[63]. QFD is a customer-driven quality management system geared toward creating higher customer satisfaction. Many companies throughout the world have used QFD throughout marketing, R&D, engineering and manufacturing stages of product development.

QFD integrates a number of different TQM tools of quality developed in Japan. Among them are the Affinity Diagram, The Fishbone (or Ishakawa) Diagram and brainstorming. These tools of quality represent a qualitative systematic approach to decomposing systems. It must be noted that in QFD and in all these methods, the Japanese perception of quality is not relegated to merely quality control, but rather applies to the entire production process from conception to retirement. The methods that are also a part of TQM are described in greater detail in the section devoted to TQM.

Typically, a complete QFD system is composed of four phases, which deploy the customer needs throughout the planning process. In QFD, each phase's important outputs ("hows") generated from phase inputs ("whats") become the inputs for the succeeding phase. Each phase is represented by an input-output or what-how matrix that is easy to understand and convenient to use. The four phases are described below.

2.1.7.1. The four phases of QFD

The QFD process has four phases:

1. Product Planning (House of Quality)
2. Design deployment (Parts Deployment)
3. Process Planning
4. Production Planning

QFD links these phases through the use of four QFD matrices, linked together as depicted below:

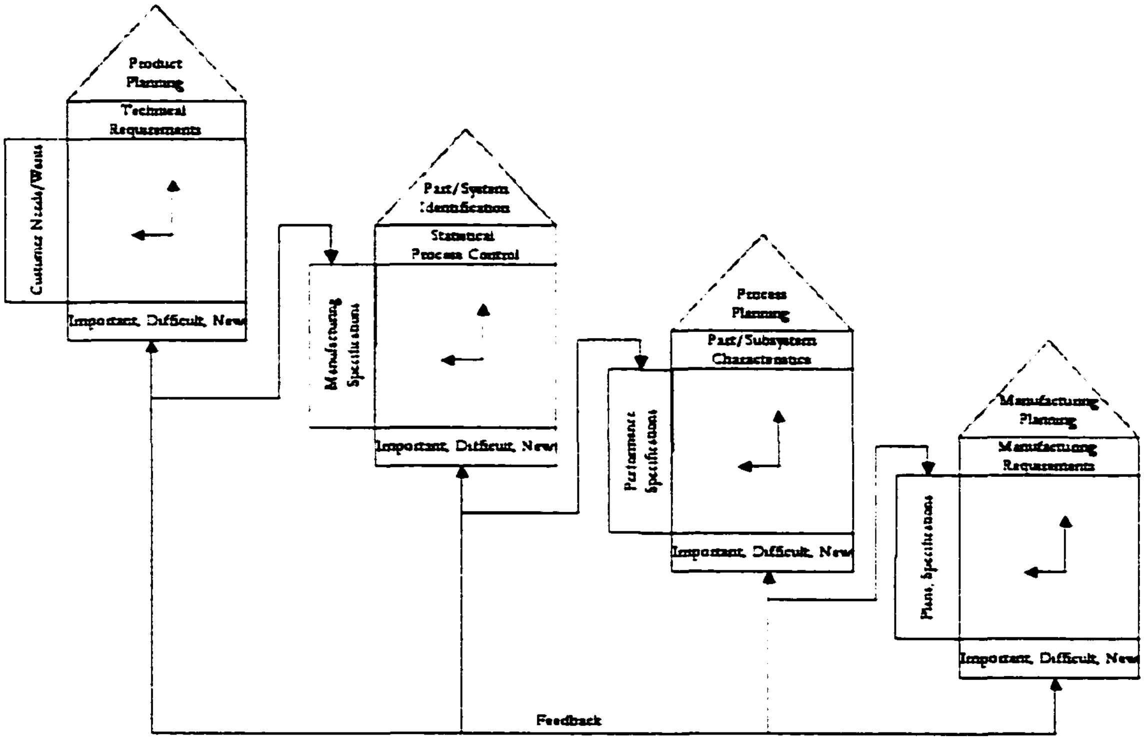


Figure 1. Relationships Between the Four Matrices of QFD

Each of the QFD matrices has a specific structure, which can be generalized in the following House of Quality (HOQ) arrangement:

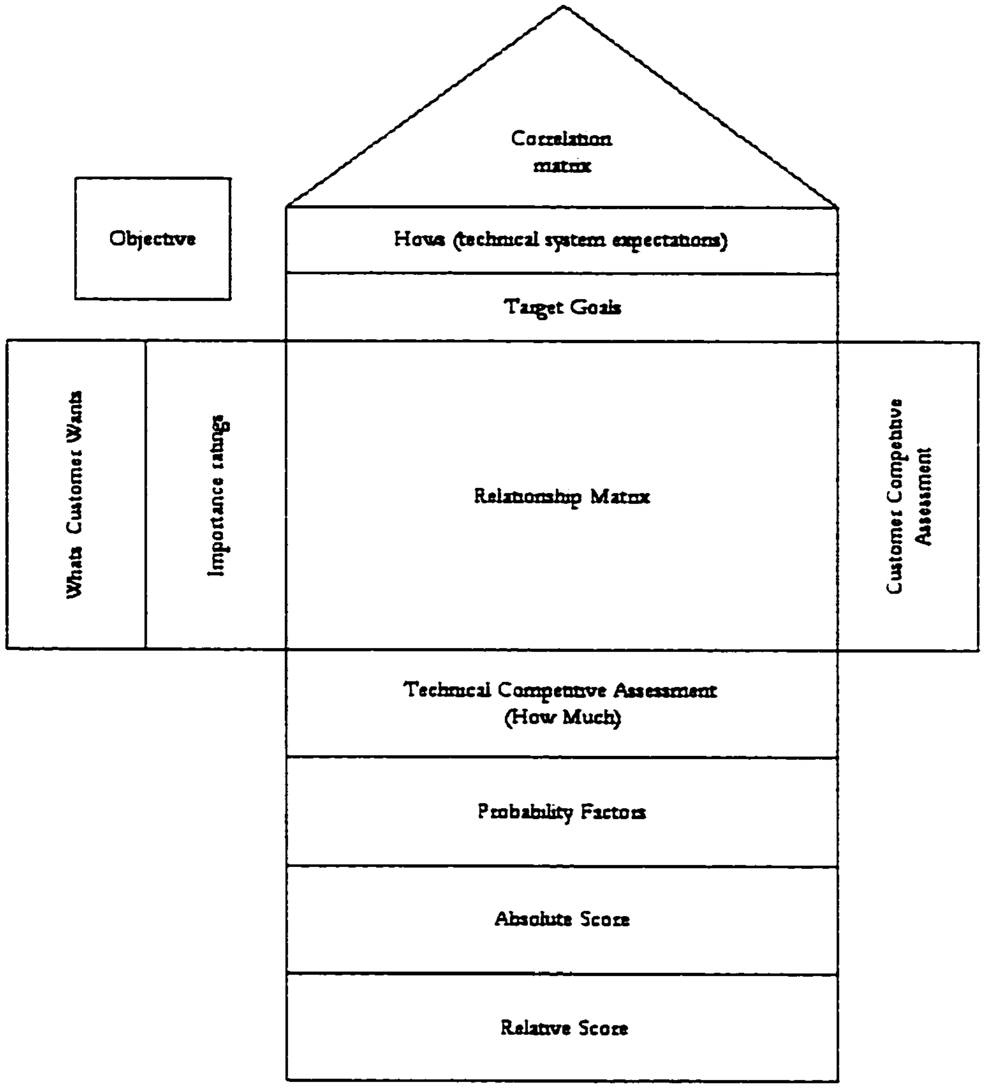


Figure 2. Product Planning (House of Quality)

2.1.7.1.1. Phase 1 - Product Planning

The product planning or HOQ phase is the first. This phase begins with customer desires, correlates those desires with technical system expectations and ends with a listing of the most effective technical system expectations to meet customer desires. The steps to accomplish this goal are described in the section "How to construct a QFD matrix."

2.1.7.1.2. Phase 2. Design deployment (Parts Deployment)

The output of the first phase is the key technical measures. The next logical challenge of design is to discover the proper part characteristics. The second QFD matrix uses the output of the first as its WHAT column. The part characteristics desired are placed in the HOW row. The method of analysis is identical to that of the HOQ matrix described below in the section "How to construct a QFD matrix."

2.1.7.1.3. Phase 3. Process Planning

The output of the second phase is the key parts characteristics. The next logical challenge of design is to discover the proper manufacturing process. The third QFD matrix uses the output of the second as its WHAT column. The process operations desired are placed in the HOW row. The method of analysis is identical to that of the HOQ matrix described below in the section "How to construct a QFD matrix."

2.1.7.1.4. Phase 4. Production Planning

The output of the third phase is the key process operations. The next logical challenge of design is to discover the proper production plan. The fourth QFD matrix uses the output of the third as its WHAT column. The production requirements desired are placed in the HOW row. The method of analysis is identical to that of the HOQ matrix described below in the section "How to construct a QFD matrix."

2.1.7.1.5. How to construct a QFD matrix

The WHAT Column

First it is necessary to understand the customer's needs and expectations. These needs are listed in the leftmost column of the QFD matrix called the WHAT column. In order to get the most out of the QFD process, it is important to take special care when listing the WHAT column items. It is recommended that the following simple procedure be used:

1. Assemble a group of people with different functional interests (called an Integrated Process Team or IPT). The group should include the customer (or an advocate for the customer, such as a member of sales), a user of the current product, engineering, quality assurance and management. The ideal size of this group is between 5 and 7 people.
2. Allow the group to brainstorm the needs of the customer. The initial brainstorming session should be allowed to continue until all ideas are exhausted.
3. Using an Affinity diagram, divide the brainstormed ideas into logical groups. Eliminate redundancies and ideas beyond the third level of indenture.
4. If the list is extremely large (over 40 items), it may be necessary to reduce its size further. Within affinity groupings, the number of subgroups may be further reduced using a nominal voting technique. Note that it is not absolutely necessary to reduce the size of the column early. The process of applying QFD may reduce the number of needs anyway.

Relative Importance Rating

Using the IPT, rate each "customer want" on a scale of zero to five, where zero corresponds to something that is relatively unimportant to the customer, and five is something they feel is absolutely vital.

In actual experience, it may be difficult for the IPT to understand the need for this step. Many customer advocates think that everything is important and will give a maximum score, or five, for each item. Such an approach, although well intentioned, will defeat the purpose of the QFD exercise. Care should be taken to assure that there is some relative ranking between the items.

Another possible problem that may occur later is that items that are highly correlated to each other may both carry the same importance rating. The porch of quality, described above, is used to identify correlated and redundant customer needs.

The numerical value of the relative importance rating is the variable g_i for the i^{th} "customer want."

Competitive Analysis

The IPT decides a variable score from one to five of each of the following factors, which are entered into the QFD matrix on the far right side in columns:

1. Company's current market state for each WHAT ($C1_i$).
2. Company's planned state for each WHAT ($C2_i$).
3. Company's planned target state for each WHAT ($C3_i$).
4. Company's required improvement rate for each WHAT ($C4_i = C3_i / C2_i$) (8)
5. Raw weight for each WHAT ($C5_i = C1_i * C4_i$) (9)
6. Demand weight (also called final importance rating) for each WHAT ($f_i = C5_i / \Sigma C5_i$) (10)

The final importance rating is in the rightmost column of the QFD matrix, and it summarizes the relative importance of each customer need.

List of HOWS or Technical System Expectations

Next, a list of all technical system expectations is constructed. The technical system expectations are the ways in which the customer's needs are met. The goal of the QFD exercise is to meet all of the customer's needs in the most technically sound, efficient, economical and effective way possible. Without the QFD, engineers would have to arrive at the best technical approaches using their collective experience and research. The QFD matrix provides a simple tool to help sort out and prioritize each method of meeting customer expectations.

The list of HOW's is generated by an IPT. The IPT that generates the list of HOW's may not be the same group as that which produced the list of WHATs and compared them. Like the earlier IPT, it should consist of five to nine individuals. The HOW IPT members are either members of the design team or are suppliers to or customers of the product of the design team.

The HOW IPT uses a cause and effect diagram to develop a list of HOW's for consideration. Other names for the cause and effect diagram are the fishbone diagram and the Ishakawa diagram. Another variation of the cause and effect diagram is the CEDAC, or the cause and effect diagram with the addition of cards. A description of how to construct a cause and effect diagram is found below.

Once generated, the list of the HOWs is placed on the top of the QFD in a row. In the next row is the target goal for each WHAT. In the area below these two rows is a matrix where each WHAT is compared to each HOW.

Target Goals Row

The target goals row is optional. It provides a relative ranking of each HOW submitted for consideration. If it is to be used, the IPT selects a rating between one and five for each HOW. The ratings are recorded as the variable h_j, where j represents the j^{th} HOW column.

The relationship matrix

The relationship matrix is used to track the strength of the interaction between each WHAT and WHO. The variable r_{ij} is used to designate the interaction of the i^{th} WHAT and the j^{th} HOW. If they are strongly correlated, a score of 9 is given; if they are medium correlated, a score of 3 is given; if they are weakly correlated, a score of 1 is given; and if they are uncorrelated, a score of 0 is given. The values are decided by the HOW IPT.

Technical Ratings (Technical Competitive Assessment)

The technical rating assessment is a score calculated to describe the technical viability of each HOW. It is designated by the variable t_j and is placed in the first row under the relationship matrix. The equation for the j^{th} t_j value is:

$$t_j = \Sigma\, r_{ij} f_i\, h_i \tag{11}$$

Probability Factors

An optional probability factor for each HOW is determined by the HOW IPT. The variable P_i takes on a value of zero to one and designates the probability that each HOW can be used.

The probability factor is used to more heavily weight the HOWs that have the greatest probability of success.

Absolute Score

A series of calculations are made from the variables already determined. The first is the Absolute Score, Aj. The absolute score is placed in the next row below the probability factor:

$$\mathbf{A_j = t_j\, P_i} \tag{12}$$

Relative Score

The relative score gives a value between zero and one and is placed in the final row of the HOQ. The highest values are given the greatest consideration in the final design. The lower value HOWs are not discounted altogether because the matrix is also used to assure that all of the WHATs are addressed in the final design. The equation for R_i is:

$$\mathbf{R_j = A_j \,/\, \Sigma A_j} \tag{13}$$

Roof of Quality

The Roof of Quality is used to assess the cross correlation between different HOWs. Although it is often omitted from the HOQ in application, it provides valuable information about technical contradictions. (Technical contradictions are commonly called engineering trade-offs. In TRIZ theory, an invention advances when technical contradictions are resolved.

For each HOW-HOW interaction a correlation value is assigned:

- 9- strong positive correlation
- 3- medium positive correlation
- 1- weak positive correlation
- 0- no correlation

- -1- weak negative correlation
- -3- medium negative correlation
- -9- strong negative correlation

HOW's that are strongly correlated may be redundant. It may be useful to eliminate the one with the lower relative score. HOWs that are strongly negatively correlated may represent technical contradictions. Although QFD does not have answers regarding resolution of technical contradictions, TRIZ theory has a wealth of information regarding technical contradiction resolution.

THE PORCH OF QUALITY

The porch of quality is used to evaluate the correlation between different WHATs. The porch of quality is used to assess the correlation and interrelationship between customer wants. It also can be used as another way to reduce the number of WHATs. Correlations in the porch of quality are only performed at the lowest level of indenture.

2.1.7.2. The weaknesses of QFD

Jacobs et al[67] present basic overviews of the history and applications of QFD. It contains a cursory description of how QFD is used, and it posits that QFD is hard to implement because its users may freely modify it.

Goel[66] presents QFD as a framework in which other methods can be incorporated. In fact, QFD is extremely arbitrary in its application and it requires alternate methodologies to bolster its results. On the other hand, QFD promotes teamwork, and it is a useful tool to visualize the customer's desires and bring these desires into the purview of the design engineer. It is a simple and logical approach, but it lacks rigor. In order to be effective and meaningful, QFD must be used with more rigorous methods.

2.1.8 Robust Engineering[71-80]

Robust Engineering[71-74] is a disciplined approach to take into account various input parameters of a design by experimentation before committing to a final design. There are two popular approaches to Robust Engineering:

- The methods espoused by Taguchi and his followers that drastically reduce the number of design combinations considered by reducing interactions and
- The methods espoused by Box and his associates that try to minimize design test considerations without sacrificing number of interactions considered.

Phadke[73] establishes and explains Taguchi's Loss Function as well as Taguchi's Design of Experiments (DOE) and Response Surface Methodology (RSM). There are three kinds of Quality Loss Functions:

- Nominal the Best (NTB)- there is some target, nominal value. Any value above or below it has some quality loss associated with it. This loss may be symmetric or asymmetric.
- Largest the Best (LTB)- the larger the value, the more desirable it is. Profit is a LTB variable, for instance. The quality loss function is generally infinite at zero and becomes asymptotic to the *x-axis* as it grows without bound.

- Smallest the Best (STB)- the smaller the value, the more desirable it is. Loss is a STB value. The Quality loss function is generally zero at zero and increases without bound as the value increases. Although the shape of the STB function is a modeling exercise, it generally accelerates rapidly the further it gets from the target. A parabolic shaped function is very popular to model STB.

Schmidt and Launsby[74] discuss Taguchi's Loss Function, DOE and RSM. These authors are clearly advocates of a special form of RSM called Central Composite Design or CCD. CCD is useful in reducing the number of experiments needed to establish a design solution space while still maintaining information on interactions between Design Variables (DV). These methods generally only deal with one Problem Definition Parameter (PDP) at a time, making them unattractive for more complex design problems.

Box and Liu[71] show that innovation is a direct result of the process of sequential learning. As such, a statistician offers little assistance if all he can do is set up statistical models because he is not able adaptively to learn the relevance of these models from a design standpoint. Box and Liu posit that the statisticians must be an integral part of the design process to use statistics as a tool to help design evolve from wrong assumptions to valid ones.

Box and Liu is useful in a study of TRIZ for several reasons. First, it validates the basic theory of TRIZ that innovation need not be merely a flash of insight left to chance. Instead, innovation can be summoned by a disciplined approach. Box and Liu's disciplined approach is to take concepts of engineering and statistics and synergistically combine them. Altshuller's method is to take the concepts of engineering and physics and synergistically combine them.

Another important point is that Box and Liu are talking about Response Surface Methodology (RSM) as a method of design optimization. They correctly point out that RSM affectivity is minimized if the model developer has no engineering background because the way the experiment is constructed depends on engineering assumptions. TRIZ effectively is also minimized if a practitioner of TRIZ does not have a working knowledge of several different disciplines and cannot bridge the gap between engineering and other sciences.

RSM is a tool to optimize a design when much of the design is already complete, and the final step of setting parameters to minimize variation while maximizing performance (robustness) is all that is left. RSM is a poor and cumbersome method to find the general solution of a problem, while TRIZ is an excellent method to find a general solution of a problem. RSM works within current understanding of the solution calculus, while TRIZ offers new, often radical approaches. Neither RSM nor TRIZ can effectively be used to identify problems that have not yet been observed.

In the second part of "Statistics as a Catalyst to Learning"[72], Box discusses the evolutionary method of the scientific method. As such, the sequential learning process works from deductive reasoning to inductive reasoning and back to deductive reasoning in a cyclic fashion. Starting with a model, the scientist deduces the way the system in its environment should behave. Then the scientist is confronted with data that conflicts with the model. The scientist must then revise the model inductively by merging the new data into the old model. From the new model, the scientist continues to deduce behavior until another contradiction is presented and the model must again be revised. Box points out that factorial designs can aid in inductive reasoning by identifying interactions and promoting robust solutions.

This again brings into focus another TRIZ concept, the concept of technical and physical contradiction. In TRIZ, an early and essential step in problem formation is the identification of a technical contradiction. A technical contradiction is a situation where what is desired (the data) is at odds with what methods are known to work (the model). It is important to identify the contradiction because the contradiction must be identified in order for it to be effectively removed or minimized. TRIZ has no mechanism to assure robustness in the final design and is very awkward in identification of interactions except to categorize them as "useful" or "harmful." RSM can be used to quantify these vague concepts of useful and harmful interactions, as it can also be used to promote robustness of the final design.

2.1.8.1. Quality Loss Function[75-80]

Phillips and Cho[75] propose an empirical loss function of the form:

$$\mathbf{ELF(y) = b_0 + b_1y + b_2y^2 + b_3y^3 + \ldots +} \quad (14)$$

To replace Taguchi's quadratic Loss Function (QLF) for nominal-the-best (NTB) case:

$$\mathbf{QLF\ (y) = C\ (y\text{-}y_0)^2} \quad (15)$$

Their loss function is then used to set upper and lower specification limits (USL, LSL) to minimize total costs given fixed costs for scrap, rework and inspection.

They show two examples of this approach in the article, one is a first order with two lines from the target value and the other is a quadratic. They state that the quadratic is the most popular. Note that Taguchi's QLF is a special case of their quadratic function that can be established in the absence of data. Taguchi starts with specifications and writes a QLF; they start with data and derive the equation for a QLF.

Although their method offers a more general solution to the QLF equation, it does not deal with the fundamental problem of the function increasing without bound at the limits. An empirical solution implies that empirical data is available and usually it is not. It is more important with a QLF for the general shape to reflect reality and to use it to model decreases in quality due to deviation from a target value.

Spiring and Yeung[76] is an expansion of a 1993 work by Spiring that proposes using an inverted normal probability density function (inverted normal loss function, INLF) as a quality loss function. The 1993 paper was further amplified by one of their references.

The INLF addresses some of the complaints regarding Taguchi's QLF in that it is minimal at the target value, increases monotonically and reaches a quantifiable maximum. (QLFs do not reach a quantifiable maximum). The INLF is symmetric and cannot account for differences in the associated losses for scrap and rework.

To address the symmetry problem, the authors suggest using other inverted probability density functions and call them inverted probability loss functions (IPLF). They demonstrate using IPLF that a variety of loss function shapes are possible creating continuous functions that are symmetric or asymmetric and can be applied to virtually any loss function scenario. They give some examples of how they have applied IPLFs.

It appears that an IPLF is descriptive of already-established Quality specifications. It is unclear how to establish the proper IPLF from the many available and how to validate that the one selected is the right one. The practical significance of the IPLF is very exciting- if a probability distribution (usually normal) is used to describe the distribution of units between two limits, then its inversion could demonstrate the quality loss as a result of missing the target. The fact that probability distributions tend to flatten out addresses the major problem with Taguchi's loss function. The unfortunate part of Spiring and Yeung's method is the complexity of the equations.

Kros and Mastrangelo[77] demonstrated that the QLF is not appropriate in some circumstances. Taguchi's method defines performance in terms of signal-to-noise (S/N) ratios, which are intrinsically tied to the QLF. This paper tries to establish a relation between the LF, S/N ratio and the three general quality characteristics (NTB, STB, LTB). The authors refer to a technical paper by Maghsoodloo relating STB and LTB QLFs to S/N ratios.

Nonquadratic LFs considered are (1) two-sided asymmetric, (2) absolute error, (3) stepwise and (4) cubed. All of these have the same problem as Taguchi's Quadratic Loss Function in that they increase without bound, although they all address the problem with asymmetry.

Kapur and Cho[78] cite Taguchi: Quality efforts during product/process design are called "off-line quality control." Off line quality control is further divided into three phases: system design, parameter design and tolerance design. Taguchi mainly focuses on parameter design to minimize product variation. If parameter design is inadequate, then variation is further narrowed through tolerances.

There are three steps for on-line QC: (1) diagnosis and adjustment, (2) prediction and correction and (3) measurement and disposition. In the third step, products are deemed conforming or nonconforming based on the LF tolerances established off-line.

Although Taguchi sets his QLF from tolerance specification, Kapur and Cho set their tolerances by considering the QLF. Kapur and Cho[78] use Taguchi's QLF for STB and LTB, but use asymmetric LF for NTB.

Moorhead and Wu[79] expand Taguchi's two-step QLF to a complicated five-step procedure in the presence of a nonquadratic loss function. Only an asymmetric loss function is considered. Their method uses an *a priori* adjustment factor.

Kapur and Cho's method is designed more for statisticians than for engineers. Although it has very clear proofs associated with it, there is no indication that it actually has any relevance to a real problem. The Moorhead and Wu[79] method may be very good, but it is more likely to be used by statisticians than by engineers because it is so difficult to follow.

Layne[80] addresses the problems encountered at Allison Transmission with a designed experiment for a gear hardening process in which there were six distinct responses of interest. The author wished to optimize all six responses simultaneously and devised three different approaches to do so. The first method used defined a loss function that would be minimized when the six responses were close to their target values and was standardized by dividing the predicted value for the response by the standard error estimate for that response:

$$Loss = \sum_{i=1}^{n} \frac{w_i |r_i - target|}{standard\ error_i} \tag{16}$$

Where: w_i is the "importance level" (an arbitrary weight provided by the user), "r_i" is the predicted value for the response and "target" is the target value for the response.

The second method, obtained from the statistical literature, was to use a desirability function, D:

$$D = \left(\prod_{i=1}^{n} d_i \right)^{1/n} \tag{17}$$

Where d_i is the desirability of one response. It takes on a value between 0 (unacceptable) and 1 (ideal). The desirability function, D, is therefore maximized and also has a range of 0 to 1. The desirability function is defined as follows:

For LTB:

$$d_i = 0, \ldots\ldots\ldots\ldots \; if \; y_i \le y_{i,\min}$$

$$d_i = \left(\frac{y_i - y_{i,\min}}{y_{i,\max} - y_{i,\min}} \right)^r, \ldots\ldots \; if \; y_{i,\min} < y_i \le y_{i,\max} \tag{18}$$

$$d_i = 1, \ldots\ldots\ldots\ldots \; if \; y_i > y_{i,\max}$$

For NTB,

$$d_i = \left(\frac{y_i - y_{i,\min}}{c_i - y_{i,\min}} \right)^s, \ldots\ldots\ldots\ldots \; if \; y_{i,\min} \le y_i \le c_i$$

$$d_i = \left(\frac{y_i - y_{i,\max}}{c_i - y_{i,\max}} \right)^t, \ldots\ldots\ldots\ldots \; if \; c_i < y_i \le y_{i,\max} \tag{19}$$

$$d_i = 0, \ldots\ldots\ldots\ldots\ldots\ldots \; if \; y_i > y_{i,\max}, or \; y_i < y_{i,\min}$$

By extension, for STB:

$$d_i = 1, \ldots\ldots\ldots\ldots \; if \; y_i < y_{i,\min}$$

$$d_i = \left(\frac{y_i - y_{i,\min}}{y_{i,\max} - y_{i,\min}} \right)^u, \ldots\ldots \; if \; y_{i,\min} \le y_i < y_{i,\max} \tag{20}$$

$$d_i = 0, \ldots\ldots\ldots\ldots \; if \; y_i \ge y_{i,\max}$$

The values of r, s, t and u are weighting factors that are set by the user; c_i is the target value. For NTB, the function can be symmetric or asymmetric.

Layne's third method is a distance function. The distance function takes into account correlations between functions.

$$D(\mathbf{Y}-\mathbf{T}) = \left(\frac{(\mathbf{Y}-\mathbf{T})' \Sigma^{-1} (\mathbf{Y}-\mathbf{T})}{\mathbf{z}'(x)(\mathbf{X}'\mathbf{X})^{-1}\mathbf{z}(x)} \right)^{1/2} \tag{21}$$

Where **Y** is the vector of predicted responses, **T** is the response target value vector, **z** (x) is the vector of factor levels for a given observation, **X** is the design matrix and Σ is the sample covariance matrix of the responses. The distance function is minimized to obtain the best solution.

Layne's first solution required setting arbitrary weight factors and increasing the amount of loss from the target linearly as one gets further away from the target. As a loss function, it was inferior, therefore, to Taguchi's QLF and other standard loss functions. Layne's second method also requires an arbitrary decision on the part of the user to set weights for leaving the target. Solver® has a hard time dealing with the desirability function unless the initial values lie within the acceptable region because the desirability is "0" and does not gradually increase outside the target region. The third method uses matrix algebra and was not considered because of its inherent complexity.

2.1.9 Theory of Constraints[8-10, 81-86] (TOC)

Goldratt developed the Theory of Constraints[8-10, 81-86]. Dettmer discusses the thinking process behind TOC. According to Dettmer, TOC answers three questions in its thinking process:

- What needs to be changed?
- What does it need to change to?
- How should the change be caused?

The thinking process[4] uses a sequential set of five tools: CRT, CRD, FRT, PRT and TT. This article describes each of these tools and illustrates how they fit into the overall thinking process. The foundation of the thinking process is a set of logical rules governing cause-and-effect relationships called the Categories of Legitimate Reservation. They are:

- Clarity- a complete understanding of what is communicated
- Entity Existence- the factual validity of what is communicated
- Causality Existence- a proposed cause produces the stated effect
- Cause insufficiency- a proposed cause is not sufficient, in itself, to produce the effect
- Additional cause- another independent cause produces the same effect
- Cause-effect reversal- the stated effect is actually the cause and vice-versa
- Predicted effect existence- an intangible cause can be validated by simultaneous independent effect
- Tautology- the stated effect is offered as the rationale for an intangible cause

Dettmer[4] posits that TQM has fallen short in many instances because it treats quality as an overarching problem in a wide variety of applications when it is not the principle cause of low profitability. Instead, a consideration of the entire system would dictate whether quality needs to be addressed first or something else needs to be addressed first. One could extend the logic of the article to TRIZ because TRIZ treats inventiveness as a panacea for all problems.

TOC takes a system focus in which a weak link is used to define where resources should be focused. If one were to look at the entire system as a chain, if one link of the chain were to break, the system would break as well. If the weak link is strengthened, then the entire system is strengthened. If quality is the weakest link, then TQM may offer the best solution to the system. But before committing a large amount of money to TQM, it would be wise to first know where the system needs to be improved. The weakest link is called the *system constraint* in TOC.

Goldratt has identified **five focusing steps** in identifying the *system constraint* and strengthening the system:

- Identify the constraint. This is usually done through the use of Current Reality Tree (CRT) or Conflict Resolution Diagram (CRD).
- Exploit the constraint. By this, the implication is to get the most from the constraint- to strengthen it.

- Subordinate everything else to the exploitation of the constraint. There may be other system elements that suffer as a result of exploiting the constraint. This subordination must be enough to make the constraint no longer the system constraint.
- Elevate the constraint. This means increasing the constraint's capacity, changing a policy or removing the constraint altogether. Keep elevating the constraint until the constraint is finally broken.
- Go back to the first step and identify the next constraint. In doing so, avoid inertia. In this usage "inertia" implies that all earlier decisions are open to reexamination. This is necessary because systems are interdependent by nature.

There are seven types of constraints identified at the system level:

- Market
- Resource
- Material
- Supplier/Vendor
- Financial
- Knowledge/competence
- Policy

In order to figure out what to change, Goldratt has conceived of five logic-based tools, listed below. The first two help to identify the current state. The third helps to visualize the system with the constraint removed, and the latter two help to identify how to cause the change.

- Current Reality Tree (CRT). A CRT is a tool of TOC that answers the question- "what needs to be changed?" The CRT is a logic diagram that reflects the current state of a system in terms of the causes and effects that create that system. There are three types of logical operators used in a CRT: an AND gate represented by an ellipse, an OR gate represented by multiple cause arrows terminating at a single effect and a MAG-AND GATE represented by a double triangle. MAG-AND is a cumulative effect. Below is a part of the CRT drawn for the Airbag case study discussed in Chapter 4:

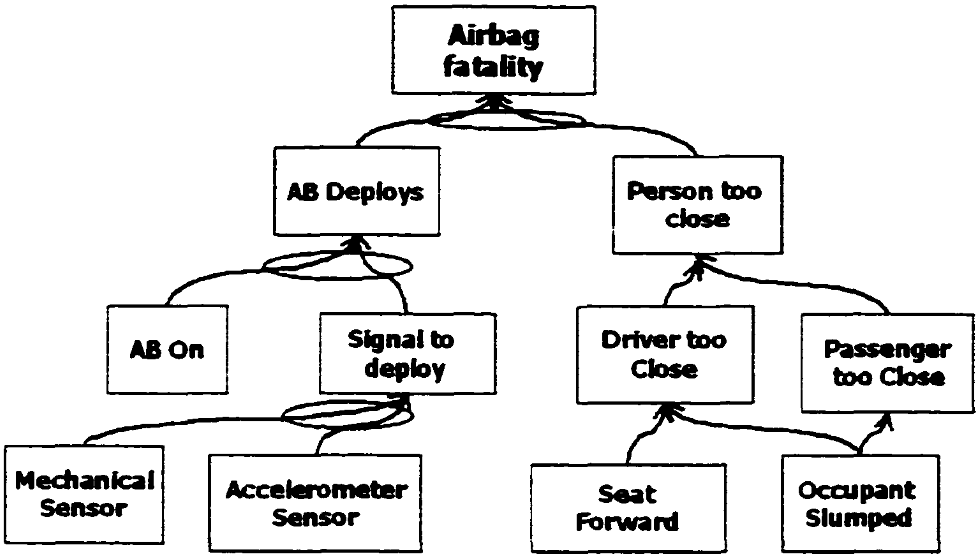


Figure 3. Example of Current Reality Tree (Airbag Case Study)

- Conflict Resolution Diagram (CRD). A CRD is another tool of TOC that answers the question- "what needs to be changed?" A Conflict Resolution Diagram or Evaporating Cloud is a diagram that displays an effect (common objective) with two different causes (requirements), each of which has a sub-cause (prerequisite). The Prerequisites are in conflict with each other. The TOC approach to solving these conflicts is to superimpose a solution or "injection" to satisfy both requirements. The injection may not satisfy the prerequisites, so long as the objective and the requirements are met. Below is an example of a CRD drawn for the Airbag problem of Chapter 4 (note that this is not a solution suggested in Chapter 4):

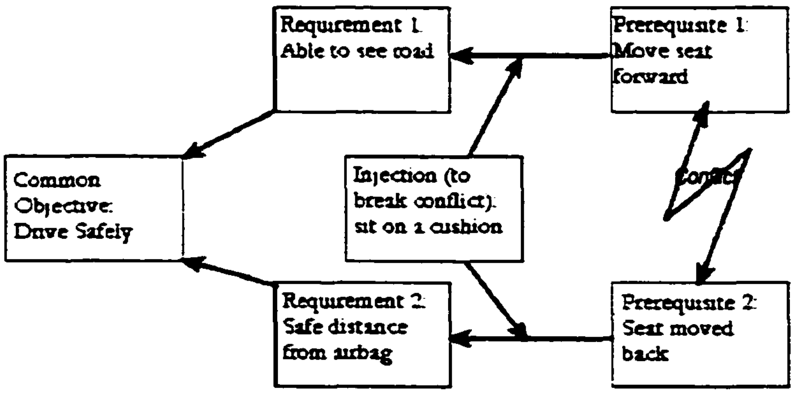


Figure 4. Example of Current Resolution Diagram for Airbag Problem

- Future Reality Tree (FRT). A Future Reality Tree is a tool of TOC that answers the question- "what does the system need to change to?" A Future Reality Tree postulates the effects that a change (injection) would have on a current system. It can be drawn by changing an "Undesirable Event" in a CRT to a "Desirable Event" with the addition of some change called an injection. Below is an illustration from the Airbag example (note this is not a solution suggested in Chapter 4):

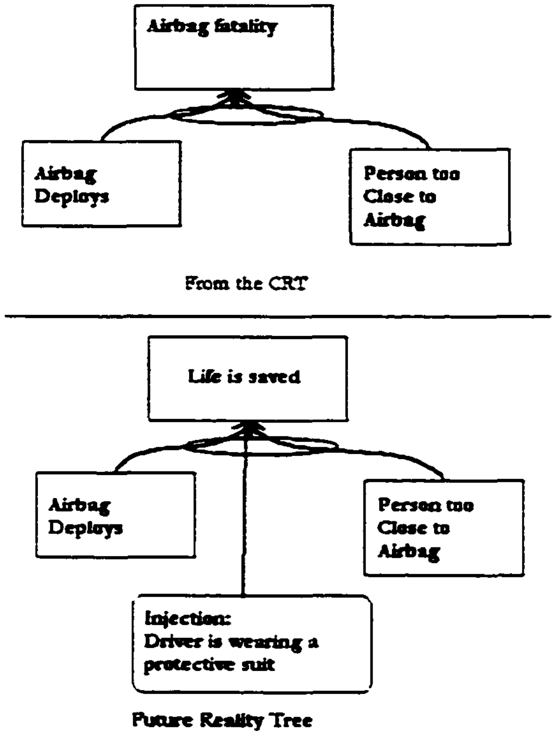


Figure 5. Example of a Future Reality Tree

- Prerequisite Tree (PRT). A prerequisite tree is another tool of TOC that answers the question- "what does the system need to change to?" It is comprised of objectives, Intermediate Objectives and Obstacles. Each Objective is shown to be comprised of Intermediate Objectives, and the relationship between Intermediate Objective and Objective is opposed by the Obstacles. Extending the illustration from the FRT above, if we asked a driver to wear a protective suit, then we would expect there would be resistance by the driver to wear the suit. A PRT drawn for this problem may look like this:

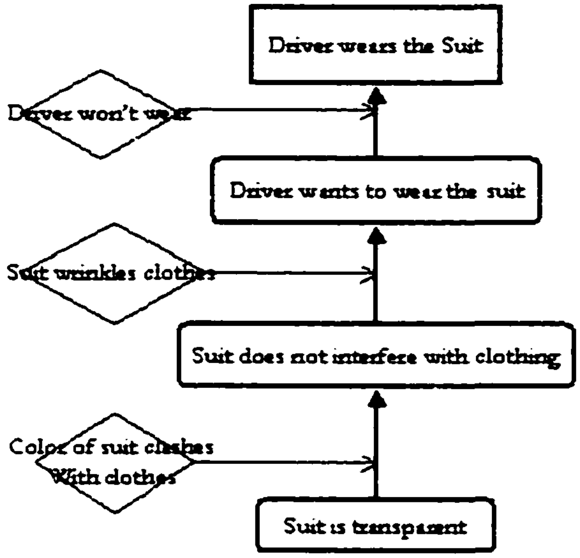


Figure 6. Example of Prerequisite Tree

- Transition Tree (TT). A Transition Tree is a tool of TOC that answers the question, "How should the change be caused?" A Transition Tree shows each desired Effect of a process to be comprised of three things- Reality, Need and Action. **Reality** is a statement about the status quo. **Need** is why an action must be taken. **Action** is what needs to be done in order to change the status quo. Back to the Airbag example- if the desired effect is to increase the distance between the driver and the airbag, a TT could be drawn that looks like this:

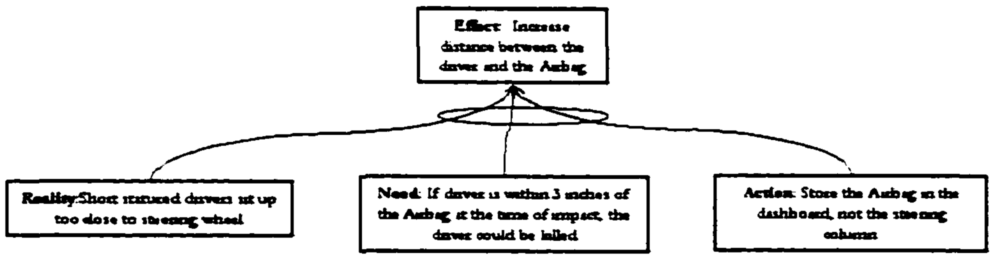


Figure 7. Example of Transition Tree

Finally, Goldratt has identified how we may know what we are improving. For this, Goldratt recommends adopting more meaningful measurements of Throughput (T), Inventory/Investment (I) and Operating Expense (OE). These measurements give a clearer picture of a company's true state than the more familiar Net Profit (NP), Return on Investment (ROI) and Cash Flow (CF). T, OE and I are intrinsically related to Net Profit (NP), Return on Investment (ROI) and Cash Flow (CF).

In terms of overall approach, Goldratt recommends the following priorities:

- Maximize T *first*
- Reduce I *second*

- Reduce OE *third*

Dettmer also demonstrates that projects that are not manufacturing based are hard to define in terms of T, OE and I. Projects are usually measured in terms of Performance, Schedule and Cost:

- Performance- did the deliverable conform to all requirements and specifications?
- Schedule- was it delivered when promised?
- Cost- did it exceed the allowed budget?

Dettmer suggests that the following priorities be used for project management:

- Increase Performance *first.*
- Decrease Schedule *second.*
- Decrease Cost *third.*

2.1.10 TQM- Quantitative and Qualitative methods[47]

The Air Force has published a 42 page manual on TQM[87] tools of quality, including:

2.1.10.1. Qualitative tools for generating ideas:

Brainstorming

Brainstorming is a tool that does not involve analysis. It builds a "shopping list" of ideas about a specific problem or topic. This guide suggests the following steps in brainstorming:

- Write the problem or topic on a blackboard or flipchart where everyone can see it.
- Structured brainstorming gives everyone an equal chance to participate.
- Free-form brainstorming gives everyone an equal chance to participate.
- Switch to silent brainstorming if team members can't resist analyzing the contributions.

The Five "Whys"

Continue asking "why" until the root cause of a problem is revealed.

Mental Imaging

Visualize achieving your goals.

- Relax
- Imagine what would happen if ideal conditions existed
- Assess the current conditions
- Define the gaps- the differences between the current conditions and the ideal conditions
- Identify obstacles that stand between the current state and the ideal state.

2.1.10.1.1. Qualitative tools for decision-making

General guidance-

- Meet in a suitable place.
- Combine items where possible.
- Number each item on the list.

- Base decisions on data.
- Understand the politics and types of decisions.
- No decision- no involvement- the issue is avoided.
- Decision by a powerful minority- (20% involvement)- minority may be only one person; other individual input is not invited.
- Bartering- (40% involvement)- competing powerful individuals or cliques make "trade offs."
- Consultative decision- (50% involvement)- decisions made by powerful individual about the expert opinion.
- Majority vote- (60% involvement)- minimal discussion of minority point of view; the minority concedes.
- Majority rule- (80% involvement)- decision made by minority vote, but minority viewpoints are explored as well.
- Consensus- (100% involvement)- needs and interests of all explored and a unified team solution is developed into an action plan.

Multi-voting

The results of a brain storming session are put into a list. Each member of the group votes for half of the items on the list. The items receiving the most votes receive immediate attention.

Nominal Group Technique

Nominal group technique (NGT) is a structured way to generate and prioritize a list. Here is the process:

- Use a silent brainstorming session to generate ideas.
- Assign a letter to each idea.
- Each member individually prioritizes the ideas; the worst idea receives a score of one, the next better idea receives a score of two and so on.
- Add the totals and the idea with the highest score receives the highest priority.

Pair wise Ranking

This is a structured method to rank a small list of ideas in priority order:

- Construct a pair wise matrix with an intersection of each group of two ideas. For instance, if there are five ideas, it would look like this (the top box represents idea 1 paired with idea 2):

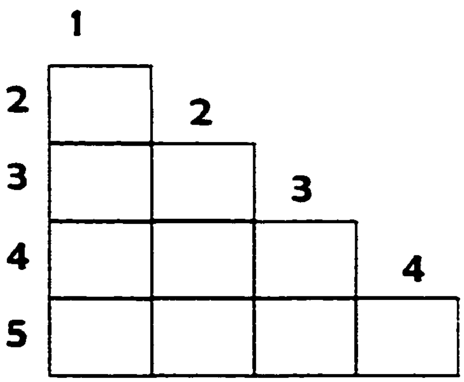


Figure 8. Pair-wise Ranking Matrix

Rank each pair. For each pair, put the number of the one you prefer in each box. For instance, in the example below, 2 is preferred over 1, 1 is preferred over 3, 2 is preferred over 3 and so on:

	1			
2	2	2		
3	1	2	3	
4	1	2	3	4
5	5	5	5	5

Figure 9. Pair-wise Ranking Matrix Example

Count the number of times each alternative appears in the matrix.

Rank all items

Alternative	1	2	3	4	5
Count	2	3	1	0	4
Rank	3rd	2nd	4th	5th	1st

Table 2. Pair-Wise Ranking Example Results

Force Field Analysis

Visualize issues or concepts influencing the problem or goal using force field analysis.

- Define the objective.
- List the forces. Forces are the key factors that promote or hinder success.
- Prioritize each force in terms of its relative impact on the goal.
- Implement by strengthening the forces that promote success and weakening or removing the forces that promote failure.

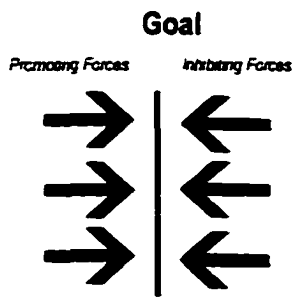


Figure 10. Force Field Analysis Diagram

2.1.10.1.2. Qualitative tools for process analysis

Flowchart

A flowchart shows how a whole process works from start to finish and identifies critical phases of a process. The steps to construct a flowchart are:

- Identify the process and its start and finish points.
- Describe the current process using the standard flowchart symbols.
- Chart the ideal process.
- Search for improvement opportunities. Find areas that hinder or add little or no value. Identify feedback loops. Look for areas where the ideal process differs from the current process.
- Update the chart.

Affinity diagram

An affinity diagram takes verbal information and organizes it into a visual pattern. It starts with specific ideas and moves to more broad categories. Affinity diagrams can help identify key areas needing improvement.

- Cluster the ideas into related groups.
- For each group, create and affinity card that has a short statement describing the entire group of ideas.
- Cluster related cards- create groups of affinity cards then create affinity cards for those groups. Keep doing this until the groups become too broad to make sense.
- Create an affinity diagram.

Cause-and-effect diagram

This diagram examines the relationships between a given outcome and the factors influencing the outcome. It moves from the general to the more specific.

- Specify the problem to analyze.
- List the major categories of factors influencing the effect being studied (use the four "Ps" policies, procedures, plant and people).
- Identify the factors and sub factors.
- Identify the significant factors.
- Prioritize the list of causes.

Thematic content analysis

Thematic content data is used to find patterns in raw data. It uses information from questionnaires, interviews and surveys.

2.1.10.1.3. Quantitative tool for process analysis

Pareto chart

Pareto charts are used to identify the few most significant causes of a problem.

- Identify the possible problems.
- Use existing reports or collect new data on the process. Count the number of occurrences for each possible cause.

- Label the chart.
- Plot the data.

2.1.10.1.4. Quantitative tools for the analysis of process data:

Check sheet

- Helps collect data easily
- Converts raw data into useful information

Histogram

- Displays the underlying distribution of a process
- Illustrates the total variability in the process

Scatter diagram

- Shows relationship between variables
- Identifies possible causes of problems

Run chart

- Shows changes in a process over time
- Helps recognize abnormal behavior in a process

Box plot

- Shows center point and variation of a set of scores
- Can be displayed repeatedly to show trend

Control chart

- Gives a detailed look at trends and variation
- Shows changes in a process over time
- Includes process driven control limits

Process capability ratio

- Links control charts to customer requirements
- Relates process variability to tolerance requirements

2.1.11 TRIZ[1, 2, 4, 88-93]

Tools of Classical TRIZ [2] is a handbook for classical TRIZ. It contains the following chapters:

Patterns of Evolution of Technological Systems.

According to Altshuller[1, 20] technological systems evolve according to certain patterns. Altshuller developed eight patterns of technical evolution.

1. Stages of evolution of the technological system
2. Evolution toward increased ideality
3. Non-Uniform development of system elements
4. Evolution toward increased dynamism and controllability

5. Increased complexity followed by simplification
6. Evolution with matching and mismatching elements
7. Evolution toward micro-levels and increased use of fields
8. Evolution toward decreased human involvement

ARIZ

ARIZ is a Russian Acronym for the Algorithm of Inventive Problem Solving. It was designed, developed and modified by Altshuller. Each version of ARIZ[90, 92] is followed by the last two digits of the year of revision. *Tools of Classical* TRIZ[90] contains Altshuller's final work, ARIZ-85. There have been subsequent changes made by those who came after him. ARIZ-85 has nine parts:

1. Analyzing the Problem
2. Analyzing the Problem Model
3. Formulating the Ideal Ultimate Result and Physical Contradiction
4. Mobilizing and Utilizing Substance-Field Resources
5. Applying the Knowledge Base
6. Changing or Substituting the Problem
7. Analyzing the Method for Resolving the Physical Contradiction
8. Capitalizing on the Solution Concept
9. Analyzing the Problem Solving Process

Contradiction Table.

Altshuller defined 39 system characteristics as being the most often associated with technical contradictions (design trade-offs). The contradiction table is a 39 x 39 matrix of all the characteristics on the rows and columns. To use it, first look up the characteristic you wish to improve and go to its appropriate row. Next, locate the column of the characteristic that degrades as a result. Where the row and column intersect are numbers that correspond to the forty inventive principles. The 39 characteristics are listed below:

1. Weight of moving object
2. Weight of stationary object
3. Length of moving object
4. Length of stationary object
5. Area of moving object
6. Area of stationary object
7. Volume of moving object
8. Volume of stationary object
9. Speed
10. Force (Intensity)
11. Stress or pressure
12. Shape
13. Stability of the object's composition
14. Strength

15. Duration of action of moving object
16. Duration of action by stationary object
17. Temperature
18. Illumination intensity
19. Use of energy by moving object
20. Use of energy by stationary object
21. Power
22. Loss of Energy
23. Loss of substance
24. Loss of Information
25. Loss of Time
26. Quantity of substance/matter
27. Reliability
28. Measurement accuracy
29. Manufacturing precision
30. Object-affected harmful factors
31. Object-generated harmful factors
32. Ease of manufacture
33. Ease of operation
34. Ease of repair
35. Adaptability or versatility
36. Device complexity
37. Difficulty of detecting and measuring
38. Extent of automation
39. Productivity

40 Inventive Principles

Based on Altshuller's patent research, he defined 40 general inventive principles[88, 93] for the resolution of technical contradictions:

1. Segmentation
2. Taking out
3. Local quality
4. Asymmetry
5. Merging
6. Universality
7. "Nested doll"
8. Anti-weight
9. Preliminary anti-action
10. Preliminary action

11. Beforehand cushioning
12. Equipotentiality
13. 'The other way round'
14. Spheroidality - Curvature
15. Dynamics
16. Partial or excessive actions
17. Another dimension
18. Mechanical vibration
19. Periodic action
20. Continuity of useful action
21. Skipping
22. "Blessing in disguise" or "Turn Lemons into Lemonade"
23. Feedback
24. Intermediary
25. Self-service
26. Copying
27. Cheap short-living objects
28. Mechanics substitution
29. Pneumatics and hydraulics
30. Flexible shells and thin films
31. Porous materials
32. Color changes
33. Homogeneity
34. Discarding and recovering
35. Parameter changes
36. Phase transitions
37. Thermal expansion
38. Strong oxidants
39. Inert atmosphere
40. Composite materials

Separation Principles

In order to resolve physical contradictions (a characteristic is self-opposing), Altshuller recommends using separation principles:

1. Separation of opposite requirements in space;
2. Separation of opposite requirements in time;
3. System transition 1a- combining homogeneous or heterogeneous systems into a super-system;
4. System transition 1b- transition from a system to an anti-system or to a combination of system and anti-system;

5. System transition 1c- the whole system has a property, *C*, while its parts have a property, *anti-C*;
6. System transition 2- transition to a system that works on the micro-level;
7. Phase transition 1- changing the phase state of a part of a system or of its environment;
8. Phase transition 2- Dynamic phase state of a system part;
9. Phase transition 3- Utilization of phenomena associated with phase transitions;
10. Phase transition 4- Replace a mono-phase substance with a dual phase state substance;
11. Physical-Chemical transition- substance creation/elimination as a result of composition/decomposition, ionization/recombination.

Substance-Field Analysis

Substance-Field (also called "Su-Field" or "S-Field") Analysis is a TRIZ analytical tool for building functional models for problems related to existing or new technological systems. Substances may be materials, tools, parts, people or environments. Fields may be mechanical, thermal, chemical, electrical or magnetic.

System of Standard Solutions

Five classes of 76 standard solutions are offered. The classes are:

Class 1. Building and destroying Su-field models

Class 2. Enhancing Su-field models

Class 3. Transition to the Super-system and Micro-levels

Class 4. Standard Solutions for Detection and Measurement

Class 5. Standards for Applying the Standard Solutions

Technical Effects and Phenomena

To use these, you look up your objective from a list of 29 objectives. Once you locate your objective, you look it up on a table of physical effects. The table of physical effects lists several effects that have been used to solve similar problems. The effects themselves are listed alphabetically after the table of physical effects. The 29 objectives are:

Objective 1. Measure Temperature

Objective 2. Decrease Temperature

Objective 3. Increase Temperature

Objective 4. Stabilize Temperature

Objective 5. Detect an object's position and movement

Objective 6. Control an Object's movement

Objective 7. Control Liquid and Gas Movement

Objective 8. Control flows of aerosols

Objective 9. Move mixtures, create solutions

Objective 10. Separate mixtures

Objective 11. Stabilize an object's position

Objective 12. Create/control force, create high pressure

Objective 13. Control friction

Objective 14. Destroy an object

Objective 15. Accumulate mechanical and thermal energy

Objective 16. Transfer energy

Objective 17. Establish interaction between moving and stable objects.

Objective 18. Measure an object's dimensions

Objective 19. Modify an object's dimensions

Objective 20. Check the state and features of a surface

Objective 21. Modify surface features

Objective 22. Check the state and features of the volume of a substance

Objective 23. Modify an object's volume features

Objective 24. Create and stabilize an object's structure

Objective 25. Detect electrical and magnetic fields

Objective 26. Detect radiation

Objective 27. Create radiation

Objective 28. Control electromagnetic fields

Objective 29. Control light

And Suddenly the Inventor Appeared[89] is a book written for children studying physics and chemistry (from 6th grade through high school). It does not cover all of the forty principles or ARIZ or Su-Field analysis in great depth. It takes inventive problems and illustrates their solutions by teaching a few principles at a time. The 27 "methods, effects and tricks" used in this book are different than the other lists of TRIZ because it is designed to get children started in TRIZ, not to be an exhaustive discussion.

Creativity as an Exact Science[1] is a difficult translation to read. It covers the motivation of Altshuller in developing TRIZ methodologies, the principles of Su-Field analysis, mechanisms for eliminating contradictions, discussion of talented thought processes, the forty inventive principles, evolution of systems and the strategy and science of invention. In the appendix is ARIZ-77, some of the standard solutions and an index of physical effects.

40 Principles: TRIZ Keys to Technical Innovation[48] is a discussion of each of the forty principles and an application of the contradiction matrix. This version of the contradiction matrix is handy for solving problems because it lists all 40 inventive solutions and all 39 characteristics on each sheet.

An Introduction to TRIZ: The Russian Theory of Inventive Problem Solving[4] is a short description of the essential TRIZ in clear English. It covers technological evolution, the forty inventive solutions, the contradiction matrix, Su-Field analysis, resolution of physical contradictions and a little Ideation-TRIZ. It is a good reference to become acquainted with the basics of TRIZ, although it is inadequate to solve problems in any depth and does not contain a copy of ARIZ in any form.

In "Advanced TRIZ Developments at the Leonardo DaVinci Institute,"[72] Kowalick explains his company's introduction to TRIZ in the 1980s and then discusses some problems with the application of TRIZ in the United States along with his company's efforts to address these problems. The problems he found with TRIZ are copied below.

"AREA # 1. PROBLEM-SOLVING ALGORITHMS. The current algorithm used by the TRIZ community is "ARIZ" -Algorithm for the Solution of Inventive Problems. ARIZ is periodically upgraded and refined by the

Russian TRIZ community. Reactions by American engineers attempting to use this algorithm have generally been negative. ARIZ is long and cumbersome, time-consuming to learn and far from "user-friendly." It is narrowly focused, aiming at "the best" design solution. It does not offer many, if any, design alternatives.

AREA # 2. FUNCTIONAL LANGUAGE. "Su-Fields" is the functional language used in TRIZ to describe generic relationships among essential "objects" and "actions" in the technical system. "Substance-Field" (also called "S-Field" and "Su-Field") models are used to describe generic problem situations as well as generic solution situations. The TRIZ community has generated a large Su-Field database. The core of this database is a collection of "standard solutions" - relationships between standard generic problems (expressed as Su-Field models) and standard generic solutions (also expressed as Su-Field models). Seventy standard solutions have been identified. The main problem with Su-Fields is that they are not complete. They inadequately express and describe engineering functions. Users of the TRIZ approach - particularly new users - find it difficult to create Su-Field models that validly describe objects and actions of their technical systems. Su-Fields have always "suffered" from being incompletely developed.

Kowalick prefers to work with "triads" instead of substance fields. Triads seem more intuitive, but Substance fields are more familiar to engineers who have had to solve problems in Statics and Dynamics. The important issue is to be able to find a technique that is easy enough to use that it will not be summarily dismissed.

AREA #3. FUNCTIONAL DECOMPOSITION. To some limit, a function can be divided or "decomposed" into sub-functions that occur sequentially. This fact is well known and is a practice used in traditional value analysis/value engineering (VA/VE). The result is a "Functional tree diagram" describing the functions of a technical system. TRIZ and other problem-solving practitioners currently use Su-Field analysis, functional analysis and flow-charting techniques to describe functional relationships among parts of a technical system. The generation of functions (and goal statements connected with them) is, however, still a subjective process. This process is not conducive to developing a better understanding of a problem situation. The process inadequately assists problem solvers who want to quickly hone in on the right problem definition.

AREA #4. TRIZ INSTRUCTION AND TRAINING. Initially the only TRIZ training available in the west was from TRIZ practitioners from the former USSR. A severe language problem still prevents effective communication. There are also cultural problems. With a few exceptions, TRIZ providers from the former USSR do not understand the needs of western companies. Too often, their "style of service" has included customer intimidation (sometimes involving legal threats or litigation about intellectual property) and a lack of customer consciousness. One former USSR TRIZ provider is on record as stating that "total quality" practices are unimportant. Another problem: TRIZ as taught in the former USSR is too often presented in a strictly "academic" way. One former USSR practitioner recently stated, "It takes twenty years to learn TRIZ." Yet, engineers from Western companies want to be able to use and apply TRIZ to real problems and to obtain design solutions in several days. The number of Western consultants and trainers who offer TRIZ training and consulting is limited. Among these, only three (in the author's opinion) are capable of actually applying the TRIZ approach - during a training session - to real problems. There are also national security considerations connected with the use of non-citizen consultants and with firms who employ non-citizen TRIZ practitioners.

AREA #5. TRIZ FOR ELEMENTARY SCHOOLS, HIGH SCHOOLS and UNIVERSITIES.

Kowalick wants to incorporate TRIZ training into US education.

AREA #6. BIOMEDICAL AND PHARMACEUTICAL TRIZ APPLICATIONS.

This is a report of the success Kowalick has experienced in this field.

AREA #7. TRANSLATION INTO ENGLISH OF TRIZ ARTICLES FROM OTHER LANGUAGES. Many of the older TRIZ books written in Russian and published in the former USSR, are obsolete or outdated. There are, however, recent TRIZ books, articles and reports from various countries (former USSR countries, Israel, the Netherlands, Germany, etc.) on current applications and advanced developments. Until recently, this information was unavailable in English.

AREA #8. ACCELERATED PROBLEM SOLVING. Little effort has been made by the TRIZ community to accelerate the problem solving process. In part, this is because of the fragmentation that has occurred in the former-USSR TRIZ community. Many former USSR practitioners have moved to other countries. The population of TRIZ organizations in countries of the former USSR has steadily decreased. There is minimal organized effort to advance the TRIZ approach (with the possible exception being in the area of invention software). Even with invention software, the role of TRIZ has been significantly de-emphasized.

Barkan[91] discusses the basic problem formulation steps that are necessary in any problem solving process. "Situation analysis- a must first step in a problem solving process" is very clear and useful in helping to define the necessary steps to complete a process. First, he states that a project process involves the following five steps:

- Recognize a need: state the functional requirements clearly
- Generate ideas on how to fulfill the need
- Develop viable concepts based on generated ideas
- Perform design based on the concepts
- Implement the design

Next, Barkan develops his basic problem solving model, which consists of three steps:

- Organize the knowledge about the system/situation
- Develop a functional model of the system/situation
- Analyze the model for problem solving ideas.

Although this article was found in a TRIZ journal, its concepts are useful whether or not TRIZ is used. His general framework is useful in creating a model that encompasses ideas from the many models in the technical literature today.

2.1.11.1. TRIZ Theory of Technical Evolution

2.1.11.1.1. Classical TRIZ Approach[94-101]

Slocum [100] and Mann[97] discuss the method that TRIZ uses to identify the potential for design improvement using S-curves. (Note: "S" refers to the shape of the curve). The method suggested is to develop four curves from existing data and compare the shape of the four curves to Altshuller's S-curves. The four curves are:

1. Performance Vs. Time
2. Number Of Inventions Vs. Time

3. Level Of Invention Vs Time And
4. Profitability Vs. Time

Slocum used data from patent activity of self-heating container technology. He presents curves for this technology, but the curves do not exhibit any of Altshuller's prescribed trends. He, therefore, concludes that the technology, although at least 23 years old, is still in the infancy stage and is ripe for improvement. As a case in point, the author demonstrates that the level of performance over time is subjective and depends on the arbitrary measure the analyst uses- he uses two different measures and obtains different results. The number of inventions vs. time is a hard measurement to obtain because it requires going through millions of patents in different languages around the world. Patents are not generally cross-referenced in a way that facilitates this kind of search, either. The level of invention vs. time cannot be accurately reported because of the level of subjectivity in the analyst's assignment of level of invention and because of the potential mix of different levels in a given data point. Profitability vs. time is the easiest to interpret, but it is impossible to know when the profitability has reached a peak until designers are actually replacing the design with another design of a system that subordinates it.

Slocum shows several fundamental flaws with TRIZ as it is currently practiced. First, Altshuller's curves describe the evolution of systems in general but do not prescribe the potential for improvement in particular. Slocum is trying to use TRIZ as a shortcut to find where designs can be improved and is using the market as an indication of whether ideas are mature or not. Unfortunately, evolution of systems cannot be translated from the macro level. It is a good idea to look at the descriptors to see how things are evolving in a given design evolution, but a mistake to use the data as a primary motivation for pursuing design.

In another article[101], Slocum demonstrates the predictive theory of S-curve Descriptors using hermetic technology. Although the theory appears sound on the macroscopic level, it is very hard to establish on the microscopic level and still does not appear to be as prescriptive as Slocum would like for us to believe. When he is done with presenting charts that do not appear to exhibit the features he claims that they do, he announces that he has discovered this technology to be in the decline stage after full maturity and that the market is now ready for new design ideas and technology.

Mann[97] uses a case analysis of refrigerant compressions to analyze S-curves. His conclusions are reproduced below (wording changed slightly to reflect American spellings of words):

1. TRIZ metrics for assessing the relative maturity of a technology have been successfully applied to gage the maturity of the refrigerant compressor industry.
2. The metrics can often be difficult or even impossible to calculate accurately. In either event, the process of analyzing a given industry sector can be both arduous and time consuming.
3. Use of simpler metrics like 'cost reduction' or 'symptom curing' patents may offer quicker, qualitative assessment measures.
4. Product maturity knowledge is an important business metric. Companies need to know how mature their technology is.
5. They also need to know whether the technology has the ability to jump to new S-curves through step change innovations.
6. TRIZ-predicted trends of evolution provide very potent means of making this kind of assessment.

7. Knowledge that a step change improvement is possible then gives rise to an optimization versus innovation R&D strategic decision.
8. Most companies opt for 'optimization.'
9. 'Optimizing' companies eventually get put out of business by 'innovating' companies.

In Mann's article[96], "The (predictable) evolution of useful things," he reviews *The Evolution of Useful Things* by Professor Henry Petroski. In the article, Mann draws several parallels with TRIZ theory and Petroski's work. Some of his conclusions follow:

1. Many useful things follow the TRIZ concept of evolution from mono-system to bi-system to poly-systems. The evolutions of the fork and of clothing fasteners are tendered as examples.
2. The notion of "form follows function" is misleading. For many objects, it is not function that drives new design but rather inadequacies in the current design, a desire for fashion or a need to follow the current and future trends. Mann refers to these trends as "form follows failure," "form follows fashion" and "form follows where the future leads."

Fey[94] demonstrates that transition is rarely smooth but does move in a predictable fashion. "Transition from solid structures to fragmented or finely dispersed media is one of the prevailing trends of evolution of technological systems." Fey demonstrated the predictable fashion by dividing the technological system into four segments: engine, transmission, control means and working means. The results were the following conclusions:

"Evolution of technological systems along the lines of increasing fragmentation is associated with a conflict: To enhance the system's primary function, the system's working means should make a transition to the micro-level; however, this transition may generate a wave of undesirable effects in the overall system.

"This conflict is resolved by non-uniform evolution of the principle parts of a system: first, the engine and transmission start transition to the micro-level and then the working means undergo the radical micro-level transformations.

"Transition of the engine and the transmission to the micro-level proceeds through specific phases. These phases, when put together, form a line of increasing fragmentation (or line of transition to the micro-level).

"While using the line for conceptual development of next-generation products, the law of shortening of energy flow path and the rule for identifying the name of physical effects can be beneficially used."

Frenklach[95] states that when two or more systems are joined, they create a super-system. When a super-system is the result of a combination of a system and its anti-system, it becomes a very powerful tool capable of control, stabilization and dynamization. Frenklach also provides an algorithm to achieve construction of a super-system:

- Determine the function of a system.
- Determine the anti-function and the system that performs it.
- Join together the system and the anti-system.
- Determine the stabilization and dynamic functions of your super-system.
- Determine the field types for the function and anti-function.
- Equate the field types, if necessary.
- Transit to one carrier that performs the functional block.

- Change the field types for the actions to transit from a macro system to a micro system.

Rantanen's "Levels of Solutions"[98] is an expansion of Altshuller's work on the five levels of innovative solution. Rantanen demonstrated that the relative percentage of inventions in the various classes changes over time. Rantanen also points out that knowledge of the innovative level is useful in guiding a solution to higher levels. He states, "TRIZ and tools of TRIZ are based on the selection and study of high level inventions. The evaluation and classification of solutions make it easier to learn and use innovative technology of design." The author also states that the objective is not only to improve products, but also to improve the capability to develop better products.

Rantanen's article, "Polysystem Approach to TRIZ[99]," proposes using TRIZ by considering multiple contradictions and multiple subsystems at one time. The illustration is the development of the bicycle and the author clearly makes his point. Rantanen shows four ways TRIZ can help in polysystem design:

- "*Engineering contradiction* is the contradiction in a bisystem. If we have an engineering contradiction, we always have an alternate system, too. And we have an alternate engineering contradiction."
- "*Physical Contradiction*. If we have the physical contradiction, we have a bisystem. Alternative systems have opposite physical properties."
- "*Ideal Final Result*. Ideal final result is a polysystem of features gotten as the result of successive combination of alternative systems."
- "*ARIZ*. The two pluses formula contains in a hidden form the key concepts of ARIZ. The formula helps to learn and use ARIZ."

The author also goes on to demonstrate that the polysystem approach is simpler when used in the context of Computer Aided Innovation (CAI) and extols the virtues of TechOptimizer for performing polysystem optimization.

2.1.11.1.2. Directed Evolution- Ideation/TRIZ Approach[11, 12, 102]

There are basically three kinds of technological forecasting:

1. Traditional technological forecasting that is based on probabilistic modeling of future characteristics of systems.
2. TRIZ forecasting is based on pre-determined Patterns of Evolution. TRIZ forecasting is distinct from traditional forecasting in that it does not just predict the future; it attempts to control it as well.
3. Directed evolution, developed by Ideation International, takes TRIZ forecasting to a higher level. It adds depth to the patterns of evolution and basically subjugates all invention processes to the idea of directed evolution.

Directed Evolution is based on postulates. (*TRIZ in Progress*[102] lists 11 postulates, which are reproduced below. Bush[11] lists five "main" postulates, which are Postulates 1, 4, 8, 10, respectively plus a fifth, "Market Driven Evolution." Market Driven Evolution is therefore listed here as Postulate 12. In Clarke's "Strategically evolving the future: directed evolution and technological systems development[12]," he lists 5 postulates, 1, 12, 4, 10 and 11.)

Postulate 1. Patterns of evolution

- Based on the study of the history of evolution, typical "correct" evolutionary steps can be identified that represent the line of evolution. Typical evolutionary mistakes can be identified as well.
- Prediction of the future can be replaced by identification of pre-determined future steps on applicable lines of evolution.
- Typical mistakes can be avoided in the future.

Postulate 2. The driving force of evolution

- A system evolves toward greater Ideality.
- Any man-made system can be improved in the direction of enhanced quality and useful functions and/or in the direction of reduced cost and other harmful effects.
- Not every problem can be solved but every situation can be improved.
- A system's evolution depends on the subjective human estimation of what is useful and what is not useful.

Postulate 3. Generation of change combined with selection

Any technological system evolves in such a way that first various ideas are generated that result in system changes or in new systems being built. Later, a selection process is applied by which the best system for satisfying the requirements is chosen.

Postulate 4. Evolution at the expense of resources

- A system's evolution proceeds via the consumption of resources existing in the system itself, its neighboring systems and the system environment.
- In the process of a system's evolution, resource consumption makes it more difficult to mobilize resources.
- A number of sequential transitions to different kinds of resources occur, for example- from readily available to derived resources and from simple resources to "smart" or intellectual resources.

Postulate 5. Excessiveness of an existing system

- The majority of existing technological systems have redundant resources; that is, they have more resources than are necessary to perform their intended function.
- Nearly any "untouched" system may be forced to work more effectively, perform additional functions, etc.

Postulate 6. Co-evolution of different systems

- Different technological systems create resources for one another.
- Different technological systems cause limitations for one another.
- Changes in one technological system can directly or indirectly lead to changes in other, connected systems.
- Feedback relationships might occur between different systems as they evolve.

Postulate 7. Co-evolution of systems belonging to different hierarchical levels

- Systems belonging to different hierarchical levels are tightly connected in their evolution and evolve in coordination with one another.
- A super-system can force its systems or subsystems to evolve according to its own lines rather than allowing them to follow their own lines.
- Limitations that occur in a subsystem might hold back the evolution of the entire system.

Postulate 8. Short versus long-term forecasting

- A system's short-term evolution depends primarily on the system's inherent resources.
- Long-term development, including the emergence of new generations, depends on the evolution of overall technology and/or market rather than on the given system's particulars and resources.
- Short term forecasting based on the given system's trends and on the opinions of experts might be sufficiently accurate.
- Long-term forecasting for a given system must be based on the analysis of the evolutionary trends of the overall technology and market.

Postulate 9. There are a limited number of ways to perform a function

- It is theoretically possible to exhaust all possible ways of performing a given function.
- If all methods of performing a given function are exhausted, then an insurmountable patent fence can be developed.
- In fields where many professionals have been working for a long time and in the presence of competitive pressure, the possibility of further evolution may be nearly exhausted.

Postulate 10. Alternative in evolution

- It is possible to direct the evolution of a system by managing its resources.
- If a specific problem has not been solved to date, there is no guarantee that Ideation/TRIZ methodology will provide one. If there is at least one solution to a problem developed, Ideation/TRIZ can be used to help identify multiple other solutions.
- Any single, patented solution can be circumvented.

Postulate 11. Standard ways to solve problems

- Common ways exist to solve problems or improve a system using the Patterns of Evolution.
- These ways can be revealed via analysis of the history of inventions, allowing innovation knowledge to be collected and transferred.

Postulate 12. Market Driven Evolution

- For complex systems, the market selects from among alternatives based on sociopolitical forces.
- The technologies behind alternatives that were not selected are available as resources for future evolution.

Trends, Patterns and Lines of Evolution

Technical Evolution can be broken down into *trends, patterns* and *lines* of evolution. An *Evolutionary trend* is a sequence of events directly and/or indirectly connected through cause-effect relationships. Each event leads to the next one and thus increases the probability of its emergence.

Trends are easily recognizable through a historical analysis of the evolution of specific systems. The following limitations on trends apply:

- Real evolution is a result of numerous trends and is not simply the "sum" of these trends.
- Multiple trends are usually connected through complex and non-linear relationships.
- Similar trends may look different and lead to different results, depending on the situation.
- A specific trend does not stay forever, but rather has its own life cycle.
- Each trend has inertia and remains for some time after the conditions under which it originated have changed.
- Each trend has its own, often unclear reasons and mechanisms. At the same time, similar mechanisms may be responsible for different trends, while similar trends may be caused by different mechanisms.
- Evolutionary trends are usually driven by feedback mechanisms. The fact that a specific trend already exists helps for it to continue to exist.
- Every trend has its own "weight" or "power" associated with the number of people involved and the strength of the involvement. The trend's power may change over time following changes in the overall situation.
- Two opposite trends may co-exist.

Altshuller offered a next generation of forecasting tools: a system of patterns and lines of evolution as the result of logical analysis and the generalization of available trends. The *Patterns of Evolution* represent a compilation of trends that document strong historically recurring tendencies in the development of manmade or natural systems. Once identified, these patterns have predicting power and thus constitute the theoretical base of the TRIZ methodology.

The first set of *patterns* of technological Evolution were discovered and described by Altshuller in the mid-1970s:

1. Completeness of the engineered system
2. Energy flow in the engineered system
3. Harmonization of the synchronization rhythms or parts in an engineered system
4. Increasing ideality of an engineered system
5. Non-uniform evolution of subsystems constituting an engineered system
6. Transition to the overall system
7. Transition from macro- to micro-level in the engineered system
8. Increasing the substance-field involvement
9. Stages of evolution (infancy, growth, maturity and decline)
10. All systems evolve according to the s-curve.

Altshuller's work was continued by the Kishinev TRIZ School and later continued by the Ideation Research Group. The resulting revision, restructuring and extension of this work produced the following set of Patterns of Technological Evolution (Clarke lists the first 8 in his work):

1) Evolution toward increased ideality
    - Every system performs functions that generate useful effects and harmful effects.
    - The general direction for system improvement maximizes ideality as determined in the marketplace.
    - The creation and selection of inventive solutions is based on efforts to improve the level of market ideality.
2) Non-uniform development of systems elements
    - Each system component has its own s-curve.
    - Different components usually evolve according to their own schedules.
    - Different system components reach their inherent limits at different times resulting in contradictions.
    - The component that reaches its limit first can hold back the overall system.
    - The elimination of contradictions allows the system to improve.
3) Evolution toward increased dynamism and controllability
    - Increasing system dynamism and controllability allows functions to be performed with greater flexibility or variety.
4) Evolution toward increased complexity followed by simplification
    - Technological systems tend to develop first toward increased complexity and then toward simplification.
5) Evolution with matching and mismatching elements: system elements are matched or mismatched to improve performance or to compensate for undesired effects. A typical sequence of evolution would be:
    - Unmatched elements
    - Matched elements
    - Mismatched elements
    - Dynamic matching and mismatching
6) Evolution toward micro-levels and the increased use of fields
    - Technological systems tend to transition from macro systems to micro systems. During this transition, different types of energy fields are used to achieve better performance or control.
7) Evolution toward decreased human involvement
    - Systems develop to perform tedious functions, thus freeing people to do more intellectual work.
8) Evolution toward increased involvement of resources

After the initial lines of evolution were developed, more detailed descriptions, called *lines* were identified. *Lines of Evolution* show typical sequences of stages that a system follows in the process of its evolution. Typically, a pattern includes multiple lines. The Ideation Research group has identified over 300 lines for technology and over 50 lines for market evolution, providing an individual or enterprise with powerful prediction tools.

The following Lines of Evolution are reproduced from *TRIZ in Progress*:

9) Lines of Evolution: Structural
   - Line of evolution of models
   - Line of evolution of models for harmful effects
   - Line of evolution of models of insufficient functions

10) Lines of Evolution: System
   - Line of transition to the micro-level
   - Line of increasing degrees of freedom
   - Line of increasing the amount of performed functions
   - Line of modifying stable states
   - Line of increasing controllability
   - Line of sequence of matching and mismatching
   - Line of changing the type of matching in the system
   - Line of changing the type of mismatching in the system
   - Line of matching of rhythms
   - Line of building and developing bi-systems
   - Line of building and developing poly-systems
   - Line of sequence of simplification
   - Line of transition to a reticular system
   - Additional lines

11) Lines of Evolution: Substance
   - Adding new substances
   - Line of adding substances in different physical conditions
   - Line of using resources at different levels of an object's structure
   - Line of matching of substances
   - Line of shifting of matching substances
   - Line of mismatching of substances

12) Lines of Evolution: Field
   - Line of main tendencies in the use of fields
   - Line of using fields in the evolution of a technological system

13) Lines of Evolution: Process
   - Line of increasing the level of process controllability
   - Line of changing the type of process
   - Line of controlling the process using flows

- Line of utilizing time resources
- Line of controlling the space of a process
- Line of involving the environment
- Line of controlling the process by changing the medium

14) Specific Lines of Evolution

- Special line of evolution for models of measurement systems
- Special line of using informational resources
- Special line of matching the work piece to the tool
- Special line of a tool's evolution
- Special line of simplification of manufacturing process
- Special line of matching the rhythms between transporting and processing

Steps of Directed Evolution

TRIZ in Progress[102], Clarke[12] and Bush[11] provide basic processes to apply directed evolution. Although Bush's formulation is slightly different, they all basically consist of the following steps:

Step 1. Analyze the system's evolution to date.

Step 2. Develop potential scenarios for future evolution.

Step 3. Define directions and make decisions.

Step 4. Structure intellectual capital.

Step 5. Prepare an action plan and support implementation.

The Stages of the classical S-curve

Stage 0- a system does not yet exist but important conditions for its emergence are developing.

Stage 1- a new system appears due to a high-level invention and begins development slowly.

Stage 2- begins when society recognizes the value of the new system.

Stage 3- begins when the resources on which the original system is based are mostly exhausted.

Stage 4- begins when a new system (or the next generation of the current system) emerges to replace the existing one.

Stage 5- begins if the new system does not completely replace the existing system, which still has limited application.

Deviations from the classical S-curve

There are two notable deviations from the classical S-curve:

The Crocodile Back- caused by difficulties in transitioning from Stage 1 to Stage 2. In it, there are a series of unsuccessful attempts followed by a successful one. The reasons for the unsuccessful attempts are usually either because the system is launched before it is ready for commercial use and sale or because the market is not ready to accept the new system.

False Third Stage- due to one of the following:

- A serious roadblock has not been overcome.
- There is a lack of competition and thus there is little need for improvement.

- A sub-system has reached a "dead end" and is holding the entire system evolution.
- Premature aging has occurred as a result of organizational decisions.

2.1.11.2. TRIZ- Ideal Final Result[103-105]

Rantanen[103] discusses the need to think in a different way in order to solve problems. He points out that TechOptimizer software generates alternatives in many areas where an individual could be stuck. The conclusion of the article is "don't improve quality, don't cut costs and don't decrease the time to market… instead… increase the innovative power of the company."

Domb[104] defines and expounds upon the definition of the Ideal Final Result, or IFR. The IFR is used to define and bound a problem statement before trying to identify the solution. The IFR asks the questions, "What do you want?" and "What would be the ideal situation if you had solved the problem?" Without an IFR, a sub optimal design solution based on incorrect perceptions of real needs may evolve.

According to Domb, "the IFR has the following 4 characteristics:

- Eliminates the deficiencies of the original system.
- Preserves the advantages of the original system.
- Does not make the system more complicated (uses free or available resources)
- Does not introduce new disadvantages."

Using the IFR helps a designer to

- "Encourage breakthrough thinking
- Inhibit moves to less ideal solutions (reject compromises)
- Lead to the discussions that will clearly establish the boundaries of the project."

IFR is an enabling tool that enables the designer to realize the full potential of TRIZ methods.

The heart of application of TRIZ problem solving techniques is a problem statement that includes the identification of technical and physical contradictions and the ideal final result. If you start with a problem that asks why a certain behavior occurs, then it is very difficult to develop a proper problem statement. Frenklach identifies such a problem as a diagnostic problem and he solves it with TRIZ by first transforming it into an inventive problem of the form "How can we obtain the result?"

Domb's article, "Using the Ideal Final Result to define the problem to be solved[105]," is a further elaboration of Domb's tutorial on IFR of February 1997. This article moves from the IFR to ask questions to move toward the solution of problem at hand. To do this, Domb cites five questions used in ARIZ:

- "What is the final aim?
- What is the ideal final result?
- What is the obstacle to this?
- Why does this interfere?
- Under what conditions would the interference disappear? What resources are available to create these conditions?"

IFR helps to eliminate prejudice and premature sub-optimal solutions to problems while focusing design effort on the real problem. IFR works well with both traditional TRIZ and Ideality.

2.1.11.3. TRIZ- Contradictions[93, 106-109]

Royzen[109] provides an overview of TRIZ and how it works. The author explains the concept of inventive principles and the contradiction matrix and explains how they are used. The author refers to ARIZ as the standard form of TRIZ problem solving, although he does not define it in detail. The author also refers to sixteen standard techniques that can be used to shorten the ARIZ process, but he does not provide the actual techniques.

The point of this paper is to introduce the strength of TRIZ. The strength is that TRIZ does not seek to design by making trade-offs but rather designs by eliminating contradictions. Its radical approach ensures faster and more reliable design changes if it is followed properly.

Altshuller's contradiction matrix is a 39 by 39 matrix in which a feature[93] to be optimized is selected from the rows on the left and a feature that may have to be sacrificed is found in the columns on the top. Domb's article is an excellent companion to the matrix because it defines each of the 39 features.

Mann[107] demonstrates that TRIZ is not to be regarded as a panacea to remove all contradictions from all problems. Instead, TRIZ is rightly regarded either as a discrete contradiction resolution or as a continuous one. A discrete contradiction resolution is one that removes the present contradiction, but invariably it introduces new contradictions or compromises.

A continuous solution is one where the original compromise is not removed, but the new design places the design on a new curve in which the trade-off is less severe.

If TRIZ is seen as a method to improve contradiction trades instead of to eliminate them, then the practice of TRIZ can be seen to be a journey in which one moves along contradiction chains towards continuous improvement.

Domb's article, "Using Analogies to Develop Breakthrough Concept[106]," is a short article used to explain how to use analogies to solve problems. In teaching, Domb instructs students to use the tools of TRIZ to find an inventive principle and then to take the inventive principle and draw the substance-field associated with its analogies or examples. Next, the practitioner is instructed to draw his own problem's Su-Field by mirroring the one used in the analogy.

In response to Domb's article on analogies[110], Rantanen[108] describes how there may be two systems that solve the same problem but made different trade-offs. (For example, a mechanical watch trades the desirable "no battery" characteristic with the undesirable "complex system" characteristic. It's complement, a Quartz watch, is simple but requires a battery.) In order to optimize, take the useful effect of both systems and combine them. (In our example, a quartz watch without batteries, either solar powered or self- winding.)

2.1.11.4. TRIZ- 40 Inventive Principles[110, 111]

Tate and Domb's "40 Inventive Principles With Examples"[110] is a reference article. It takes each of the 40 inventive principles, subdivides them and provides a familiar example of an invention that uses each one. The article is so important and useful that it is reproduced in its entirety below:

40 Inventive Principles With Examples

Principle 1. Segmentation

Divide an object into independent parts.

Replace mainframe computer by personal computers.

Replace a large truck by a truck and trailer.

Use a work breakdown structure for a large project.

Make an object easy to disassemble.

Modular furniture

Quick disconnect joints in plumbing

Increase the degree of fragmentation or segmentation.

Replace solid shades with Venetian blinds.

Use powdered welding metal instead of foil or rod to get better penetration of the joint.

Principle 2. Taking out

Separate an interfering part or property from an object or single out the only necessary part (or property) of an object.

Locate a noisy compressor outside the building where compressed air is used.

Use fiber optics or a light pipe to separate the hot light source from the location where light is needed.

Use the sound of a barking dog, without the dog, as a burglar alarm.

Principle 3. Local quality

Change an object's structure from uniform to non-uniform; change an external environment (or external influence) from uniform to non-uniform.

Use a temperature, density or pressure gradient instead of constant temperature, density or pressure.

Make each part of an object function in conditions most suitable for its operation.

Lunch box with special compartments for hot and cold solid foods and for liquids

(Part C continued on the next page.)

Make each part of an object fulfill a different and useful function.

Pencil with eraser

Hammer with nail puller

Multi-function tool that scales fish, acts as a pliers, a wire stripper, a flat-blade screwdriver, a Phillips screwdriver, manicure set, etc.

Principle 4. Asymmetry

A. Change the shape of an object from symmetrical to asymmetrical.

Asymmetrical mixing vessels or asymmetrical vanes in symmetrical vessels improve mixing (cement trucks, cake mixers, blenders).

Put a flat spot on a cylindrical shaft to attach a knob securely.

If an object is asymmetrical, increase its degree of asymmetry.

Change from circular O-rings to oval cross-section to specialized shapes to improve sealing.

Use astigmatic optics to merge colors.

Principle 5. Merging

Bring closer together (or merge) identical or similar objects; assemble identical or similar parts to perform parallel operations.

Personal computers in a network

Thousands of microprocessors in a parallel processor computer

Vanes in a ventilation system

Electronic chips mounted on both sides of a circuit board or subassembly

Make operations contiguous or parallel; bring them together in time.

Link slats together in Venetian or vertical blinds.

Medical diagnostic instruments that analyze multiple blood parameters simultaneously

Mulching lawnmower

Principle 6. Universality

Make a part or object perform multiple functions; eliminate the need for other parts.

Handle of a toothbrush contains toothpaste

Child's car safety seat converts to a stroller

Mulching lawnmower (Yes, it demonstrates both Principles 5 and 6, Merging and Universality.)

Team leader acts as recorder and timekeeper.

CCD (Charge coupled device) with micro-lenses formed on the surface

Principle 7. "Nested doll"

Place one object inside another; place each object, in turn, inside the other.

Measuring cups or spoons

Russian dolls

Portable audio system (microphone fits inside transmitter, which fits inside amplifier case)

Make one part pass through a cavity in the other.

Extending radio antenna

Extending pointer

Zoom lens

Seat belt retraction mechanism

Retractable aircraft landing gear stow inside the fuselage (also demonstrates Principle 15, Dynamism)

Principle 8. Anti-weight

To compensate for the weight of an object, merge it with other objects that provide lift.

Inject foaming agent into a bundle of logs to make it float better.

Use helium balloon to support advertising signs.

To compensate for the weight of an object, make it interact with the environment (e.g. use aerodynamic, hydrodynamic, buoyancy and other forces).

Aircraft wing shape reduces air density above the wing, increases density below wing, to create lift. (This also demonstrates Principle 4, Asymmetry.)

Vortex strips improve lift of aircraft wings.

Hydrofoils lift ship out of the water to reduce drag.

Principle 9. Preliminary anti-action

If it will be necessary to do an action with both harmful and useful effects, this action should be replaced with anti-actions to control harmful effects.

Buffer a solution to prevent harm from extremes of pH.

Create beforehand stresses in an object that will oppose known undesirable working stresses later on.

Pre-stress rebar before pouring concrete.

Masking anything before harmful exposure: Use a lead apron on parts of the body that will not be exposed to X-rays. Use masking tape to protect the part of an object not being painted.

Principle 10. Preliminary action

. Perform, before it is needed, the required change of an object (either fully or partially).

Pre-pasted wallpaper

Sterilize all instruments needed for a surgical procedure on a sealed tray.

Pre-arrange objects such that they can come into action from the most convenient place and without losing time for their delivery.

Kanban arrangements in a Just-In-Time factory

Flexible manufacturing cell

Principle 11. Beforehand cushioning

Prepare emergency means beforehand to compensate for the relatively low reliability of an object.

Magnetic strip on photographic film that directs the developer to compensate for poor exposure

Back-up parachute

Alternate air system for aircraft instruments

Principle 12. Equipotentiality

In a potential field, limit position changes (e.g. change operating conditions to eliminate the need to raise or lower objects in a gravity field).

Spring loaded parts delivery system in a factory

Locks in a channel between 2 bodies of water (Panama Canal)

"Skillets" in an automobile plant that bring all tools to the right position (also demonstrates Principle 10, Preliminary Action)

Principle 13. 'The other way round'

Invert the action(s) used to solve the problem (e.g. instead of cooling an object, heat it).

To loosen stuck parts, cool the inner part instead of heating the outer part.

Bring the mountain to Mohammed, instead of bringing Mohammed to the mountain.

(Part B continued on the next page.)

Make movable parts fixed and fixed parts movable.

Rotate the part instead of the tool.

Moving sidewalk with standing people

Treadmill (for walking or running in place)

Turn the object (or process) 'upside down.'

Turn an assembly upside down to insert fasteners (especially screws).

Empty grain from containers (ship or railroad) by inverting them.

Principle 14. Spheroidality - Curvature

Instead of using rectilinear parts, surfaces or forms, use curvilinear ones; move from flat surfaces to spherical ones; from parts shaped as a cube (parallelepiped) to ball-shaped structures.

Use arches and domes for strength in architecture.

Use rollers, balls, spirals and domes.

Spiral gear (Nautilus) produces continuous resistance for weight lifting.

Ballpoint and roller point pens for smooth ink distribution

Go from linear to rotary motion, use centrifugal forces.

Produce linear motion of the cursor on the computer screen using a mouse or a trackball.

Replace wringing clothes to remove water with spinning clothes in a washing machine.

Use spherical casters instead of cylindrical wheels to move furniture.

Principle 15. Dynamics

Allow (or design) the characteristics of an object, external environment or process to change to be optimal or to find an optimal operating condition.

Adjustable steering wheel (or seat, or back support, or mirror position...)

(Part B continued on the next page.)

Divide an object into parts capable of movement relative to each other.

The "butterfly" computer keyboard, (also demonstrates Principle 7, "Nested doll.")

If an object (or process) is rigid or inflexible, make it movable or adaptive.

The flexible boroscope for examining engines

The flexible sigmoidoscope for medical examination

Principle 16. Partial or excessive actions

If 100 percent of an object is hard to achieve using a given solution method then, by using 'slightly less' or 'slightly more' of the same method, the problem may be considerably easier to solve.

Over spray when painting, then remove excess. (Or, use a stencil—this is an application of Principle 3, Local Quality and Principle 9, Preliminary anti-action).

Fill, then "top off" when filling the gas tank of your car.

Principle 17. Another dimension

Move an object in two- or three-dimensional space.

Infrared computer mouse moves in space, instead of on a surface, for presentations.

Five-axis cutting tool can be positioned where needed.

Use a multi-story arrangement of objects instead of a single-story arrangement.

Cassette with 6 CD's to increase music time and variety

Electronic chips on both sides of a printed circuit board

Employees "disappear" from the customers in a theme park, descend into a tunnel and walk to their next assignment, where they return to the surface and magically reappear.

Tilt or re-orient the object; lay it on its side.

Dump truck

Use 'another side' of a given area.

Stack microelectronic hybrid circuits to improve density.

Principle 18. Mechanical vibration

Cause an object to oscillate or vibrate.

Electric carving knife with vibrating blades

Increase its frequency (even up to the ultrasonic).

Distribute powder with vibration.

Use an object's resonant frequency.

Destroy gallstones or kidney stones using ultrasonic resonance.

Use piezoelectric vibrators instead of mechanical ones.

Quartz crystal oscillations drive high accuracy clocks.

Use combined ultrasonic and electromagnetic field oscillations.

Mixing alloys in an induction furnace

Principle 19. Periodic action

Instead of continuous action, use periodic or pulsating actions.

Hitting something repeatedly with a hammer

Replace a continuous siren with a pulsed sound.

If an action is already periodic, change the periodic magnitude or frequency.

Use Frequency Modulation to convey information, instead of Morse code.

Replace a continuous siren with sound that changes amplitude and frequency.

Use pauses between impulses to perform a different action.

In cardio-pulmonary respiration (CPR) breathe after every 5-chest compressions.

Principle 20. Continuity of useful action

Carry on work continuously; make all parts of an object work at full load, all the time.

Flywheel (or hydraulic system) stores energy when a vehicle stops, so the motor can keep running at optimum power.

Run the bottleneck operations in a factory continuously to reach the optimum pace. (From theory of constraints, or take time operations)

Eliminate all idle or intermittent actions or work.

Print during the return of a printer carriage—dot matrix printer, daisy wheel printers and inkjet printers.

Principle 21. Skipping

Conduct a process, or certain stages (e.g. destructible, harmful or hazardous operations) at high speed.

Use a high-speed dentist's drill to avoid heating tissue.

Cut plastic faster than heat can propagate in the material to avoid deforming the shape.

Principle 22. "Blessing in disguise" or "Turn Lemons into Lemonade"

Use harmful factors (particularly, harmful effects of the environment or surroundings) to achieve a positive effect.

Use waste heat to generate electric power.

Recycle waste (scrap) material from one process as raw materials for another.

Eliminate the primary harmful action by adding it to another harmful action to resolve the problem.

Add a buffering material to a corrosive solution.

Use a helium-oxygen mix for diving, to eliminate both nitrogen narcosis and oxygen poisoning from air and other nitrox mixes.

Amplify a harmful factor to such a degree that it is no longer harmful.

Use a backfire to eliminate the fuel from a forest fire.

Principle 23. Feedback

Introduce feedback (referring back, cross-checking) to improve a process or action.

Automatic volume control in audio circuits

Signal from gyrocompass is used to control simple aircraft autopilots.

Statistical Process Control (SPC) -- Measurements are used to decide when to modify a process.

(Not all feedback systems are automated!)

Budgets—Measurements are used to decide when to modify a process.

If feedback is already used, change its magnitude or influence.

Change sensitivity of an autopilot when within 5 miles of an airport.

Change sensitivity of a thermostat when cooling vs. heating, since it uses energy less efficiently when cooling.

Change a management measure from budget variance to customer satisfaction.

Principle 24. 'Intermediary'

Use an intermediary carrier article or intermediary process.

Carpenter's nail set, used between the hammer and the nail

Merge one object temporarily with another (which can be easily removed).

Potholder to carry hot dishes to the table

Principle 25. Self-service

Make an object serve itself by performing auxiliary helpful functions

A soda fountain pump that runs on the pressure of the carbon dioxide that is used to "fizz" the drinks. This assures that drinks will not be flat and eliminates the need for sensors.

Halogen lamps regenerate the filament during use—evaporated material is redeposited.

To weld steel to aluminum, create an interface from alternating thin strips of the 2 materials. Cold weld the surface into a single unit with steel on one face and copper on the other, then use normal welding techniques to attach the steel object to the interface and the interface to the aluminum. (This concept also has elements of Principle 24, Intermediary and Principle 4, Asymmetry.)

Use waste resources, energy or substances.

Use heat from a process to generate electricity: "Co-generation."

Use animal waste as fertilizer.

Use food and lawn waste to create compost.

Principle 26. Copying

Instead of an unavailable, expensive, fragile object, use simpler and inexpensive copies.

Virtual reality via computer instead of an expensive vacation

Listen to an audiotape instead of attending a seminar.

Replace an object or process with optical copies.

Do surveying from space photographs instead of on the ground.

Measure an object by measuring the photograph.

Make sonograms to evaluate the health of a fetus, instead of risking damage by direct testing.

If visible optical copies are already used, move to infrared or ultraviolet copies.

Make images in infrared to detect heat sources, such as diseases in crops or intruders in a security system.

Principle 27. Cheap short-living objects

Replace an inexpensive object with a multiple of inexpensive objects, comprising certain qualities (such as service life, for instance).

Use disposable paper objects to avoid the cost of cleaning and storing durable objects. Plastic cups in motels, disposable diapers, many kinds of medical supplies.

Principle 28 Mechanics substitution

Replace a mechanical means with a sensory (optical, acoustic, taste or smell) means.

Replace a physical fence to confine a dog or cat with an acoustic "fence" (signal audible to the animal).

Use a bad smelling compound in natural gas to alert users to leakage, instead of a mechanical or electrical sensor.

Use electric, magnetic and electromagnetic fields to interact with the object.

To mix 2 powders, electrostatically charge one positive and the other negative. Either use fields to direct them, or mix them mechanically and let their acquired fields cause the grains of powder to pair up.

Change from static to movable fields, from unstructured fields to those having structure.

Early communications used omni directional broadcasting. We now use antennas with very detailed structure of the pattern of radiation.

Use fields in conjunction with field-activated (e.g. ferromagnetic) particles.

Heat a substance containing ferromagnetic material by using varying magnetic field. When the temperature exceeds the Curie point, the material becomes paramagnetic and no longer absorbs heat.

Principle 29. Pneumatics and hydraulics

Use gas and liquid parts of an object instead of solid parts (e.g. inflatable, filled with liquids, air cushion, hydrostatic, hydro-reactive).

Comfortable shoe sole inserts filled with gel

Store energy from decelerating a vehicle in a hydraulic system and then use the stored energy to accelerate later.

Principle 30. Flexible shells and thin films

Use flexible shells and thin films instead of three-dimensional structures.

Use inflatable (thin film) structures as winter covers on tennis courts.

Isolate the object from the external environment using flexible shells and thin films.

Float a film of bipolar material (one end hydrophilic, one end hydrophobic) on a reservoir to limit evaporation.

Principle 31. Porous materials

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

Drill holes in a structure to reduce the weight.

If an object is already porous, use the pores to introduce a useful substance or function.

Use a porous metal mesh to wick excess solder away from a joint.

Store hydrogen in the pores of a palladium sponge (Fuel "tank" for the hydrogen car—much safer than storing hydrogen gas).

Principle 32. Color changes

Change the color of an object or its external environment.

Use safe lights in a photographic darkroom.

Change the transparency of an object or its external environment.

Use photolithography to change transparent material to a solid mask for semiconductor processing. Similarly, change mask material from transparent to opaque for silkscreen processing.

Principle 33. Homogeneity

Make objects interacting with a given object of the same material (or material with identical properties).

Make the container out of the same material as the contents to reduce chemical reactions.

Make a diamond-cutting tool out of diamonds.

Principle 34. Discarding and recovering

Make portions of an object that have fulfilled their functions go away (discard by dissolving, evaporating, etc.) or modify these directly during operation.

Use a dissolving capsule for medicine.

Sprinkle water on cornstarch-based packaging and watch it reduce its volume by more than 1000X!

Ice structures: use water ice or carbon dioxide (dry ice) to make a template for a rammed earth structure, such as a temporary dam. Fill with earth, then, let the ice melt or sublime to leave the final structure.

Conversely, restore consumable parts of an object directly in operation.

Self-sharpening lawn mower blades

Automobile engines that give themselves a "tune up" while running (the ones that say "100,000 miles between tune ups")

Principle 35. Parameter changes

Change an object's physical state (e.g. to a gas, liquid or solid).

Freeze the liquid centers of filled candies and then dip in melted chocolate, instead of handling the messy, gooey, hot liquid.

Transport oxygen or nitrogen or petroleum gas as a liquid, instead of a gas, to reduce volume.

Change the concentration or consistency.

Liquid hand soap is concentrated and more viscous than bar soap at the point of use, making it easier to dispense in the correct amount and more sanitary when shared by several people.

Change the degree of flexibility.

Use adjustable dampers to reduce the noise of parts falling into a container by restricting the motion of the walls of the container.

Vulcanize rubber to change its flexibility and durability.

Change the temperature.

Raise the temperature above the Curie point to change a ferromagnetic substance to a paramagnetic substance.

Raise the temperature of food to cook it. (Changes taste, aroma, texture, chemical properties, etc.)

Lower the temperature of medical specimens to preserve them for later analysis.

Principle 36. Phase transitions

Use phenomena occurring during phase transitions (e.g. volume changes, loss or absorption of heat, etc.).

Water expands when frozen, unlike most other liquids. Hannibal is reputed to have used this when marching on Rome a few thousand years ago. Large rocks blocked passages in the Alps. He poured water on them at night. The overnight cold froze the water and the expansion split the rocks into small pieces, which could be pushed aside.

Heat pumps use the heat of vaporization and heat of condensation of a closed thermodynamic cycle to do useful work.

Principle 37. Thermal expansion

Use thermal expansion (or contraction) of materials.

Fit a tight joint together by cooling the inner part to contract, heating the outer part to expand, putting the joint together and returning to equilibrium.

If thermal expansion is being used, use multiple materials with different coefficients of thermal expansion.

The basic leaf spring thermostat: (2 metals with different coefficients of expansion are linked so that it bends one way when warmer than nominal and the opposite way when cooler.)

Principle 38. Strong oxidants

Replace common air with oxygen-enriched air.

Scuba diving with Nitrox or other non-air mixtures for extended endurance

Replace enriched air with pure oxygen.

Cut at a higher temperature using an oxy-acetylene torch.

Treat wounds in a high-pressure oxygen environment to kill anaerobic bacteria and aid healing.

Expose air or oxygen to ionizing radiation.

Use ionized oxygen.

Ionize air to trap pollutants in an air cleaner.

Replace ozonized (or ionized) oxygen with ozone.

Speed up chemical reactions by ionizing the gas before use.

Principle 39. Inert atmosphere

Replace a normal environment with an inert one.

Prevent degradation of a hot metal filament by using an argon atmosphere.

Add neutral parts or inert additives to an object.

Increase the volume of powdered detergent by adding inert ingredients. This makes it easier to measure with conventional tools.

Principle 40. Composite materials

Change from uniform to composite (multiple) materials.

Composite epoxy resin/carbon fiber golf club shafts are lighter, stronger and more flexible than metal. Same for airplane parts.

Fiberglass surfboards are lighter and more controllable and easier to form into a variety of shapes than wooden ones.

Williams and Domb's "Reversibility of the 40 principles of problem solving"[111] is a very simple and profound paper. Every one of the 40 principles of problem solving can be reversed. The authors point out that some of the reverses are already found in TRIZ (symmetric) and some are not (asymmetric). The author states that the asymmetric complements may not be inventive in nature. Note that the premise of DFMA, for instance, is that a more complex part is better than a less complex part if it reduced the total number of parts. Such an approach is a complement to the TRIZ principle 27 (**Principle 27. Cheap short-living objects** - Replace an inexpensive object with a multiple of inexpensive objects, comprising certain qualities (such as service life, for instance). *Use disposable paper objects to avoid the cost of cleaning and storing durable objects. Plastic cups in motels, disposable diapers and many kinds of medical supplies*) such an approach was originally thought to be in contradiction to the theory of TRIZ.

TRIZ principle 13 is "the other way around," and the authors apply this idea to TRIZ itself.

2.1.11.5. TRIZ- ARIZ[112]

Marconi[112] presents the ARIZ algorithm in a way that is visual and easier to follow than the standard ARIZ questionnaire. In her version, she uses a flow chart for the overall process and "knowledge maps" for each set up sub steps. She also adds notes for clarification. She hasn't changed ARIZ much, but she has made it more usable.

2.1.11.6. TRIZ- Effects[113, 114]

Frenklach[113] classifies technical effects in terms of the object to be transformed and the field by which it is transformed. The transformation may be qualitative, meaning it changes from one state to a new state or it may be quantitative, meaning that a descriptive property is changed, like a raise in temperature. Once these operators are defined, the inventor must pose questions relating to how to achieve the desired effect, how to eliminate undesirable side effects, how to control the effect and the development of the substance, how to measure the effect and what other effects may be associated with the effect.

Rantanen[114] listed eleven applications of effects:

- Effects databases as a smart encyclopedia
- Evolution trends and effects
- Functional analysis and effects
- Engineering contradiction and effects
- Physical contradiction and effects
- Forty principles and effects
- The resources of the system and effects
- Standard solutions and effects
- Feature transfer and effects
- Effects databases as a knowledge organizer
- Ideal final result and effects

2.1.11.7. TRIZ- Operators[115-117]

In "Efficient Use of the System Operator[115]," Frenklach demonstrates the use of a system operator. To create a system operator, first create a table, conceptualize the system in its past, present and future contexts and also conceptualize the system as a component of a greater super-system and a super-system to various subsystems.

Undesirable effect (UDE) System Operators	Subsystem	System	Super-system
Past	Effect of past UDE on subsystem, possibly precipitating changes to subsystems.	Past UDE that caused the present one.	Effect of past UDE on the past super-system.
Present	Effect of the UDE on subsystems.	Describe the UDE in the present system.	Effect of present UDE on the Super-system.

Future	Effect of the new UDE on subsystems.	New UDE that will emerge when the present one is eliminated	Projected effect of the new UDE on the super-system.

Table 3. System Operators

In "Efficient Use of the DTC Operator[116]," Frenklach states, "the DTC (dimensions, time, cost) operator is aimed at breaking the psychological stereotypes which are connected with an object to be improved." This operator was developed by Altshuller and discussed in *Creativity as an Exact Science*[1]. In order to use the operator, try to think of your problem with each of these factors carried to an extreme-

- What if the size of the system was increased without bound or decreased to subatomic levels?
- What would happen if the operation of the system was sped up to a nanosecond or expanded to a million years?
- What would happen if the system were free or priceless?
- As with the system operator, these parameters can also be considered for the super-system or the subsystem.

Savransky[117] enumerates more contradictions for consideration. The classical TRIZ contradictions are first defined and discussed (technical and physical). Next, Savransky defines and discusses the following contradictions:

1. Mathematical contradictions- these arise in the context of automated control. Savransky describes a system of equations that is inconsistent. ($a + b = x$, $a + b = y$, $a \neq b$).
2. Natural Contradictions
   - Fundamental physical laws- absolute zero and the speed of light
   - Cosmological contradictions- related to Earth- you cannot have a pure hydrogen exhaust, for instance.
3. Human Contradictions
   - Individual- human limitations, lack of memory, fear of failure
   - Managerial- time management limitations, decision-making and leadership styles
   - Organizational- working within the corporate framework
   - Cultural- prejudice to change, Western versus Eastern views of goals

Resistance to change is therefore defined as a type of human contradiction- we expect more profits, but we don't want to do anything different. When introducing a new idea, it is a good idea to identify this contradiction and resolve it. If TRIZ experts only deal with technical and physical contradictions, they may have a hard time working with others or within organizations.

2.1.11.8. TRIZ- Case Studies[118-124]

Mann[118] has been given a problem to solve and he solves it using TRIZ. He discusses how one approaches a problem with TRIZ and demonstrates that there is room for even more improvement. He shows that a careful construction of an IFR not only shows the ideal (if unobtainable) solution, but also can be used to decide how close to the IFR one can travel, by tracing back the path to present methods from the IFR. He not only solved the present problem, but also offered a better solution that would not work within the confines of his problem statement.

The problem was for a competition so he could not change it to suit a larger need. The problem, as stated, was twofold:

1. Design a new, failsafe wheel locking nut system that can be readily used for high speed wheel changes during a formula one race.
2. Design a failsafe device that locks the wrench to the nut until an automatic locking mechanism is activated, which would prevent the nut from coming off the axle.

Mann discusses the formulation of an Ideal Final Result (IFR) for this problem. His IFR is to change the system to one that does not require wheel changes. Such a solution may more appropriately concentrate on tire design than nut design. However, in the absence of such a solution, a better self-locking nut is a good start.

Mann discusses several possible current methods of securing nuts and posits that the most likely three methods are a Nyloc nut, a Claveloc nut or an airtight nut. Altshuller would have removed Nyloc immediately from consideration because it introduces a foreign substance. Mann demonstrates that all three have a fundamental problem in that they lose their locking properties with repeated use.

Having dispensed with these methods, Mann turned to the Inventive principle of merging- finding a nut that acts as if it were two nuts in a double jam configuration. After identifying this possible solution, he discovered such a hybrid nut in Illinois Tool Works, patented in 1997. This nut would obviate the need for a failsafe mechanism because it does not degrade with use, but the author was confined to the competition problem formulation.

In this case, the author did not have to design but merely discover a design presently in existence. Had the author designed a new nut or a new tire-lug-nut system, he would have had to do more than merely buy a nut out of a catalog. He clearly has delineated the approach he would recommend to obtain such a solution but was unable to develop it in the time constraints of his project. This article was a very informative application of TRIZ principles to real problems.

In his second case study[119], Mann begins by defining the problem of bicycle seat design as an attempt to compromise between the need for support and the need for freedom of movement. The design is therefore very narrow so that the bicyclist may peddle without chafing his legs. The problem is that it is very uncomfortable to sit on a narrow seat. Mann points out that the design of a bicycle seat is an example of design compromise. A fundamental principle of TRIZ is that compromises are to be avoided.

In TRIZ, the technical contradiction is that the seat must be ***wide*** in order to be comfortable, but it must be ***narrow*** in order to allow freedom of movement. Using Altshuller's contradiction matrix, the thing to be improved is the "length of a Stationary Object" and the thing that tends to worsen is the "Shape." The contradiction matrix suggests a design that uses one of the four inventive principles:

- The other way around
- Curvature increase
- Dynamic Parts, or

- Nested Doll

Mann combined the idea from "the other way around" to "make moveable parts fixed and fixed parts moveable" with an idea of "dynamic parts" to "divide an object into parts capable of moving relative to each another." The resulting design is a seat with two moveable parts that move with the bicyclist's legs, a design found from ABS Sports.

This is a good example of how TRIZ works, but Mann designed nothing. The design from ABS sports already existed and he merely recommended it. Had Mann the resources to optimize a design, he could have taken the idea from ABS sports and worked with its rotational axis, contours and interior mechanisms to create the ideal bicycle seat configuration. RSM would be an excellent resource to create a much better design, given that TRIZ had already identified the general form of the design.

In a third case study[120], Mann provides another idea of how to apply a TRIZ principle to an existing problem. After applying the discipline of TRIZ, Mann discovers an available solution. The problem is that flanged joints in large engine casings are exposed to high temperature and pressure and thus require a large number of bolts. Maintenance on these engines is complicated because all the bolts must be removed and they may be difficult to remove because of the property changes metal experiences when exposed to heat over time.

Mann identifies the Technical contradiction as "there must be a large number of bolts to seal the flange" and "there must be few bolts for ease of maintenance and weight reduction." Using Altshuller's contradiction Matrix, we are trying to improve the following:

- The weight of a stationary object
- Ease of operation
- Device Complexity

When we do improve these things, the following things tend to worsen:

- Stability
- Reliability

From the matrix, the following inventive principles are suggested:

- Another dimension
- Taking out
- Flexible shells and thin films

Mann chose the first and found a patented flange that used fewer bolts because one side of the flange was curved away causing greater tension. Mann did not optimize the design further. He could have spent some time defining the right angle of curvature, the right metal composition of bolts and the right bolthole geometry for maximum seal with minimum bolts. He also could have discussed the design of the nuts and bolts, using the self-locking bolt he unearthed in April of 1999. He does not offer design optimization because TRIZ has finished with the design when it solves the basic form of the solution.

Helicopter engines deliver a great deal of power and are extremely sensitive to contamination[121]. For this reason, helicopter engines are fitted with an inlet protection device. The inlet protection devices in use today were first developed in the mid-1970s and have changed very little since then. The physical contradiction inherent in this design lies in the fact that the dust removal duct area must be large enough to trap the maximum amount of dust, and it must also be small enough to minimize the amount of wasted air pumped through it. A second physical contradiction is that the air duct must be large to allow the most air to pass through the engine, and it must be small to minimize the potential for dust and minimize the overall weight of the design.

Mann attempted two TRIZ methods to solve this problem. First, he attempted to formulate a technical contradiction and use it to look up potential inventive principles. For this, he used the *area of the stationary object* (6) as the attribute to improve and the *length of the stationary object* (4) as the attribute that worsens. Such a problem formulation provides for the following inventive principles:

- 26 (Copying)
- 7 (Nesting)
- 9 (Prior Counteraction)
- 39 (Inert Environment)

None of these principles yielded useful results. Instead, Mann began applying others of the 40 principles and finally found a satisfactory solution in 13 (Do it in reverse). From this experience, Mann concludes that the contradiction matrix is not a panacea, and it is often better simply to scan the inventive principles without consulting the contradiction matrix.

However, if Mann had chosen "weight of a stationary object" as the worsening attribute, he would have found the following technical inventive principles:

- 30 (Flexible films or thin Membranes)
- 2 (Extraction)
- 14 (Spheroidality)
- 18 (Mechanical Vibration)

The point is that what seemed like an arbitrary decision resulted in very different results. There may be several possible inventive solutions from these ideas.

In addition, if a technical contradiction is thought of as a trade-off, then when "A" worsens, "B" is improved and conversely when "B" worsens, "A" improves. This would lead one to believe that the possible solutions garnered from a technical matrix could be improved if the coordinates were transposed. In this case, consider the improving characteristic as "weight of the stationary object" and the worsening feature as the "area of the stationary object," the suggested innovative principles are now:

- 35 (Transformation Properties)
- 30 (Flexible films or membranes)
- 13 (Do it in reverse)
- 7 (Nesting)

Observe that even Mann's solution is found in this list. Therefore, the lesson of this exercise might not be randomly to peruse all forty-innovation principles, but rather to seek other contradictions and their compliments until one can be found that yields satisfactory results.

"Windshield/Backlight Molding: Squeak and Buzz Project"[122] is about a problem that has emerged in the last ten years. Windshields make a squeaking sound when the molding lip edge transitions between sticking and slipping against the sheet metal, and they make a buzzing sound when subject to a cross wind at speeds in excess of 55 mph. The problem was solved by a large team of engineers from Ford Motor Company and presented at the American Supplier Institute Total Product Development Symposium in November of 1997.

The article discusses the evolution of several different possible solutions to the squeak and buzz problem of the windshield using various TRIZ inventive principles, although the authors may never have performed a Su-Field analysis or used a contradiction matrix. Most of the generated solutions addressed either the squeak problem or the buzz problem and there appeared to be a trade-off between the two characteristics until a final solution was offered at the end.

The following solutions were offered:

1. Allow the molding to slip by applying lubrication, thus eliminating squeak. Since the lubrication is expensive and wears off, make the lubrication a part of the rubber molding. This is the TRIZ principle of transition from the macro level to the micro level.
2. Use a high-density polyethylene and thermo-plastic olefins, or a fluorine treatment to molding to reduce friction and eliminate squeak.
3. Prohibit motion of the molding by sealing it to the windshield, using either a rolling lip (which worsens buzzing), a solid glue (like that used on envelopes), a non-marking glue (like that used on Post-it ® notes), magnetic molding or by melting the molding to the window.
4. Flutter or buzzing can be reduced by changing the shape of the molding to make the aerodynamic effect to hold it down towards the windshield instead of pulling it away from the windshield (TRIZ principle of working in reverse).
5. Stiffen the molding to prevent buzz.
6. Soften the molding to prevent squeak.

The final solution offered was to create a composite material that was softer in the tangential direction and stiffer in the lift-off direction. This is not difficult with proper fiber placement. Such a design would accomplish both objectives. In addition, the material used would allow lubrication while shape could reverse the aerodynamic effect. No adhesion is necessary.

The point of using TRIZ in an exercise such as this one is that it allows the designer to generate a number of possible solutions quickly and therefore decrease development time. It also allows the designer to avoid making the mistake of trading one problem for another.

Killander[123] presents another case study of the use of TRIZ. The author had to create a power source for houses in remote sections of Sweden capable of generating 20 W per hour without the use of a generator. He chose the iron woodstove as his energy source and used TRIZ to identify a method to convert the thermal energy to electrical energy.

The TRIZ concept he used is called the Peltier/Seebeck effect, and he located it using an index of physical effects. A path to this particular effect could not be found in *Creativity as an Exact Science*[1] or in *Tools of Classical TRIZ*[90]. However, a description of the Peltier effect is reproduced below[124]:

"In 1834, J. C. A. Peltier discovered that if an electric current is passed through homogenous conductors, the heat developed is distributed evenly; however, if the two conductors are of different chemical composition, an additional heat is developed (or absorbed) where the conductors join."

"The Peltier effect is used in the construction of cooling machines (where heating is combined with the Joule-Lenz effect). As in the case of the Seebeck effect, greater efficiency is achieved if the heterogeneous materials are semiconductors rather than metals, because the value of the Peltier coefficient in semiconductors is greater than that of metals."

The Seebeck effect[125], the work of Thomas Johann Seebeck (1770 - 1831), refers to the appearance of a thermo-emf in an electric circuit composed of heterogeneous conductors, with contacts that have different temperatures. The conductors are connected in series. The temperature difference causes a flow of electrons in the conductors, said flow being directed from the hot end to the cold one. In the point of the conductors' contact, a potential difference occurs. The magnitude of thermo-emf depends on the material of the conducts, contact temperature and does not depend on the temperature distribution along the conductors. The thermoelectric ability of the couple is evaluated by the Seebeck coefficient which lies for different materials with the range from +43 to -38 mcV/deg."

NASA uses a similar use of the Seebeck effect[126]. "In the 1960's, the NASA expanded a number of Seebeck's theories for use in space programs. His work in thermocouples was used to help create a mechanism to provide continuous power to measurement instruments left on the moon by the Apollo program. The Seebeck co-efficient has been used to provide temperature measurement in creating a "Seebeck event." These measurements have been used extensively in the MEPHISTO program that is part of the Shuttle Program in a joint program sponsored by the United States and France."

There is a handbook devoted to the thermo-electric effects discussed in this article on the Internet. If one wishes to design a power source for an application such as this, it is a valuable resource. TRIZ provided the information needed to look for the correct effect. Here is the information on the handbook from the website[124]:

"Description:

"Thermoelectrics is the science and technology associated with thermoelectric converters, that is, the generation of electrical power by the Seebeck effect and refrigeration by the Peltier effect. Thermoelectric generators are being used in increasing numbers to provide electrical power in medical, military and deep space applications where combinations of their desirable properties outweigh their relatively high cost and low generating efficiency. In recent years there also has been an increase in the requirement for thermoelectric coolers (Peltier devices) for use in infrared detectors and in optical communications. Information on thermoelectrics is not readily available as it is widely scattered throughout the literature. The Handbook centralizes this information in a convenient format under a single cover.

"Sixty of the world's foremost authorities on thermoelectrics have contributed to this Handbook. It is comprised of fifty-five chapters, a number of which contain previously unpublished material. The contents are arranged in eight sections: general principles and theoretical considerations, material preparation, measurement of thermoelectric properties, thermoelectric materials, thermoelectric generation, generator applications, thermoelectric refrigeration and applications of thermoelectric cooling. The CRC Handbook of Thermoelectrics has a broad-based scope. It will interest researchers, technologists and manufacturers, as well as students and the well-informed, non-specialist reader."

2.1.11.9. TRIZ- Psychological Inertia[127]

Domb[127] uses the popular time management parable where a jar is filled with large rocks but is not full because smaller rocks, gravel and even water can be added to it. When the leader asks what the moral of the parable is, a student says that no matter how full your schedule, there is always room for one more thing. The instructor then corrects the student to say that the moral is- if you don't put the 'big rocks' in your jar first, you'll never have room for them at all. Metaphorically, if you don't make room for important things in your schedule, then you'll never have room for anything but trivia.

Domb uses the parable to illustrate two kinds of psychological inertia to be overcome- authoritarianism and subject matter specialization.

"Authoritarianism" is at work because the instructor is telling the class that their definition of "full" is faulty and only his definition is valid. The class' creativity in problem solving is quashed by the instructor's analysis of the problem. They therefore "learn" by repeating the expert's words, not by performing their own analyses.

"Subject Matter Specialization" is at play because the class is conditioned to find a moral with time management at its root simply because the question was framed in the context of a class on time management. Therefore the title of the class, "Time Management," created a subject matter bias and set up the environment for psychological inertia.

2.1.11.10. TRIZ- Ideation[13, 128-132]

Zlotin and Zusman[13] discuss the modern application of TRIZ as practiced by Ideation International. The authors, Zlotin and Zusman, took the foundation laid by Altshuller and brought it to another level. In doing so, they established two useful computer programs to aid the inventor in the application of TRIZ concepts, Problem Formulator™ and Knowledge Wizard™. Their summary and conclusions are reproduced below:

"The definitions of an innovation knowledge base and its value levels were presented; these were used to support the strategy chosen for development of the Ideation knowledge-based tools, with the focus on Integrated System of Operators and the Lines of Evolution.

"A new approach based on the hybridization (combination) of two alternative approaches to the development of an innovation knowledge base can result in a breakthrough informational technology.

"Changing the problem statement is very often a key to success. The problem formulation process and Problem Formulator™ software tool allow the user to obtain a set of nearly exhaustive problem statements and thus help him/her unveil promising, non-obvious approaches.

"A graphical model (functional graph, event diagram, knowledge map) built with the help of the Problem Formulator or Knowledge Wizard™ reflect the natural structure of knowledge stored in the human brain and serves as one of the best ways to transfer and/or utilize knowledge for the creativity process.

"The system comprising the "graphical model and the formulation module" provides the "translation" from the functional or cause-effect description of a situation into a new type of description – called the problem description – allowing each problem statement to be automatically connected and thus its own knowledge base be obtained for further consideration."

Changing the problem is indeed an important step that must be performed before the problem can be solved. Having not seen Ideation's list of 400 operators and 300 lines of evolution, it is hard to know the value these may have in the solution of problems. Increasing the complexity of TRIZ to the level they have necessitates the solution of problems with a computer program and search engine. Their claim that working at a higher level (of abstraction) requires operators to possess the highest degree of TRIZ qualification and experience suggests that this is a step toward greater complexity and greater dependence of consultants- a step in the wrong direction. The idea that translating complex work into a computer program will cause greater appeal and acceptance is dubious. If one were to work on an invention without the requisite knowledge and with the computer software then he would never know if the path chosen was optimal or not. This is not meant to impugn the modern TRIZ techniques; it is only an appeal to keep methods as simple as possible to attain the widest acceptance and use.

"Establishing the TRIZ market"[128] chronicles the difficulties in establishing a TRIZ market in the United States. The authors faced many obstacles, including skepticism over a product invented in the USSR and confusion in the United States from novices who barely understand Classical TRIZ. It is the authors' sincere desire to bring the US TRIZ market to the state where the USSR left off without repeating lessons learned many years ago.

Crucial to understanding and use of Ideation's products and techniques is purchase and use of their software. Only through use of their software can a practitioner have full access to their system of operators and fast access to many different problem solution paths. The authors also advocate using a hybridized approach to mitigate concerns about cost and corporate buy-in. This approach incorporates education, software, facilitation/coaching and consultation. As the authors point out, these are necessary ingredients for any method embarkation.

Finally, the article includes an appendix with six powerful reasons why a prospective TRIZ practitioner should purchase and use TRIZSoft™:

- It provides step-by-step guidance through the problem solving process.
- It provides full advantage of the I-TRIZ knowledge base.
- It automates the most boring and difficult tasks related to problem solving.
- It saves time and eliminates the frustration of having to select the appropriate TRIZ tool for each particular problem.
- It becomes a sort of "partner" to support your innovation activity.
- It allows you to expedite the process of becoming a TRIZ master.

Ungvari[129] makes an analogy to Dr Kano's expansion of quality to account for two dimensions, satisfaction and performance. Kano demonstrated that if quality was conceived as a two-dimensional model of satisfaction and performance, that there were three possible customer responses to quality, Basic, Performance and Excitement. Once the author defines Kano's model, he shows how Ideation-TRIZ (I-TRIZ) adds a further dimension to the understanding of quality and the solution of the quality problem.

Basic Quality refers to quality characteristics that the customer expects. If the characteristics exist, the customer is neither happy nor sad because these qualities are expected. If these needs are not met, however, the customer is demonstrably dissatisfied. In Ideation, the author describes AFD. AFD goes beyond the current practice of FMECA, which asks the question, "What can go wrong?" and asks the *inventive* question, "how can I make the system fail?" The AFD approach therefore overcomes the limitations of psychological inertia inherent in the FMECA approach.

Performance quality is concerned with those characteristics that can please the customer more by being offered in a better way. To enhance performance quality I-TRIZ offers a host of problem solution techniques associated with overcoming physical and technical conflicts. Listed are the 40 inventive principles, the contradiction matrix, Su-field modeling, ARIZ, Ideation's Problem Formulator and System of Operators.

Excitement quality addresses the unexpected consumer needs, which may be unanticipated functionality or innovations. For this, TRIZ offers a methodology of predicting the evolution of technological development. Altshuller developed the theory of technological evolution and associated S-curves. Zlotin and Zusman developed the idea of Directed Evolution to assist in the identification of future needs to delight the customer.

"The dilemma of improving quality in new product development"[130] reiterates a well-established problem for TQM. The problem is the difficulty encountered when introducing a new methodology into an organization. The objectives of the study were to:

- Share an important generic problem with others
- Demonstrate how TRIZ can be used in a non-technical situation
- Provide an example of working with the Ideation products, Problem Formulator and Operators
- Provide an example of a situation related to the introduction of new engineering technology

Although the prospects for this study were very high, the results were disappointing. The authors used a basic TQM framework to approach the problem, relying heavily on brainstorming and not on TRIZ techniques. A popular quote heard amongst TRIZ experts is "TRIZ is based on technology, not psychology." This study was a reversion to methods that are inherently inferior to a disciplined TRIZ approach. Apparently TRIZ was only used to create extensive Su-Fields and Ideation software was then used to generate numerous problem formulations. The problems generated by the software are supposed to be insightful, but instead land up being wordy, tedious and overdone. There are so many statements that it is difficult to locate a useful one. These statements are generated using software that creates statements that are hard to read grammatically.

At the end of the article, three insights were listed. Unfortunately these "insights" were well known before the study commenced, each of them ending with a question the participants couldn't answer.

Zusman[131] analyzed over 90 different methods to break out of psychological inertia, based on the presence of the following seven creative techniques:

- Conditioning, motivating and organizing techniques
- Randomization
- Focusing techniques
- Systems
- Pointed techniques

- Evolutionary directed techniques
- Innovation knowledge-based techniques

Most of the 90 problem solving methods cited were unfamiliar to me, but can be found in one of Zusman's references (in Russian). TRIZ and its derivative, Ideation, were the only methods that scored high in the last two categories. Neither TRIZ nor I-TRIZ uses randomization techniques, because it does not need to add randomization to facilitate "thinking out of the box." TRIZ and I-TRIZ use all of the other techniques to help produce a competitive advantage to their practitioners.

"TRIZ and pedagogy"[132] is about how to use TRIZ to maximize creativity in the classroom. It was originally published in Russian and cites several sources that are not yet translated into English. It is a useful article for those dealing with education of children, but of little value for this work. Perhaps if the cited references were available in English, they may shed further light on this problem.

There was a little discussion of directed evolution or patterns of technological evolution. It has become increasingly apparent that a firm understanding of technological evolution would be quite useful in identifying candidates for redesign. The current model uses TOC to clarify the problem at hand but not to discover the problem. Ideation experts contend that candidate problems can be identified through directed evolution, but other than its necessity, little has yet been found on how to conduct directed evolution from a "cold start."

2.1.11.11. TRIZ- in Business Context[133, 134]

Blosiu and Kowalick[133] explore technological evolution and describe the eight laws of engineering system evolution.

- "Completeness of parts of an engineering system" states that every technical system has four parts, an engine (source of energy), a transmission (method to carry the energy to limbs), limbs (the part that does the work) and the controls (control the operation of the system).
- "Energy conductivity of the system" states that the system must have the capability to transfer energy throughout the system. A substance, a field or a substance-field can accomplish energy transfer.
- "Harmonizing the rhythms of parts of the system," means that the four parts of the system must work together.
- "Ideality" means that all systems evolve towards decreasing cost and undesirable effects and increasing useful effects. This is the reverse of entropy.
- "Uneven system parts development" means that even though a system has four basic components and they must work together, some parts will evolve more quickly than others will.
- "Transition to a super-system" means that, when a system has evolved as far as it can, it becomes a subsystem of a larger system that performs other functions in addition to the original system.
- "Transition from macro-level to micro-level" means that a system will naturally progress further towards miniaturization.
- "Dynamization" means that technology will evolve from a more rigid structure to an adaptive and flexible one.

After discussing the eight laws of technical evolution, the authors briefly discussed administrative, technical and physical contradictions and the basics of using a contradiction matrix and the forty inventive principles.

In "40 Inventive (Business) Principles with Examples"[134], Mann and Domb explore business management texts, technical papers and company literature in an attempt to apply the forty inventive principles to business applications. Altshuller observed successful patents and derived inventive principles from the solutions developed. Mann and Domb examined popular business philosophies and methodologies and then applied them to the forty inventive principles. Although their literature survey was not exhaustive, the forty-one references run the gamut of business ideology popular in today's business environment. It was interesting that, in their research, they did not discover a 41st Inventive (business) principle. This article is useful for understanding of the application of TRIZ methodologies to layout planning, because it shows how a disciplined understanding of the forty principles can lead to structured solution to any problem, from design to business.

2.1.12 FMEA/FMECA[135]

Luke and Jacobs[135] describe the mechanics of a FMECA analysis in the context of software development. FMECA is a convenient multi-dimensional tool used to identify potential weak points in a design by systematically identifying failure modes and the effects of failures. For each failure mode, the probability of failure is considered along with the severity of failure. Once these are identified, design or redesign priority is assigned to the areas of design that are most likely to fail in the most catastrophic way.

FMECA compliments almost any design methodology and it has been very popular over the years because of its straightforward application and ease of use. TOC offers an alternate method of discovery of weak-links in a design. TOC theory contends that the weakest link of the design, the constraint, must be repaired before overall design improvement can be established, but TOC tools only document the possible causes of design failure, not the probability or severity of any particular failure mode. The FMECA method of failure mode identification is difficult to apply and open to interpretation but TOC does a tremendous job of identifying failure modes. The combination of these two approaches provides strength to both.

TRIZ offers a similar methodology called anticipatory failure determination (AFD). AFD presupposes that a failure has occurred and challenges the engineer to devise a way to cause the failure. From there, the engineer uses TRIZ techniques in reverse to discover possible design enhancements.

2.2 DISCUSSION OF ARTICLES THAT INTEGRATE TWO OR MORE METHODS

2.2.1 TRIZ with TOC[136-139]

Rizzo[136] identifies limited creativity as a major constraint. From there, he observes that TOC tools can be used in conjunction with TRIZ to identify and resolve conflicts:

- The evaporating cloud from TOC can be used to identify conflicts for TRIZ.
- The 40 inventive principles from TRIZ can be considered "injections" for TOC.
- Two TOC tools, the Current Reality Tree and the Future Reality Tree, can be used to develop the Ideal Final Result from TRIZ.

- TOC's Prerequisite Tree can be used to identify TRIZ's Technical contradictions.

Domb and Dettmer[137] use the Challenger accident as an illustration of how TRIZ and TOC can be used together.

The main thrust of the article was similar to Rizzo's points that the evaporating cloud (also called a conflict resolution diagram) of TOC can provide conflicts for TRIZ, the Current Reality Tree of TOC can decompose a problem and the problem solving techniques of TRIZ can provide the "injections" needed to solve a problem. Basically, TOC is used in problem identification and TRIZ is used in problem solution.

The steps to construction of the Conflict resolution diagram:

1. Articulate the conflict
2. Determine the requirements
3. Identify the objective
4. Polish the diagram
5. Expose the assumptions and identify the invalid ones
6. Create injections to replace one or both prerequisites

A generic conflict resolution diagram is shown below:

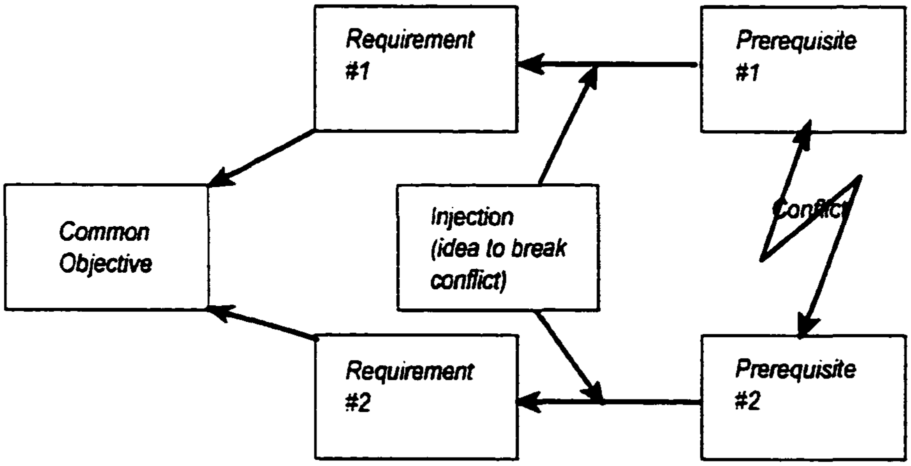


Figure 11. Evaporating Cloud Diagram from TOC

An overall view of the TRIZ approach is shown in Figure 12:

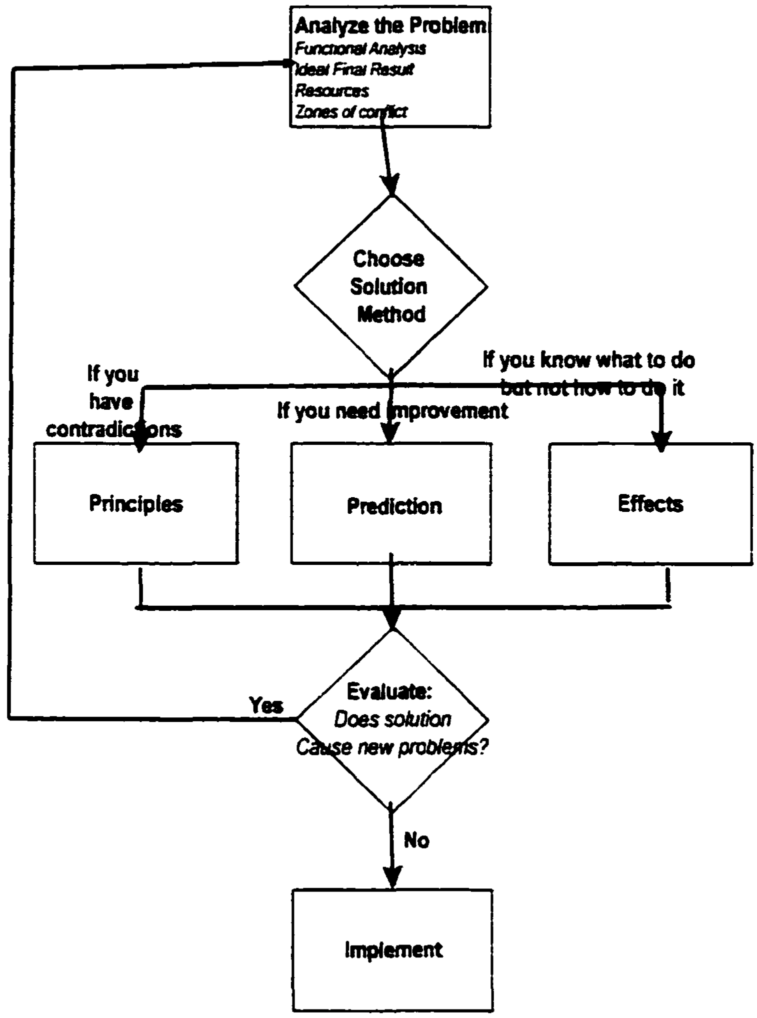


Figure 12. TRIZ Flowchart

Moura[138] is a TRIZ practitioner who has found in his experience that it is not difficult to find a problem to attack with TRIZ and it is not hard to identify the contradictions to be solved. It is hard to ensure that you are solving the right problem. In order to address this issue, he uses Current Reality Trees (CRT) and Conflict Resolution Diagrams (CRD or Evaporating Cloud) borrowed from TOC. The author references the Rizzo article and the Domb and Dettmer article discussed above and then points out that the earlier articles do not develop the usefulness of the Current Reality Tree. It is Moura's desire to develop the usefulness of the CRT.

Moura first tells how to read a CRT. CRTs are read from top to bottom. In the top box is an entity. Entities are single-idea, clear statements about the current reality, enclosed in a text box. Leading up to the current entities are the entities that are conditions for it to exist. The conditional entities lead into the top entity through the use of arrows. Arrows that are grouped together by an ellipse are considered joined by an AND logical gate. Arrows not joined are considered OR logical gates.

Moura then demonstrates drawing CRTs and CRDs for several problems:

- Automobile air conditioning odor when starting up the system - TRIZ functional diagram yielded less useful information than TOC CRT

- Rear spring noise in a truck – the functional diagram from TRIZ is not useful, but CRT from TOC yielded two solutions from TRIZ's 40 standard solutions.
- Car air exhaust valve – the functional diagram shed little light on the problem but TOC's Evaporating Cloud identified the central physical contradiction for solution.
- Damaged fuel level meter - two simple Evaporating Cloud diagrams led to the identification of central two physical contradictions.

Mann and Stratton[139] also discuss the link between TRIZ and TOC through use of the Evaporating Cloud to identify physical constraints. They present three case studies to illustrate their point-

- A TOC originated non-technical case concerning production manufacturing logistics
- A TRIZ originated case concerning the solving of a technical problem associated with a piece of manufacture equipment
- A TRIZ originated case examining the use of a combined TRIZ/TOC approach to help solve a human relations problem

The authors offer the following conclusions:

- The evaporating cloud model in TOC offers much to help TRIZ problem solvers in first identifying and then systematically challenging the assumptions underlying a Contradiction.
- The Physical Contradiction solution strategies contained within TRIZ offer much to help Evaporate Clouds - at least where the conflict is physical in nature.
- The respective system mapping tools complement each other and provide opportunity for further development.
- There is considerable scope for further integration between TRIZ and TOC.

2.2.2 TRIZ with TQM[140-143]

Domb[140] links TRIZ with the theories of Deming and Juran and with the Balderidge award. She points out that, until TRIZ, creativity was always stimulated with left-brain techniques like brainstorming. TRIZ is a right-brain technique to promote creativity by recognizing existing patterns of prior innovation and codifying them. Domb derived the following observations from Altshuller:

"Patterns and solutions were repeated across industries and sciences.

"Patterns of technical evolution were repeated across industries and sciences.

"Innovations used scientific effects outside the fields in which they were developed."

Domb's conclusion is reproduced below:

"Creativity improvement enhances quality improvement. Quality analysis tells us what our customers want, what our processes need and what our employees need, but creativity is needed to find ways to make these new products, services, systems and processes happen.

"All employees can learn both right-brain and left-brain creativity methods and can learn to apply them to the appropriate situations."

In another article[141], Domb finds common ground with W. Edwards Deming is the need to discover the true nature of a problem before rushing into a solution. If you use the ARIZ method of analysis, identification of the true problem may take as many as 100 steps. In reality, the author claims there are only two "zones of conflict," spatial (also called "zone of operation" or "where") and temporal (sometimes called "time of operation" or "when"). Practitioners of TRIZ are more familiar with technical contradictions and physical contradictions. Identification of the contradictions will lead to these two zones of conflict. The author suggests using the well-known 6 basic questions of journalism:

- Who?
- What?
- When?
- Where?
- Why?
- How?

If you ask these six basic questions, along with an understanding of the concepts of contradiction, you will be able to identify the technical and physical contradictions, the zones of conflict and the ideal final solution. Then solving the problem is greatly simplified.

"Innovative problem solving"[142] discusses both TRIZ and TQM, but does not link the two. The author states that, as a result of the increase of global technology, there is a need for a systematic, logical approach to technology development. The author further states, "there are several innovative problem solving tools such as TRIZ, SIT and axiomatic design." In my opinion, axiomatic design is not an innovation problem-solving tool because it seeks to restructure an existing problem instead of innovating new approaches. This is not intended to impugn the power of AD, just to state that its focus was misstated. The author's review of TRIZ is very sketchy, indicating only a very cursory understanding of the methods. The only discussion of a TRIZ technique was a definition of Su-field analysis, a concept not unique to TRIZ and one that is often not used by TRIZ practitioners.

After discussion TRIZ briefly, the author lists the five basic principles of TQM without linking the general methodologies together. The five principles listed are:

- Focus on the process for better results
- Continuous improvement of processes
- Management with facts
- Management established priorities
- Involvement of everyone

Goel[143] posits early in the article that there is some universal truth regarding quality even though many differ on its definition. One characteristic of quality the author cites is that it is motivated by profit. An extension of that idea is that in a competitive market, one must be able to introduce innovative features without compromise. To address the problem of innovation, the author mentions TRIZ. The only concept of TRIZ the author mentions is the idea of taking generalized solutions of one field and applying them to another field (Altshuller calls this a Level 3 innovation).

From this discussion, Goel discusses creativity and the different types of intellectual activity necessary for creativity. Having now established that cross-pollination of ideas is useful, the author discusses the popular TQM tool of using cross-functional teams to solve problems from a myriad of perspectives.

Next, the author attempts to link innovation with motivation and suggests incorporating motivation theories to stimulate innovation. The author never cited innovation development algorithms that are the backbone of TRIZ.

2.2.3 TRIZ with QFD[144-149]

The American Supplier Institute presented the Third Annual Total Product Development Symposium[144] in Dearborn, Michigan. The symposium brings together practitioners of Taguchi, QFD and TRIZ to learn more about each other's discipline and to bring about methods to integrate the tools and methods and to improve product design and process development. TRIZ case studies were presented and are available in the Symposium notes from the American Supplier Institute.

Domb reported on a design for side airbag deployment offered by Ford Motor Company, a design to eliminate windshield/backlight molding noise and two case studies regarding the development of pharmaceuticals. TRIZ consultants demonstrated their software and Wayne State University presented its results using TRIZ in senior design projects.

León-Rovira and Aguayo[3] link TRIZ to Functional Analysis and QFD. The link they demonstrate with QFD is to let the QFD matrices be drawn first and then derive the technical contradictions from the roof of the House of Quality. The link between Functional Analysis and QFD was hard to follow, but the authors concluded that it was useful to perform QFD first and Functional Analysis later when the problem was better defined.

The problem with synchronizing QFD and TRIZ through the conflicts in the house of quality is mainly that the identification of technical conflicts is generally not the main problem of TRIZ applications. In fact, technical contradictions are generally obvious in a well-formed problem statement.

In "QFD and TIPS/TRIZ"[145], Domb establishes links between TRIZ and QFD by defining well-known processes of one method in terms of the other. She concludes the article by providing a useful matrix that shows QFD tools on the x-axis and TRIZ tools on the y-axis. She explains the basics of TRIZ in very clear terms and demonstrates a common purpose between the two disciplines.

Domb explained the three basic findings of TRIZ research as being:

1. Problems and solutions were repeated across industries and sciences.
2. Patterns of technical evolution were repeated across industries and sciences.
3. Innovations used scientific effects outside the field where they were developed.

Domb defines the following tools and places them within a flowchart of basic TRIZ application: Functional analysis (and trimming), The ideal final result, Resource analysis, locating the zone of conflict, principles/ resolution of contradictions, prediction/technology forecasting and effects.

This article is written for the QFD practitioner to use TRIZ tools to enhance decision-making in the course of applying QFD, which is a logical approach because TRIZ is not as well established as QFD.

Terninko is an instructor and practitioner of all three of these methods and is qualified to make comments on their integration. In an extremely well written and informative article[146], Terninko substantiates the need for integration of QFD, TRIZ and Taguchi effectively.

Terninko begins by establishing and defining the basic essences, complete with strengths and weaknesses of each of the three methods. Next, he goes through the five-step QFD process and comments on where each step could be enhanced with either TRIZ or Taguchi's methods. In doing so, he establishes twelve links to TRIZ and seven links to Taguchi's methodology. He sums up by offering a next step method, working with *comprehensive* QFD and modern TRIZ.

Like Domb, Terninko uses QFD as a framework to implement the ideas of TRIZ and Taguchi. There are more connections between the three methods that could be established than Terninko establishes in this brief article. In addition, Response Surface Methodology can provide far more useful information than Taguchi methods provide, especially regarding interactions between parameters.

The greatest strength of TRIZ is also its greatest weakness and that is the establishment and resolution of technical contradictions. It is a strength because TRIZ has firmly established that compromise or design trade-off is a sub-optimal design approach. Expert design eliminates trade-offs instead of merely minimizing them.

However, it is also a weakness because TRIZ, by itself, often cannot resolve its own defined technical conflicts. The contradiction matrix may provide some approaches, but many authors have shown that the matrix does not establish the best inventive principle. It is also inadequate because it does not capture the nature of interactions between design parameters. RSM offers assistance with the analysis of interactions that Taguchi's methods cannot provide. All three of the methods proposed for integration by Terninko tend to be subjective and conjectural so that an incorrect opinion or false assumption can cause the entire method to fall apart like a house of cards. (QFD starts with opinions and ideas of everything from perceived market position and customer complaint forms to the degree of interaction between crucial factors. TRIZ is subjective in the establishment of the central technical contradiction, so that two independent practitioners may offer very different solutions to the same problem. Taguchi is subjective in the establishment of critical factors and effects.) An optimal system of design deployment minimizes bias and a major improvement could be made to all three disciplines if a method to minimize bias could be established.

"Dialog on TRIZ and Quality Function Deployment"[147] recounts some electronic mail between Domb and a reader from Singapore. The reader concluded that QFD was more generally useful for product development than TRIZ. Domb replied that both are effective tools for product design and are so interrelated that they can easily be used together without duplication of effort.

"Report from the International TRIZ Conference, Nov. 17-19, 1998: A Personal Perspective"[148] is a report by Domb on the International TRIZ conference. She explained some of the lively panel discussion that took place and then gave some of her ideas on the integration of QFD, TRIZ and Taguchi methods. Initially, she claims she saw a cycle beginning with QFD (Customer needs and company capability) then proceeding to TRIZ (creative concepts and implementation methods and finally ending with Taguchi (process optimization and robust design). The output of the first cycle is then fed back into QFD for next generation design and improvement. After hearing three technical papers on the Taguchi methods where all three authors pointed out that their initial understanding of noise and control factors were wrong, Domb concluded that there needed to be a feedback loop from Taguchi back to TRIZ before the final experiments were run.

This is a very interesting concept. If the methods used by the Taguchi presenters did not include the formative steps of QFD and TRIZ, then it could be argued that their approach would have been correct if they had considered QFD and TRIZ first. At any rate, any technical design process should include model verification and sensitivity testing before proceeding.

"Selecting the Best Direction to Create the Ideal Product Design"[149] discusses a method to integrate the concepts and framework of QFD with TRIZ, Anticipatory Failure Determination (AFD) and Analytical Hierarchy Process (AHP). The author discusses a flashlight development project where the inventors started with QFD, then integrated it with the *new* TRIZ method, Ideality. Finally, the author introduces AFD and useful and harmful function analysis into his design. The author states that the problem statements lead to concepts which were ranked using AHP based on their performance measures and importance in the output of the House of Quality and the reliability issues defined by the failure modes.

2.2.4 TOC with TQM[9, 150]

"Theory of constraints: The missing link between quality and profitability"[9] posits that TQM has fallen short in many instances because it treats quality as an overarching problem in a wide variety of applications when it is not the principle cause of low profitability. Instead, a consideration of the entire system would dictate whether quality needs to be addressed first or something else needs to be addressed first. One could extend the logic of the article to TRIZ because TRIZ treats inventiveness as a panacea for all problems.

In trying to reconcile the concepts of TQM with those of TOC, Dettmer[150] noted that there was an apparent discontinuity regarding measurement. Proponents of TQM suggest the ultimate measure should be cost of quality (COQ) while TOC practitioners suggest that it is Throughput (T). Dettmer points out that TOC practitioners could learn from TQM in this instance. In fact, COQ takes into account cost factors often ignored by TOC. If T were properly computed it would take into account the "cost of correction" as a variable cost. When cost of correction is ignored, then a false indication for T is obtained. High quality alone is not sufficient to ensure business success, but it is a necessary condition.

2.2.5 AFD with FMECA[151, 152]

In "Diversionary Method"[151], Frenklach describes the TRIZ function commonly called "Anticipatory Failure Determination or AFD. He uses its original name: "Diversionary Method" because he feels it is more descriptive of the function being performed.

Anticipatory Failure Determination is TRIZ in reverse. To implement AFD, you first take a possible failure mode and instead of asking, "What is wrong with the system?" you ask, "How could one make the system cause the maximum harm?" Frenklach points out that there are a number of methods like Failure Modes Effects and Criticality Analysis (FMECA) in which the possible failure modes are enumerated. AFD goes a step beyond enumeration of the failure mode to establishment of a method to cause the failure mode.

To perform AFD, it is useful to divide the system into life cycle phases and then look for potential harmful effects in each life cycle. The stages Frenklach offers are:

- Manufacture
- Operation
- Maintenance
- Storage

The types of harmful effect to be decomposed are:

- Harm creation (associated with changing parameters or properties of the analyzed element)
- Creation harm (associated with the wrong measurement)
- Intensifying of harm that already exists and
- Useful interactions' elimination

Once the kinds of harm are enumerated and presented then the process of discovering inventive methods to create the harmful effects are developed. The existing system and resources bound the problem of creation of harmful effects. Once the inventor knows how to create a harmful effect, it is easy to devise a method to eliminate it.

I see two possible ideas to add to Frenklach's AFD approach:

1. Use FMECA first instead of taking the more difficult decomposition methodology proposed by TRIZ. The output is more useable in today's society where FMECA is commonplace and TRIZ is still a novelty.
2. Use the contradiction matrix complement to discover harmful effect establishment. I discussed this idea in review of Mann's article on helicopter engines.

It should be noted that AFD is from the modern school of TRIZ established by Zlotin and Zusman, not the classical school of TRIZ established by Altshuller.

"Usage of Direct and Preliminary Extra-Effect Determination Methods for Diagnostic Problem Solving"[152] relates to the modern TRIZ technique of Anticipatory Failure Determination or AFD. There are two types of diagnostics problems, one is concerned with removal of the undesirable effect (UDE) and the other is concerned with the prevention of the UDE. For the former, Root Cause Analysis is cited, for the latter, AFD and FMECA are cited. When a particularly difficult problem with feedback elements, AFD becomes cumbersome and Frenklach recommends using a modified approach called the "preliminary extra-effort determination method." FMECA methods ask, "What is wrong with the system?" AFD methods ask, "How can you make the system fail?" and Preliminary extra-effort failure determination methods ask, "Assuming the primary failure has already occurred, solve the problems caused by secondary effects."

2.2.6 TRIZ with Functional Analysis[153]

In "Tutorial: Use of Functional analysis and Pruning, with TRIZ and ARIZ, to Solve 'Impossible-to-Solve" Problems"[153], Kowalick defines a number of terms, including functions, value, functional statements, systems, subsystems, tree diagrams, psychological inertia, real problems, ideal final result, Su-Fields, triads, TRIZ, ARIZ, functional analysis, pruning (called "trimming" elsewhere), functional tree diagrams, systems parts diagrams, functional matrix and functional line diagrams. He illustrates the modern TRIZ method of functional analysis and pruning by using the examples of a toothbrush and an airbag. His overall functional analysis/pruning method is reproduced below:

- State the problem
- State the Ideal Final Result
- Create the function tree
- Analyze each function as a candidate for pruning
- Analyze each subsystem as a candidate for pruning
- Prune as needed
- Apply TRIZ techniques to the remaining problem
- Evaluate solutions.

Note that he has created a new pattern where classical TRIZ techniques and pruning are introduced as subsystems of Functional Analysis.

2.2.7 TRIZ with Neuro-Linguistic Programming[154]

Becker and Domb[154] note that TRIZ is a left-brain method to accelerate product innovation by disciplined analysis of patterns. There are other methodologies that are used to identify and teach the patterns of thinking that people use to develop theories. One such method is Neuro-Linguistic Programming (NLP). The authors posit that if users of NLP were exposed to the methods of TRIZ, they would be less likely to resist TRIZ ideas.

2.2.8 TRIZ with B. Joseph Pine II's Mass Customization[155]

"Business Contradictions – 1) 'Mass Customization'"[155] examines the application of the philosophies of TRIZ to the philosophies of B. Joseph Pine II in his book, *Mass Customization: the New Frontier in Business Competition*. Mann uses this opportunity to demonstrate that the Contradiction Matrix, in its present form, is unable to provide the best-suggested solutions to the problem presented by Pine. The thesis that the contradiction matrix is inadequate to lead a designer to the right inventive principle is a theme Mann has carried from earlier work. Mann suggests in his earlier work and again here, that one should use the contradiction matrix, but also peruse the entire 40 Inventive Principles list in pursuit of solution of any design problem.

The topic of Pine's book is of considerable interest in the application of TRIZ to layout planning. This article outlines several customization principles and their companion TRIZ Inventive Principles. In addition, the article demonstrates the inadequacy of direct application of the contradiction matrix to the fundamental contradiction of "Adaptability and Versatility" versus "Productivity."

The authors demonstrate the use of several TRIZ theories in solution of the "Mass Customization" problem, including:

- Use of the Contradiction Matrix
- Use of the Inventive Principles
- Use of the theory of Ideality
- Use of the theory of Trends of Evolution

The author clearly shows how TRIZ could have been used to offer the same solutions already present in Mass Customization problem solution, but does not show how a TRIZ paradigm could be developed to generate better solutions to Mass Customization problems in the future.

2.2.9 TRIZ with Knowledge Based Design[156]

TRIZ was being discussed in "Virtual Manufacturing and Knowledge-Based Design: Society of Automotive Engineers Topical Technical Conference"[156] because its history of development from the knowledge base of the world wide patent collection and because TRIZ' s ability to accelerate the conceptual design and problem resolution process. Domb presented a paper at the conference and provided commentary in this article on other papers presented. She demonstrates that TRIZ is an excellent companion to virtual reality because Virtual Reality (VR) allows the designer to conceptualize the design parameters in three dimensions earlier. TRIZ is a good companion to knowledge-based and artificial intelligence solutions because the latter tend to accelerate the alternative generation process to the point that the number of design options increases beyond the capacity for investigation, while TRIZ narrows the number of options to a manageable few.

2.2.10 TRIZ with Axiomatic Design[157, 158]

Mann[157, 158] applies the concepts of TRIZ, which were developed in Russia separately and independently from other design methods outside Russia. In this case, TRIZ is being compared to AD.

Mann reviews Dr. Nam Suh's seminal work on AD, *The Principles of Design*. In this work, Suh establishes a design framework based on two axioms, the independence axiom and the information axiom.

The first axiom strongly implies that the goal of good design engineering is to reduce the number of functional requirements (FRs) and the second implies that the design should be as simple as possible. Mann demonstrates that reduction of the FRs presupposes that the right FRs were established in the first place and effectively denies the evolutionary nature of customer needs in FRs. For example, the airplane was first successfully designed by the Wright Brothers because they distilled all the functional requirements for bird wings (vertical take-off, horizontal take-off, climb, dive, cruise, hover, pitch, yaw, roll, retract and provide thermal insulation) to a smaller subset of FRs for airplanes (horizontal take-off, slow cruise speed and limited need for change in direction). From Suh's standpoint, the minimization of FRs made the design of airplane wings possible. However, from a broader standpoint, the Wright plane could not perform in a way consistent with subsequent need of consumers. Eventually, the number of FRs increased and new planes were introduced. The evolution of functional need is well established and developed in TRIZ theory.

Another weakness cited by Mann in AD is that it fails to recognize the "delight" aspects when a customer buys a product and later finds that it has additional functionality.

In a wheel cover example, Suh points out that AD can be used to find a good engineering compromise. According to the article, General Motors (GM) had a problem with the spring clips used to secure wheel covers. If the clips were too weak, customers were dissatisfied because they fell off. If the clips were too tight, the customers were dissatisfied because they were difficult to remove. Through a customer survey, GM discovered that a retention force of 34±4 N was sufficient to minimize both complaints. Mann points out that in TRIZ, this would be considered a physical contradiction: "the wheel cover must be held tightly in order to hold the wheel cover on and the wheel cover must be held loosely in order to remove the wheel cover." Using TRIZ methods, an inventor would easily find a solution that satisfies both needs without compromise. For instance, use a push and twist type cover like on medicine bottles. According to Mann, "the GM designers were using Suh to optimize the wrong design. The 'right' design- according to TRIZ- is the one which eliminates trade-offs rather than seeking a balance between them."

AD does offer TRIZ some wisdom:

- It teaches that there is an intrinsic link between functional requirements and design parameters. AD does not accept the notion that DPs only flow from FRs. Instead, it requires the designer to rethink both.
- AD can correctly deploy design in the proper hierarchical order and makes a careful distinction between the functional domain and the physical domain of design solution.
- Additionally, AD also considers manufacturing concerns early in the design process by considering the "process domain."

2.2.11 Robust methods with SPC[159]

Sauers[159] tries to create a relationship between SPC, QLF and C_p. He succeeds, but misses the point that the shape of the QLF was arbitrarily chosen by Taguchi in the first place. He uses an example (with data) of a shaft with specifications of 4.037 ± 0.0013 inches. An INLF makes more sense since quality loss levels out when past the tolerance limits; it does not continue to grow exponentially. The QLF is a mathematical equivalent of an extended metaphor; it works well within the tolerance region, but poorly outside of it.

2.2.12 TRIZ with Taguchi methods[160]

Monplaisir, Jugulum and Mian[160] take two processes and use TRIZ and Taguchi methods in each to try to develop an optimal design. The first process is aimed at improving the process of fluorination in the manufacture of plastic bottles. Using TRIZ, the authors decided to optimize the incorporation of fluorine in plastic bottles by using gravity. After converging on the form of the solution, the authors further optimized by applying Taguchi methods to maximize the production of plastic bottles. Using both methods, yield was increased from 65% to 90%.

The second case study was to develop a coordinate measuring machine to support all kinds of manufactured parts for measurements. The authors used TRIZ to discover a design method, but did not document their use of Taguchi methods to complete the design.

The article's conclusion is integration of Taguchi methods with TRIZ will improve the product development process. This is certainly true, since TRIZ and Taguchi methods both provide improvements to different aspects of the design process. TRIZ offers good innovative methods to establish the form of the design, where Taguchi methods optimize parameters once the form of the design is already established.

Taguchi methods are based on an intrinsic compromise: reduce the number of experiments by sacrificing potential information about interactions between parameters. Robust engineering methods, such as central composite design, have overcome this compromise by establishing designs of experiments that maintain interaction data without using many experiments. Since the spirit of TRIZ is to reject compromise in favor of optimization, it would be advisable to use CCD in lieu of Taguchi methods.

2.2.13 DFMA with TRIZ[161]

The article "How to Bring TRIZ into Your Organization"[161] is designed to assist the reader in bringing TRIZ into his or her own organization after being "sold" on TRIZ at a conference or a lecture. Research shows that implementation of TRIZ can yield a twelve-fold increase in idea generation for those whose regard themselves as "uncreative" and a three-fold increase in idea generation for those regarded as creative "superstars." There are four obstacles to company-wide adoption of TRIZ:

- Time
- Suspicion
- Traditional methods of project management
- The NIH ("not invented here") syndrome

The authors suggest using a three-step process to introduce TRIZ to an organization:

- Organization makes a decision/commitment to support increased innovation
- Selection of pilot projects for TRIZ introduction in a classroom setting
- Implement the results of the class and train TRIZ instructors from the initial class.

The benefits of the class are:

- Concepts for inventive solutions are generated for the selected projects or problems.
- The participants themselves generate the results.
- The participants learn to sort the results and get immediate and long-term benefits.
- The participants learn the TRIZ methodology well enough to apply it themselves.

After the class, the authors discuss organizations can begin to integrate TRIZ with other tools. They suggest, among others, "TRIZ/DFM-A: Design for Manufacturability and Design for Assembly identify and prioritize features of design that make manufacturing and assembly low cost, high yield and short cycle time. TRIZ resolves the technical problems encountered when implementing these features. Similarly, many organizations have developed their own guidelines for 'Design for Serviceability' which are enhanced by TRIZ creativity in achieving serviceable designs." No references were cited for integration of TRIZ and DFM.

2.2.14 TQM with FMEA and CAIV[162]

Goel and Singh[162] initially posit that the "single factor that influences and improves the competitive edge of a company is 'Customer satisfaction.'" From this statement, they develop a design methodology that seeks to optimize customer satisfaction by considering quality, reliability, durability and cost considerations. Their model entails using QFD, RSM and FMEA. Although QFD and RSM are incorporated in the model, they are not discussed extensively in this article. Most of the article is devoted to developing a mathematical model for failure rate and reliability and using it in a feedback loop to ensure product reliability and durability and ultimately customer satisfaction.

Goel and Singh present the following as the basic flow diagram for a typical product development process:

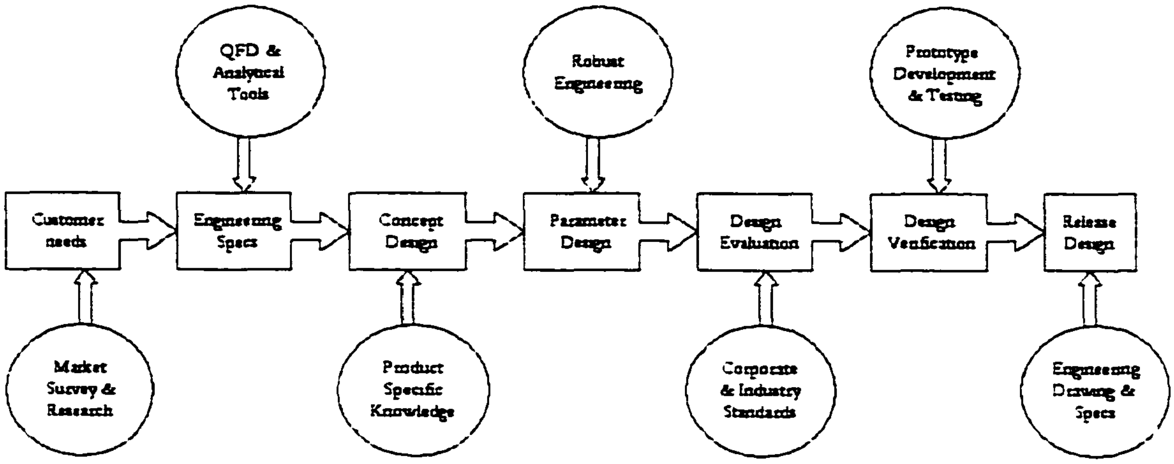


Figure 13. Goel and Singh Product Development Process Flowchart

In this typical model, Each design phase uses a tool, like QFD or market survey, but there is no feedback or feed-forward from one phase to another. The tools are not revisited unless there is a redesign. Goel and Singh demonstrate that a better model is one that has feedback integrated into it. In their case, the feedback is in the form of failure data and mathematical modeling of reliability and durability. The resulting system model for design is given as this:

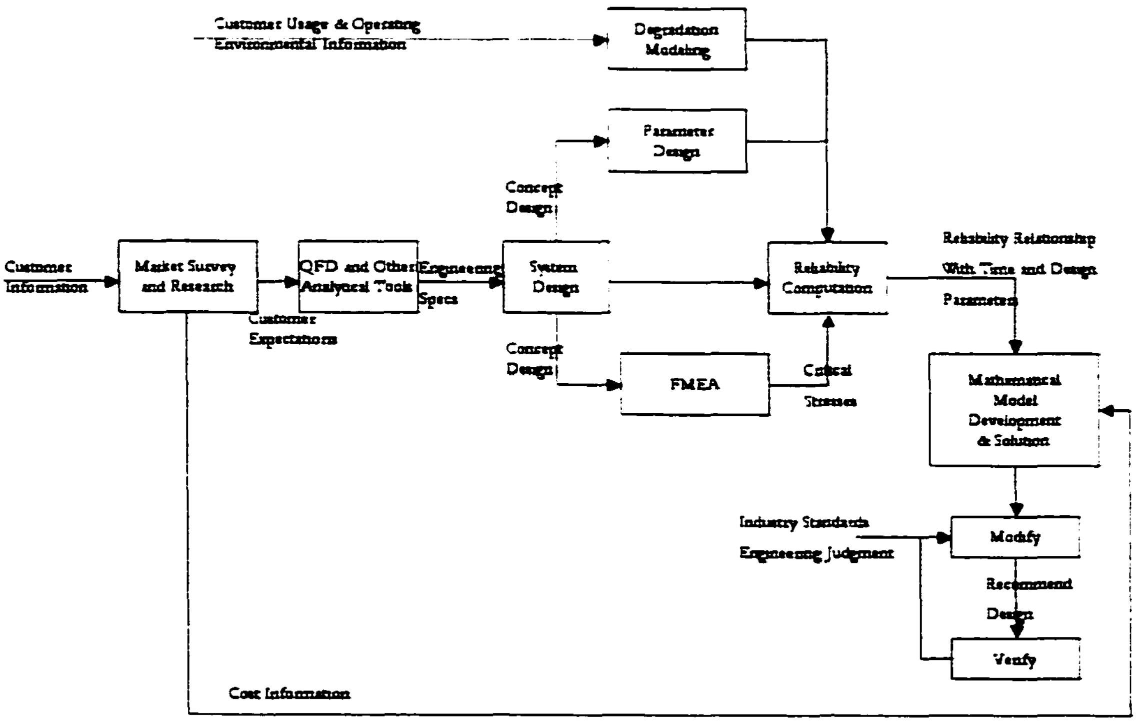


Figure 14. System Model with Feedback Loops

Goel and Singh make a few very good points, although their model does not go far enough, in my opinion. I agree that the model for product development must be dynamic and contain feedback loops. I do not agree, however, that the overall factor for company competitive edge is necessarily customer satisfaction. They point out that successful and safe operations of a product are considered hygiene-like factors, necessary but not sufficient. Such lower-level motives are dissatisfiers if not present, but may are not sufficient to create customer satisfaction. I believe that customer satisfaction is also a lower-level motive, from the company's perspective. If it does not exist, the company will certainly fail but its existence is not sufficient to ensure the company's success. Theory of Constraints points out that a fundamental flaw of TQM is that it is often used to promote quality in an organization when another factor is the root cause (or constraint) keeping the company from meeting its goal. From a TOC standpoint, quality is to be optimized only if it is the weakest link of many possible constraints[150].

The ten methodological steps for product design presented in this paper are:

1. Define the scope of the problem
2. Gather relevant information
3. Identify critical failure modes
4. Identify design variables associated with the failure modes
5. Establish the degradation pattern of design variables
6. Calculate statistics; that is, the mean and variance of stress and strength
7. Calculate reliability using stress-strength model
8. Establish time-dependent relationship between reliability and design variables
9. Develop mathematical model
10. Solve the model and analyze results

2.2.15 QFD, Axiomatic Design, FMEA and Robust Engineering[163, 15, 16]

Goel and Singh[163] have set quality as the variable of interest and have integrated QFD, axiomatic design (AD), FMECA and Robust engineering into a generalized development process. According to the authors, "quality of products depends on several factors and product design is one of the most important ones." They use QFD to process customer preferences and to generate/process competitive benchmarking data. They use AD to develop a design that has the proper relationship of design parameters and functional requirements. FMEA is used to understand what can go wrong, along with the cause, effect, periodicity and probability of occurrence. Finally, robust engineering is used to focus on various types of "noise" that can exist in the product and reduce the inherent variation of the product.

The QFD process has four phases:

1. Product Planning
2. Design deployment
3. Process Planning
4. Production Planning

QFD links these phases through the use of four QFD matrices, linked together as discussed in section 2.1.7.

Each of the QFD matrices has a specific structure, which can be generalized in the following House of Quality (HOQ) arrangement (also discussed in section 2.1.7).

A detailed discussion of how to complete a QFD matrix can be found in Luke et al[135].

Goel and Singh had a very brief discussion of FMEA. More useful than FMEA is FMECA, which takes into account criticality as well. An excellent discussion of FMECA (for a software application) is found in Luke and Jacobs[135].

Axiomatic design relates functional requirements (FRs) to design parameters (DPs) using information theory and matrix algebra. Suh developed it and it is based on two axioms[15, 16]:

- Independence axiom- sections of the design should be separable so that changes in one have no (or as little as possible) effect on the others
- Information axiom- the information inherent in the product design should be minimized

The first axiom leads the engineer to use a sensitivity matrix[15, 16] to relate FRs and DPs with the goal of creating a one-to-one relationship between FRs and DPs. This leads to seven corollaries[15, 16]:

- Corollary 1- Decoupling- we should attempt to decouple or separate different design elements. If done using the matrix method, this would result in an identity matrix (or equivalent).
- Corollary 2- Minimize FRs- If we can reduce the number of FRs, it will simplify the design.
- Corollary 3- Integrate parts- When possible, without significantly compromising the other principles, we want to reduce the number of parts.
- Corollary 4- Standardization- Standardized parts tend to satisfy design axioms and should be used when possible to reduce the information content.
- Corollary 5- Symmetry- When possible, use symmetry to reduce the information content of the product.
- Corollary 6- Large tolerances- Reduce the information content by using the largest tolerances possible.
- Corollary 7- Uncouple and minimize information- When possible, the designer should strive to minimize information and interdependence between design components.

There are two objectives from the corollaries of the first axiom above[15, 16]:

- Strive for the same number of FRs and DPs and have each be independent.
- Minimize the values in the relationship matrix by reducing the information in each part

There are many differences between these methods in their objectives and in their methodologies. Goel and Singh[163] illustrate that there are ways to link them together in order to capitalize on their inherent strengths without compromising their underlying tenets. Goel and Singh make the following recommendations for integration (quoted from Goel and Singh with parenthetical comments added for clarification):

- The designer should try first to satisfy the first design axiom as far as possible and use it as a guiding principle. (Axiom 1 of AD - the Independence axiom)
- QFD should be used as a visual aid for systematic representation of all the information.
- The relationship matrix (from QFD) should be divided into smaller matrices based on hierarchies of functions and design parameters.

- Emphasis should be placed on target value and variability of FRs instead of specification limits.
- Consideration must be given to the effects of noise or uncontrollable parameters by selecting appropriate tolerances and constraints.
- DOE should be used as described earlier in the paper.
- Design should be selected on the basis of the information axiom if the first axiom is satisfied.
- The effects of design and process parameters on business planning need to be considered.

Clearly, the methodology above is based primarily on AD and uses the other methods to buttress AD findings. The authors are vague on how they will incorporate FMEA into their design schema, although it is not incompatible with their approach. The authors use QFD throughout their process as a visual aid, but do not rely at all on results from QFD.

Robust engineering and DOE only consider the design after the design has been made to be as independent as possible. If true independence were obtained, then DOE would not be needed. DOE exploits dependent relationships for the design but AD removes all dependencies; as the authors point out, this is not a conflict. Although DOE is used to exploit dependencies, it does not seek to establish them. DOE and AD are unified in the desire to eliminate dependencies whenever possible to lower the overall complexity of the design.

2.3 DISCUSSION OF LITERATURE REVIEW OF CASE STUDY: AIRBAG DESIGN PROBLEM

2.3.1 Problem Identified[164-192]

According to the articles[164-192], airbags are designed to save the lives of the majority of adults. Airbags are designed to be a passive restraint system to be used in conjunction with an active restraint system, the seat belt with a shoulder harness. Estimates of the number of lives that have been saved are as high as 4,758 or more (United States only).

Airbags are designed to deploy very rapidly (200-mph estimate) upon impact. In order to minimize the possibility of an accidental airbag deployment, there are two independent sets of crash sensors to detect deceleration. Once both sensors confirm impact deceleration, a firing circuit sends a current to a gas generator, which activates an initiator device. The severity of impact necessary for activation varies. In Europe, the setting used is based on the premise that the occupant is wearing a seat belt; in the United States, it is based on the premise that the occupant is not wearing a seat belt. Therefore, the deployment threshold for American cars tends to be lower than for European cars. A low threshold creates an additional risk for occupants from the airbag itself. For this reason, some "smart" airbags detect whether or not a seat belt is being worn and adjust the initiation threshold accordingly.

Safety experts advise that if the occupant is at least ten inches from the airbag and is seated upright with both seatbelt and shoulder harness in place, the occupant will not sustain fatal injuries from the air bag itself. However, an individual who is not restrained by a shoulder harness will be thrust forward during a crash and will encounter the air bag too soon, possibly causing serious or fatal injuries. Additionally, a driver who is sitting less than ten inches from the airbag will also encounter the airbag too soon in a crash scenario and may be seriously or fatally injured, leading many to believe that individuals of diminutive stature are especially susceptible to airbag-caused fatalities.

At this point, it is useful to discuss how the ten-inch distance threshold was obtained. According to the NHTSA, the ten-inch distance is a general guideline that includes a clear safety margin. IIHS recommended the same distance in its comments. The ten-inch distance ensures that vehicle occupants start far enough back so that, between the time that pre-crash braking begins and time that the air bag begins to inflate, the occupants will not have time to move forward and contact the air bag until it has completed or nearly completed its inflation. The ten- inch distance was calculated by allowing two to three inches for the size of the risk zone around the air bag cover, five inches for the distance that occupants may move forward while the airbags are fully inflating and two to three more inches to give a margin of safety.

There are four identified groups of individuals who have been fatally injured in the 146 confirmed airbag deaths:

1. Drivers
2. Adult passengers
3. Child passengers
4. Infants

2.3.1.1. Drivers

There are 60 cases of drivers who have been killed in airbag fatalities. Size of the victim is only a factor in driver airbag fatalities. The rationale for this statement is that the victim is killed because the victim is seated too close to the steering column where the airbag is deployed. In passenger airbags, the occupant is always at least 10 inches from the airbag if they are seated and wearing their seatbelts. For this reason, many have declared that airbags are a hazard for short people, especially short women (because women tend to be shorter than men).

The NHTSA has demonstrated that nearly all women between the heights of 56 and 62 inches can maintain a distance of 10 or more inches from the steering wheel. Of all the fatalities, only one fatality was an adult driver under 56 inches, a 17-year-old woman who was only 47 inches (a midget). Unique problems of dwarves and midgets will be discussed separately. However, just because a national organization has demonstrated that a person can sit ten inches from the steering column and should sit ten inches from the steering column does not mean that they will sit ten inches from the steering column.

The statement that the problem is the height of the victim is a misstatement of the real problem, although many make this error. The real problem is that the driver is seated too close to the airbag. The reason most drivers sit too close to the airbag is because they need to do so in order for their *feet* to reach the control pedals. There are virtually no people with arms so short they cannot maintain a distance of ten inches from the steering wheel. An aggregating factor is the fact that many shorter people will not wear shoulder harnesses because the harnesses cannot be set low enough to lay over their shoulder not their throat. Some short people also complain that they must sit close to the wheel because they need to do so to see the road.

Two drivers were killed by airbags because they passed out while driving and were slumped over the wheel of the car, although they were belted and were taller men (72 inches and 66 inches). Effectively, this is the same problem as the one for shorter women.

The statement that not wearing seatbelts is a cause of driver airbag fatalities is also a misstatement of the real problem. The reason these drivers were killed by their airbag is the same as for the drivers who are seated within ten inches of the steering column. They are too close to the airbag while it is being deployed. The reason they are too close to the steering wheel is because they have been pitched forward due to inertial forces encountered during the accident and they could have countered those inertial forces by using their seatbelts. Presumption that not wearing seatbelts is the cause of the fatality assumes that the *only* solution is for drivers to wear seatbelts. It may well be the *best* solution, but not the only one.

Midgets and dwarves generally drive cars that are equipped with hand controls in place of traditional foot-pedals. It is not known if such devices were used by the midget mentioned above. If hand controls are being used, then the only factor that would prevent a midget or a dwarf from sitting at least ten inches from the steering column is their arm length, which is generally adequate to allow necessary clearance.

2.3.1.2. Adult Passengers

Airbags have killed six adult passengers and have seriously injured five more. Of these eleven adult passengers, five were not wearing their seat belts, five were wearing seatbelts and one may or may not have been wearing his seatbelt. There is a strong presumption that those who were not wearing their seatbelts were too close to the airbag at the time of impact.

2.3.1.3. Child Passengers

Airbags have killed 74 children and seriously injured 19 more. Serious injuries in these cases are almost all either non-fatal brain injuries or spinal cord injuries. In this case, "children" excludes all infants who should be restrained in a rear-facing child safety seat (RFCSS). Most were not wearing seat belts or not wearing them properly. There were at least three incidents of children wearing seatbelts who were too small to be in seatbelts and should have been in forward facing child restraining seats placed in the back seat. There was one incident of a child who was leaning forward to pick up an object at the time of impact.

2.3.1.4. Infants

In this case, "infants" refers to children under the age of one who should be in a RFCSS. Airbags killed 18 such infants, 15 of whom were riding in a RFCSS, mounted in the front seat; the other 3 were in the laps of a passenger. RFCSS should never be placed in front of an airbag because they virtually guarantee that the infant will be within 10 inches from the airbag.

One child, a 2-month-old boy, was killed while riding in a RFCSS in a light truck with no back seat. The father, who was driving the truck, was sentenced to jail for not disabling the airbag.

2.3.2 Problem Solutions in Current Literature

There are several solutions to this problem available in the technical literature and in patents. A query of the patent database over the last 25 years reveals over 500 patents with the term "airbag" in the title. Not all of these airbag patents address this particular problem, but many do. Patents are issued on Tuesdays and new airbag patents appear almost every week. Problem solutions encountered fall into the following categories:

- Live with the fatalities or accept them as a reasonable trade-off. Clearly more lives are being saved by airbags than are being lost, so it has been suggested that it is a necessary risk that some should die as a result of having an airbag.
- Create more laws and enforce existing laws requiring seatbelt usage. This does not correct the engineering problem, but it does mitigate it somewhat.
- Disable the airbag with a switch. Public outcry over deaths caused by airbags has manifested itself in a request for unilateral permission to disable airbags. The law now allows for individuals who can demonstrate a need to disable their airbags. A legitimate need is defined as a short driver or a child who must ride in front. New cars and light trucks without rear seats have a disabling switch built-in.
- Automatically disable airbags when child safety seat is connected. At least one of these devices has malfunctioned causing the death of an infant in Germany.
- Diminish the power of airbag deployment. This is actually another trade-off in human life. If airbags have diminished power, then they may not be able to save people in crashes.
- Provide extensions for foot-pedals in vehicles driven by shorter people. There is no guarantee that an individual will use the device.
- Educate short drivers to set at least 10 inches from the steering wheel. There is no way to ensure the persons will learn this or will use this instruction if taught.
- Provide a sensor to detect the weight of an occupant of a seat and automatically switch the airbag off if the individual weighs less than 100 pounds. Alternately, it could also switch the airbag to a lower setting if the seat occupant is below a threshold weight. This does not address the root cause of any accident. Neither height nor weight of an individual causes airbag fatalities.
- Deploy the airbag at different speeds for different levels of impact. If the impact level is below a certain threshold, the bag will not inflate. If it is above a higher threshold, it will deflate at maximum speed. If it is between the two levels, a control circuit will select a proper speed of inflation. This addresses a need to not excessively deploy an airbag in a minor crash but does not address the specific needs of individuals seated too close to the airbag.
- Provide a sensor to the airbag circuitry to indicate whether or not the driver is wearing a seatbelt. For a belted driver, deploy the airbag at impact of 16 mph or greater. For an unbelted driver, deploy the airbag at an impact of 11 mph or greater. This solution may work best if used in combination with the last one that controls the speed of deployment with the severity of impact.

- Provide sensors regarding the distance between the airbag and the occupant and either diminish the impact or disable the airbag, depending on the maintained distance. There may be a problem with a sensor reading that does not have time to reflect forward inertia of a person during a crash.
- Provide a sensor regarding the weight of the occupant. If the occupant weighs less than 60 lbs., disable the airbag.
- Create baffles in the fabric of the airbag causing a diminished impact if it encounters a solid object (like a driver's head) earlier than expected.

In the next section is a review of technical articles that address the airbag problem in TRIZ literature and in current patents. In chapter 4, I offer my solution that was developed using the methodology described in this dissertation.

2.3.3 Technical articles

2.3.3.1. TRIZ articles[193-194]

Airbags in automobiles save lives by deploying a very fast, very forceful bag to the driver upon impact. Airbags are designed to be effective in saving lives of drivers between 5-foot 5 inches and 6 feet. The force deployed by airbags and the angle at which they are deployed may be dangerous or fatal for drivers who are too close to the steering column due to having short legs. They may also be fatal to children in the passenger seat. It has been estimated that if the common air bag were installed on the driver and passenger sides of all cars, 3000 lives would be saved each year while about 150 additional lives would be lost as a direct result of the deployment of the airbag. A compromise of human lives is an unacceptable compromise.

Kowalick[193] describes the problem in detail and then begins to solve the problem using Innovation Software. The Innovation Software he uses is just an automation of the Contradiction matrix and the 40 inventive principles. Everything done with the software could be done with the tables in about the same amount of time.

Kowalick identifies two characteristics to be improved, the *speed of the object* (9) and the *force of the object* (10). The harmful effect defined by the author is "*object oriented harmful factors*" (31). Looking at the intersection of 9 and 31, the following inventive principles are suggested:

- 2 (extraction)
- 24 (mediation)
- 35 (Transformation properties)
- 21 (Rushing through)

Looking at the intersection of 10 and 31, the following inventive principles are suggested:

- 13 (Do it in reverse)
- 3 (Local quality)
- 36 (phase transition)
- 24 (mediation)

Since "Mediation" is listed in both areas, there are a total of seven possible inventive solutions from the contradiction matrix. Kowalick generated 48 possible design approaches from the seven invention principles to eliminate the design tradeoff inherent in the present design of airbags. He did not solve the problem in this paper, but did refer to a report he wrote that discusses the problem in more detail.

Although this is a fairly lengthy article, it did not offer any solutions to the problem and did not even select a solution approach. A few months later, Domb wrote an article on the same problem, but also did not solve it or offer an approach to solve it.

Domb's article[194] on airbags is a tutorial to illustrate the meaning and application of physical and technical contradictions. Domb used the design of airbags as an example. "Technical contradictions" are what engineers call trade-offs. For airbags, the following trade-offs exist:

1. If the threshold for deployment is set low, more belted adults are protected, but more of the following people are at risk: children, unbelted adults and short adults.
2. If the threshold for deployment is set high, more children, unbelted adults and short adults are protected but more belted adults are at risk.
3. Higher power deployment saves the lives of average sized drivers, but increases injuries to smaller drivers and children.
4. Adding more sensors to customize the deployment of the system saves the lives of children and small drivers, but increases the complexity of the system.
5. Adding more sensors decreases the reliability of the system.
6. Weight sensors give erroneous information when an individual is short and heavy.

"Physical Contradictions" are situations where one object has contradictory, opposite requirement. For example,

- The deployment threshold should be high for children, etc., and low for belted normal height drivers.
- The airbag should be aggressive and depowered.
- The airbag should protect everyone and harm no one.
- The gas should be generated quickly and slowly.
- The sensor should be complex and simple.
- The airbag should exist and should not exist.

The author then illustrates how to solve the problem using the contradiction matrix and the inventive principles. Because of the method in which Domb formulated the problem, she had 6 improving features and 11 worsening features. The contradiction matrix yielded 206 different citations of invention principles. In those 206 citations, 37 principles out of 40 were cited at least once (20, 23 and 31 were omitted). Therefore, using the contradiction matrix only helps if you narrow the field to as few contradictions as possible. The author recognized this and advised the designer to choose the most relevant contradiction.

For this example, Domb felt the most relevant useful effect is "duration of action of a moving object (Row 15)" and the most relevant harmful effect is "object-generated harmful effects (column 31)." These yielded a possible four-invention principles- Rushing Through (21), Inert environment (39), Partial or excessive action (16) and Convert harm into benefit (22). Notice that for the same problem as Kowalick, Domb found a different calculus of solutions from the same contradiction matrix.

Domb expands the four inventive principles to suggest air bag solutions:

- Rushing Through (21)- Inflate the airbag faster so that it is fully inflated when a small person impacts it.
- Inert environment (39)- Soften the blow of the airbag by changing the structure of the bag where it impacts the person.
- Partial or excessive action (16)- use less power or more power to fill the airbag.
- Convert harm into benefit (22)- inflate the bag faster, so that it is no longer harmful by the time a person reaches it.

After the technical contradiction discussion, Domb solves the problem using physical contradictions by separating the problem in time, separating the problem in space or by causing a phase transformation.

2.3.3.2. Patents[195-224]

USPTO Web Patent Databases[195] is the website for accessing the US Patent and Trademark Office's databases. It allows searches of patents from 1976 to the present.

US Patent 6,040,532[196] is one of a number of weight sensors for sensing a load applied to a vehicle seat. Although this presents one solution to the problem of airbag fatalities of short adults and children, it does not directly address the problem, thus lessening the danger without eliminating it. The problem with short people in the front seat is their height and the relative position of their heads, not their weight. Although there is a correlation between height and weight, this device would not be effective for an obese, short individual.

US Patent 5,975,568[197] is another weight sensor in the seat used to deactivate the airbag for individuals under a threshold weight. It does not address the problem posed by short and obese individuals. Patent 6,040,531 references this patent.

US Patent 5,938,234[198] is a key-operated switch used to turn off one or both airbags. It also has a read-out to allow the driver and passenger to see the present state of airbag activation. Although the switch affords the flexibility to turn off the airbag, its presence changes the airbag from a passive restraint to an active restraint. If the airbag were turned off for one passenger, then left off, another passenger would not be protected. There is no guarantee that an individual would notice the LED read-out.

Similar to Patent 5,938,234, US Patent 5,992,880[199] is also a key-activated deactivation switch for the driver and passenger airbags. Its abstract is identical to the earlier patent, but the drawings are slightly different. It has the same problem as the earlier solution in that it is not automatic.

From the abstract, Patent 5,999,871[200] is a control circuit for an airbag with two or more inflators. The logic of the control circuit allows for one inflator to be inflated in a crash that is not severe and two inflators to be deployed for more serious crashes. When two inflators are deployed, the time between the two deployments is controlled by the relative severity of the crash. This patent addresses the problem of controlling deployment to limit the severity of the airbag impact, but does not take into account the problem of shorter passengers or drivers.

Patents 5,938,234 and 5,992,880 reference US Patent 5,816,611[201]. Like the latter two patents, this patent deactivates an airbag and has a visible indication that the airbag is deactivated. This patent differs in that it is a mechanical device and the indication is the relative position of a lever. In this regard, it is simpler and has less potential for failure. Like the latter patents, this patent does not preclude an activated airbag from striking a smaller individual nor does it present accidental or intentional disabling of an airbag when it should be activated.

US Patent 5,468,014[202] addresses automobiles with attachment devices for child seats in the passenger seat and passenger airbags. The design incorporates an airbag disabler when the child seat is used. This addresses the problem for infants and children in child seats only. In many US communities, child seats are not allowed in the front of the car anyway. This design does not address the problems encountered by short adults or children too old for car seats.

US Patent 5,605,348[203] references patent 5,468,014 and has similar characteristics. The sensor for the child's seat is not in the buckle as in the earlier patent, but in the seat itself. The problem with this device is that it does not address children in forward facing car seats, older children under five feet tall and short adults in the passenger seat. It does not address any problems with airbags in the driver's seat.

US Patent 5,992,874[204] also references 5,468,014. In this arrangement, a car seat can be retrofitted with the device. It has the same limitation of not being able to disable an airbag for children out of car seats or short adults or drivers. It has the same limitation of not being able to disable an airbag for children out of car seats or short adults or drivers.

US Patent 6,007,093[205] is very similar to patent 5,992,874. The former is the arrangement; this is the electrical control circuitry.

The root cause of the problem with airbags is not the size of the recipient, but the speed and direction of the airbag on impact. If an airbag strikes a child in the head, it snaps his head back, causing potentially fatal injuries. US Patent 5,851,030[206] addresses the speed of the airbag deployment, but the body of the potential victim does not control it.

US Patent 6,036,226[207] is one of the "smart airbags" in which the speed of deployment is controlled by the amount of impact, ensuring that the airbag does not exert excessive force on the occupant. US Patent 6,036,226[207] does not address the size or weight of the occupant in conjunction with airbag deployment.

US Patent 6,039,347[208] can also regulate the speed of deployment of the airbag and thus protect passengers in low impact collisions. It does not allow for small passengers.

US Patent 6,043,566[208] is an electronic control circuit designed to control airbag deployment based on the magnitude of impact. It does not address small passengers.

US Patent 5,332,260[209], US Patent 5,267,480[210] and US Patent 4,481,838[211] provide designs to retract the steering wheel. Although they do not pertain specifically to airbags, they could be used to maintain a ten-inch distance between short-legged drivers and airbags who push their seats forward in order to reach the foot controls.

US Patent 5,551,723[212] is for a pulse shaping inflation control of airbags. It allows the airbag to inflate as effectively as conventional models, but without the initial high flow rate. Its design makes the airbag inherently safer than conventional airbags for individuals seated too close to the bag without jeopardizing the lives of those seated the proper distance away. This design makes the same trade-off as the original design: individuals too close to the airbag may still be killed during deployment, but the envelope of safely seated passengers is widened by this invention. There is no quantification of the improvement, so it is impossible to measure how much distance from an airbag is considered safe with this design.

US Patent 5,865,463[213] is a design for a control system based on weight sensors in the seat of the occupant. It only allows for shutting off the airbag initiation circuitry. It will not augment the force of airbag deployment. An individual below the threshold weight will not be protected by the airbag.

US Patent 5,893,582[214] is a design for a control system for an airbag that disables the airbag if the individual is seated too close to the airbag. The sensor used is mounted on the seat adjustment track. The design does not augment the intensity of the airbag; it merely turns it off. There are two weakness in this design, 1) if an individual is seated too close to the airbag they will not be protected by the airbag and 2) addition of an electronic sensor to the system increases the complexity of the system (i.e. it could fail or give a false signal).

US Patent 6,036,226[215] allows an airbag inflation rate to be modulated depending on the severity of an accident. It modulates the force of inflation by integrating liquid into the control mechanism, thus providing a damping effect.

US Patent 6,014,602[216] is a roof-mounted sensor used to shut off the passenger airbag if the passenger is too close to the airbag. If the proximity of the passenger to the airbag is sufficient, but the passenger is unrestrained, this will allow the airbag to deploy, despite the fact that inertial force will carry the passenger toward the airbag at the time of the crash.

US Patent 6,012,008[217] predicts whether an accident is imminent and deploys the airbag before the accident occurs. In doing so, it could actually cause an accident where one would not have otherwise occurred.

US Patent 5,993,015[218] is an invention for a sensing device that locates a driver and passenger's eye location and automatically adjusts rear view mirror for blind spot minimization and can also disable an airbag firing circuit. There is an inherent risk of over-adjustment through movement within the vehicle and false signaling from the sensory devices.

US Patent 5,943,295[219] uses ultrasonic waves to determine an individual's location within a vehicle and then uses the signal to disable the airbag.

Similar to the previously cited patent of the same name (6,014,602), US Patent 5,802,479[220] is of a roof-mounted sensor used to shut off the passenger airbag if the passenger is too close to the airbag. If the proximity of the passenger to the airbag is sufficient, but the passenger is unrestrained, this will allow the airbag o deploy, despite the fact that inertial force will carry the passenger toward the airbag at the time of the crash.

US Patent 5,992,875[221] is a design for assembly-related patent for airbags in which the airbag and the mounting assembly are contained in one unit and the unit is secured to the car by means of snap fit fastening.

US Patent 6,059,312[222] has three individual chambers inside that regulate the amount an airbag will inflate. If an airbag encounters an obstacle (occupant) too soon, then not all the chambers will be inflated. Thus, it lessens the severity of impact without using sensors only when the occupant is too close to the airbag. Its only major drawback is in the fact that by the time the bag encounters the occupant, it is already forceful enough to cause injury or death- it is not the extent of the inflation that injures but the speed of the inflation.

US Patent 5,829,310[223] does not address airbags. It causes a steering column to retract at the time of a crash in an attempt to less the likelihood that the driver will strike the steering wheel. It is constructed of relatively few simple parts that can be easily and inexpensively manufactured and assembled.

US Patent 5,737,970[224] also allows a steering wheel to retract at the time of an accident. In order to maintain the proper angle of airbag deployment, there is another support member in the steering wheel that will maintain its orientation during retraction.

US Patent 5,356,178[225] is an invention that does not address the airbag, but rather the steering wheel. At the time of an accident, this will cause the steering wheel to break apart. Since many accidents occur when the driver strikes the steering wheel, the steering wheel disintegration will minimize the probability of injury due to striking the steering wheel.

US Patent 6,042,143[226] is a design aimed at reducing the cost of manufacturing a steering wheel and airbag assembly by allowing the airbag to be assembled with the steering wheel in one complete unit.

CHAPTER 3. METHODOLOGY

3.1 OVERVIEW

There are many design optimization methods available today. Two of them are the theory of constraints (TOC) and the theory of inventive problem solving (TRIZ). TOC is used to systematically identify one or more core problems in order to give direction to the problem solving process. TRIZ is used to solve problems using analogies.

The weakness of TRIZ is that it has no focus and the number of possible problems and possible solutions increase exponentially as the problem is defined. TOC does a good job of isolating the critical constraint for analysis but is very poor at actually solving the problem. Although both are logically based, they both lack an extensive logical foundation that can be converted to a set of logical equations and solved automatically. The proposed method integrates a revised TOC method to create a problem description with TRIZ problem solution methods using rigorous rules of logic.

The proposed method is a four-step process to develop a design solution from a problem statement. The first step identifies the problem and gathers information about the system. In the second step, the designer constructs a logic diagram to model the problem. In the third step, the logic diagram is analyzed to identify the best places to apply innovative problem solving techniques. The fourth step applies the innovative techniques of TRIZ to solve the problem.

The proposed method provides six contributions to the body of research:

1. This research presents a new method to identify and solve design problems in the conceptual stage.
2. This research integrates and expands the disciplines of TRIZ, TOC and logic.
3. This research creates a new logic diagram that can be used in the solution of a design concept.
4. This researches improves upon a problem solving worksheet that is useful in guiding the designer through the design process (see Appendix B).
5. This research establishes codes for design entities that are useful in analyzing designs, including 3 degrees of Desirability and 5 levels of Control.
6. This research provides a bridge between qualitative and quantitative design elements such that one diagram and method can be used in the presence of both factors.

A more detailed discussion of the proposed method is described below.

Step 1. GATHER INFORMATION ABOUT THE PROBLEM

The goal of this step is to gather all relevant facts on existing problem:

- Step 1.1. Describe the **problem** in non-technical terms
- Step 1.2. Define and describe the **system**
- Step 1.3. Refine the definition of the **problem**
- Step 1.4. Define the **solution** space
- Step 1.5. Define available **resources**
- Step 1.6. Consider allowable changes to the **system**

- Step 1.7. Further refine **solution** space

When Step 1 begins, all that is known is a vague description of a perceived problem. When Step 1 is completed, a fairly complete picture of the problem has been established, along with an idea of what constitutes an acceptable solution.

It is very important that the solution is not defined at the onset of this process. It's typical to have a solution in mind when first describing the problem in non-technical terms. Often the wording of the problem will suggest a particular solution or solution form. The discipline of developing the problem definition and the solution space is intended to identify the best solution. Often, a solution offered too quickly is sub-optimal.

In developing the problem statement and the solution space, several solution forms will often become evident to the designer. Since these ideas may be in the form of the final solution, the designer should keep a log of ideas along with the file where the problem is described. These ideas can be investigated in detail at a later time.

Step 1.1 DESCRIBE THE PROBLEM IN NON-TECHNICAL TERMS

One of the advantages of TRIZ is that it solves problems abstractly. Often designers will look for problem solutions only within the narrow confines of their problem statement that is written in very specific technical terms. The TRIZ approach is to establish a general problem statement, then look at analogous solution types (called operators) that have been proven to work in the past. The solution types are also stated in general terms so that they can easily be applied to a particular problem.

Sometimes it helps to not be an expert because "experts" have preconceived ideas of how to solve problems within their domain.

If an expert is developing the problem statement, he should review it to ensure that a layman can understand it. It's often useful to have a friend who has not been involved in the problem read the problem statement, then ask the friend to describe the problem in their own terms.

Next, gather information about the system.

Step 1.2 DEFINE AND DESCRIBE THE SYSTEM

The problem that must be solved already resides within a technical system. At this point, describe the nature of the technical system and how it fits together. Sometimes finding an optimal solution means looking beyond the system boundaries. In order to make an informed decision around the system boundaries, the designer must know what those boundaries are.

This step can be further broken down into the following sub-steps:

- Step 1.2.1. Name the system
- Step 1.2.2. Define the system structure
- Step 1.2.3. Define the sphere of influence and span of control on a system level
- Step 1.2.4. Define the way the system functions
- Step 1.2.5. Define the system boundaries and environment

Step 1.2.1 NAME THE SYSTEM

State the common or technical name of the system being improved or created. Once the name of the system is written down, questions about the systemic level of the problem are easier to address. Later, other associated systems are identified, namely:

- The super-system into which the identified system exists
- Other systems that interface with the system in the same super-system
- Sub-systems that are a subset of the identified system.

Step 1.2.2 DEFINE THE SYSTEM STRUCTURE

Systems can be defined statically and dynamically. According to IWB2000[7], this is the opportunity to define the sub-systems, the important elements of the system and the connections between them.

Draw the system structure showing the elements of the system, the subsystems that make up the system and the interfaces between them. Sometimes there are obvious systemic problems that can be identified at this point. Although it is not recommended that the problem be solved yet, consideration of the system structure provides an opportunity to identify room for systemic improvement. Make notes on a system improvement ideas that have surfaced from the system diagram.

Step 1.2.3 DEFINE THE SPHERE OF INFLUENCE AND SPAN OF CONTROL ON A SYSTEM

While considering system structure, identify the Span of control and Sphere of influence. Span of control is defined in TOC as the areas of the system in which the designer has a high degree of control. Sphere of influence is defined in TOC as the areas of the system where things can be influenced to varying degrees but not directly controlled. Beyond the sphere of influence are those items that cannot be controlled or influenced by the designer at all. It is useful to know where these control boundaries so that

- Focus is applied to areas that are practical to change
- Time is not wasted on system elements that cannot be influenced
- A clear understanding of the operating environment is developed

Even if an element is outside of the span of control and sphere of influence, it may be possible to circumvent it or nullify its effect by creating a system that is robust in respect to that element. Knowledge of the system empowers us to make an informed decision on the nature of the solution. Later, when we define the individual entities that make up the system, we will code each one regarding our relative control over it (see step 2.2.1.4).

Step 1.2.4 DEFINE THE WAY THE SYSTEM FUNCTIONS

Identify the primary function of the system. A function is an action performed by the system on another system or within a super-system.

Next, define the primary function of the super-system.

Define the dynamic functioning of the system. From IWB2000[7] "The functioning of the system as described here is the intended "work" of the system. This means that the goal of problem solving is to provide this functioning as it is (or was) intended."

Step 1.2.5 DEFINE THE SYSTEM BOUNDARIES AND ENVIRONMENT

Define what belongs in the system and what is outside of the system.

Define the supersystem that includes this system, along with any other system that may also be in the same supersystem.

Define other systems that are related to the system, such as those that supply energy to the system or those that are recipients of the system's by-products.

Define the environmental conditions for the system. According to Innovation Workbench 2000[7], "The system environment is an extremely important resource "pool" for problem solving. Elements, fields, functions and information from the environment can be extremely useful for effectively implementing a solution."

Define the requirements for interactions between the system and other systems and between the system and the supersystem.

Next, gather information about the problem:

Step 1.3 REFINE THE DEFINITION OF THE PROBLEM

In step 1.1, a non-technical description of the problem was developed. In this step, the problem is defined in more detail using the information garnered from the analysis of the system in step 1.2.

Sometimes there is no specific problem to be solved. For instance, maybe the designer is only interesting in gaining competitive advantage or offering the next design improvement to the marketplace. In such a case, proceed directly to step 1.4.

In step 1.3, the following is accomplished:

- Step 1.3.1. Identify the problem to be resolved.
- Step 1.3.2. Establish the mechanism causing the problem.
- Step 1.3.3. Describe the undesired consequences of an unresolved problem.
- Step 1.3.4. Briefly describe the history of the problem.
- Step 1.3.5. Identify other systems in which a similar problem exists.
- Step 1.3.6. Identify any other problem that should also be solved in the course of solving the primary problem.

Step 1.3.1 IDENTIFY THE PROBLEM TO BE RESOLVED

Describe the problem into one of four generic categories (from IWB2000[7]):

1. A failure or drawback must be eliminated/corrected:
   i) A harmful action or effect is present in the system
   ii) An undesired parameter or characteristic is too high
2. The root causes of a failure or drawback must be discovered (Failure Analysis):
   i) The mechanism causing the failure or drawback is not clear
   ii) One or more obstacles connected with the failure/drawback have no apparent explanation
3. A product/process or its part/operation must be improved:
   i) A useful parameter or characteristic is insufficient
   ii) A required useful action is absent
   iii) A required useful action is implemented ineffectively or incompletely
4. Information about an object's condition must be detected:

i) Required information about an object's condition is absent

ii) Required information about an object's condition is insufficient

Step 1.3.2 ESTABLISH THE MECHANISM CAUSING THE PROBLEM.

Identify all known ways in which a failure can occur at the systemic level. Later, in step 2, the system will be drawn in a logic diagram and more ideas for potential failure mechanisms will be identified.

In TRIZ methodology, this is an opportunity to "describe all known hypotheses (mechanisms) regarding the cause of this problem using 'cause-and-effect' chains." From this point, Ideation recommends departing from a straightforward problem solving approach and developing the causes of failure using Anticipatory Failure Determination or AFD. The problem with using AFD at this point is that AFD is actually a harder system to apply than I-TRIZ and TOC combined. The way AFD works is to:

- Draw the system diagram.
- Identify the kinds of failure that may occur.
- Apply all the methods of TRIZ to "design" a system in which each failure occurs.
- Remove at least one of the necessary inputs to each failure, making it impossible to occur.

Although the AFD method is logical, it causes the design process to grow exponentially as every single failure mode is designed into the system, then eliminated. As such, the application of AFD methodology should only be applied at a single failure cause level, not at the system level as suggested by the AFD model.

Step 1.3.3 DESCRIBE THE UNDESIRED CONSEQUENCES OF AN UNRESOLVED PROBLEM.

In any cost-benefit analysis, a designer must consider the "do nothing alternative." Likewise, before considering a large redesign project, consider the consequences of doing nothing.

Often the best plan is to do nothing. If the problem is someone's "pet project" that is not very important to the overall supersystem, maybe resources would better be directed elsewhere. Likewise, if the problem is temporal and will most likely go away on its own, now is a good time to document that fact and move on to something else.

From a cost perspective, it is crucial that any decision made to stop the design and development process be applied at the earliest possible opportunity. From this point onward, the designer must keep clearly in mind the consequences of leaving the problem alone.

Step 1.3.4 BRIEFLY DESCRIBE THE HISTORY OF THE PROBLEM

If this problem has previously been addressed, discuss the features and success of earlier design solutions. Check the patent database to see if there are any patents that deal with the particular problem at hand.

Describe when the problem was first observed. Often, problems are a byproduct of earlier solutions to different problems. Note the previous problem and why the solution caused this problem. An acceptable solution should not reintroduce earlier problems.

If there is a known solution to the problem that has undesired consequences, document the solution and the consequence. It is possible TRIZ Design techniques can be applied to remove the technical contradiction later on.

Step 1.3.5 IDENTIFY OTHER SYSTEMS IN WHICH A SIMILAR PROBLEM EXISTS

If there is a similar system in which a similar problem has been addressed and resolved, make a note of it. Since design techniques are based on analogies, be extremely creative in deciding what is similar.

If there were secondary effects introduced in the other system, make a note of them. They may be unacceptable in applying a similar to the problem at hand.

Step 1.3.6 IDENTIFY ANY OTHER PROBLEM THAT SHOULD ALSO BE SOLVED IN THE COURSE OF SOLVING THE PRIMARY PROBLEM.

There are often other ways around solving the problem at hand. In many cases it is unsolvable or at least unsolvable with today's technology. In such instances, it is useful to consider alternatives to directly solving the problem.

For instance, could the system be changed in such a way that the "problem" is actually useful in some other part of the system? This kind of approach is a solution at the supersystem level.

If the problem cannot be avoided with the current system, consider whether the useful function of the system could be achieved by a different system without the consequence of the problem.

After identifying the problem, proceed to identifying the solution space.

Step 1.4 DEFINE THE SOLUTION SPACE

In TRIZ theory, the ideal solution is called the ideal final result Answer the question, "If there were an ideal design, what would its features be?" State the problem in terms of a system that is "ideal" in that it has no undesirable entities and optimized desirable entities. It does not matter if this design description is neither practical nor possible to design.

Step 1.5 DEFINE AVAILABLE RESOURCES

Usually, all that is needed to solve a problem can be found in readily available resources; it is just a question of finding what those resources are and figuring out a way to apply them to the problem. From Innovation Workbench 2000[7], "Resources are substances, fields (energy), their properties, functional characteristics and other attributes existing in a system and its surroundings, which can be utilized for system improvement. Readily available resources are resources that can be used as they are."

IWB2000 has divided available resources into the following categories for consideration:

- Substance resources
- Field resources
- Space resources
- Time resources
- Informational resources
- Functional resources

Likewise, also consider that available resources may also be *derived* from the system using some sort of transformation.

Step 1.6 CONSIDER ALLOWABLE CHANGES TO THE SYSTEM

In order to further define the possible form of the final solution, consider what changes are acceptable to the system. For instance, is a complete change to the system acceptable, or are the changes confined to only slight modifications of the existing system?

If there are areas within the system that cannot be changed, define how they are constrained. For instance, perhaps a certain variable cannot decrease below a certain value or must remain constant.

If there are constraints to the system, define the reasons for the imposed restrictions. It may be possible to remove the restriction instead of living with it. Consider whether removing the restrictions causes new (secondary) problems and evaluate if it might be better to resolve these problems rather than the "original" problem.

Step 1.7 FURTHER REFINE SOLUTION SPACE

From Innovation Workbench 2000[7]:

"Any process must have a measure for success. Some criteria are so obvious that they are not even mentioned until they are violated by an already developed concept. To avoid wasting time and effort developing useless solutions, it is better to document the success criteria beforehand.

1. Indicate the desired technical characteristics compared to the existing characteristics.
2. Indicate the desired economic characteristics compared to the existing characteristics. In particular, specify an acceptable cost of each prospective change, an acceptable amount of investment for implementing each change, etc.
3. Indicate the desired timetables for the realization of each stage of work; i.e., the development of concepts, evaluation of potential solutions and implementation of the solutions.
4. Indicate the expected degree of novelty of the solutions (e.g., is it desirable to patent new concepts?).
5. Consider additional criteria, such as:
    - Product appearance
    - Convenience and low cost of maintenance and service
    - Other."

Step 2. CONSTRUCT A LOGIC DIAGRAM

This is the most crucial step of this approach and does not follow either a pure TRIZ Problem formulation or the TOC's Current Reality Tree. Instead, it uses a logic diagram that incorporates ideas from both as well as using basic Boolean algebra. The logic diagram looks similar to an electrical schematic, but it is not intended to be one. The electrical schematic look is intended to get the designer/engineer to think of ways to "turn on" desirable characteristics and "turn off" undesirable characteristics.

The greatest difficulty experienced with this approach was to code entities that are not Boolean in nature but are quantitative. To address this problem, variables are allowed to be either quantitative or Boolean and are transformed from one type to the other using amplifiers to convert signals from one type to another. Also, special operators are defined to deal with non-Boolean logic, called Converter gates.

Step 2.1 IDENTIFY CHIEF UNDESIRABLE EFFECTS

A logic diagram is visual model of the system. Before constructing the wiring diagram, it helps to clarify the identifying the undesirable effects or outcomes of the system.

In all likelihood, the system was designed to have a desirable end effect that is the considered the purpose of the design. Often, while seeking a terminal desirable effect, there is a byproduct that is undesirable. For the design to be improved, these undesirable byproducts are removed. For instance, from the case study presented in Chapter 4, an airbag is designed to save lives by deploying during an accident. An undesirable side effect of their design is that some people have died as a result of the design of the airbag.

In many cases, the motivation to redesign an existing product is to address an undesirable effect of the process. A classical engineering approach to design is to find a way to make a technical trade-off (called a technical contradiction in TRIZ literature) of some desirable effect and another undesirable one. We want to find a solution that is superior to such a compromise that retains the desirable effects while neutralizing or eliminating the undesirable ones.

For these reasons, the logic diagram will demonstrate how these undesirable effects are caused by the system. Knowledge of how these undesirable effects are caused by the system helps to diagnose the system. If there are any known undesirable effects, they'll be identified now and used as "end effects" in the logic diagram.

In *Goldratt's Theory of Constraints*[10], Dettmer outlines the following process:

1. Beginning with the problem statement, list as many UDEs as you can that confirm the existence of the problem
2. Write UDEs in grammatically correct sentences
3. Check UDEs for undesirability.
4. Verify that the UDE really exists
5. Choose the worst five UDEs, setting the rest aside

There are two ways to control an undesirable entity:

1. Operate directly on the entity, eliminating it or neutralizing it
2. Find out what causes the effect and eliminate the cause so that the effect never occurs in the first place.

In the first case, operators can be directly developed from the TRIZ toolkit. The method to develop operators is identified in step 4.1.

In the latter case, the logical design of the entire system must be defined. The latter approach is generally superior because, with a picture of the entire system, systemic solutions can be developed. A systemic solution can address more than one UDE at a time. For these reasons, the UDE is incorporated into a logic diagram of the system.

Step 2.2 DRAW THE LOGIC DIAGRAM

In this step, a picture of the system in which our problem is created is developed. It is in the form of a logical diagram that has logic gates to define the relationships between cause and effects. These entities are treated as electrical signals that are either supplied by some outside power supply or are created by other signals that are manipulated by Boolean operators.

Boolean algebra can be used to describe any logical relationship and can be built with three logical operators, the AND gate, the OR Gate ad the NOT gate. Although these basic building blocks are sufficient, they are sometimes unwieldy to use. For this reason, other logical operators that are derived from the basic three, like the XOR Gate are also used.

Another inadequacy of using only Boolean algebra is that there are many design factors that are not truly logical but are variable in nature, like weight, cost or distance. These can be modeled these by using amplifiers and other operators on *qualitative* variables. Care must be used when converting entities between their *logical* and their *quantitative* variable counterparts. The Converter gate, the Inverter and the Amplifier can all be used to accomplish this purpose.

Step 2.2.1 CONNECTING ENTITIES

In an analog logic diagram, entities are related causally to each other. In order to do this, first link the UDEs identified in step 2.1 together. Later, adding the Desirable Entities and rest of the logical operators completes the system picture.

Step 2.2.1.1 CODE THE ENTITIES

First, identify each entity as either:

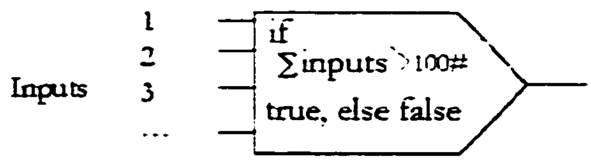
- A Boolean Variable -true or false, taking a value of 1 or 0, respectively, or
- A Quantitative Variable – define threshold values if possible, too. For instance:

1) Weight cannot exceed 1,000 lbs
2) Cost must be below $100 per unit
3) Maximum speed must be at least 60 feet per second.

Quantitative Variables must be converted to Boolean Variables before they can used as inputs to logical gates (AND, OR, NOT or XOR). Likewise, outputs of logical gates can only take on values of 0 or 1 and thus must be converted if a quantitative variable is needed. The Converter operator is semi-logical, meaning it takes quantitative variables as inputs and delivers a logical output. The AMPLIFIER is not a logical operator, but is used to convert between logical and quantitative variables.

Converting a quantitative variable to a logical one:

Suppose you need to have a weight of more than 100 lb to declare success for entity C. The diagram would look like this:



If the sum of all the inputs is less than 100 lb, then the output of the Converter gate is false (0), otherwise the output is true (1).

Converting a logical variable to a quantitative one:

Suppose that if an electrical signal is a logical "thrue," then 15 volts are present. If the signal is a logical "false," 5 volts are present. The diagram would look like this:

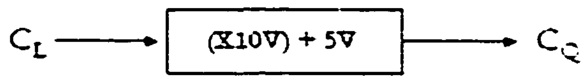


Figure 15. Converting Between Logical and Quantitative Values

Entities are coded as "qualitative" or "logical" by assigning the letters "Q" and "L" after the number for the entity.

Step 2.2.1.2 IDENTIFY CONNECTIONS BETWEEN ENTITIES

The connections between entities are of the following types of gates:

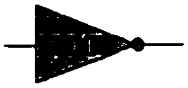
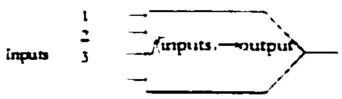
AND Gate		**A * B → C**	If A and B are true, then C is true
OR Gate		**A + B →C**	If A is true, C is true. If B is true, C is true. If A and B are false, C is false
Inverter Gate		**A → ~B**	If A is true, B is false, If A is false, B is true
Invert an input or an output			Circle designates inversion
X-OR Gate		**A ⊕ B → C**	If both A and B are true, then C is true, if both a and b are false, C is true
Amplifier Gate		**B = 100A**	If A has a value of 1, B has a value of 100
Converter (Black Box) Gate		**Converts from Quantitative to logic or any other necessar function- for example** **Σ Inputs > x →C** **Π Inputs > x →C**	Ex: If the sum of A and B is greater than x, then C is true (TOC MAG AND) If the product of A and B is greater than x, then C is true

Figure 16. Table of Logical Operators

Relationships between entities can be either Causal or Counteractive. The relationships are built with the gates listed above and the gates assume all relationships to be causal. Counteractive relationships are built using inverter gates and amplifiers.

Step 2.2.1.3 CODE ENTITIES AS DESIRABLE, UNDESIRABLE OR NEUTRAL

The entities are now coded as Desirable, Undesirable or Neutral. It is a design goal that Desirable entities (DEs) that are end effects should be "TRUE" and UDEs that are end effects should be "FALSE." Causes may be either TRUE or FALSE, depending on how they are used to control the end effects. Circumstance dictates whether a Cause is Desirable, Undesirable or Neutral. For instance, in the design of an airbag a crash may be considered to be a desirable cause because the airbag is designed to save lives in the presence of an accident. But for consistency, it is considered an undesirable (but also unavoidable) cause, which cannot have its value set to FALSE.

For coding purposes, a prefix is used for each entity indicating the desirability of the entity:

- "D-" for desirable entities
- "U-" for undesirable entities
- "N-" for neutral entities.

Step 2.2.1.4 CODE CONTROL OF ENTITIES

Next, each entity is coded for relative degree of control. Span of control is defined in TOC as the areas of the system in which you have a high degree of control. Sphere of influence is defined in TOC as the areas of the system where we can influence things to varying degrees but don't have direct control. Beyond the sphere of influence are those items, which cannot be controlled or influenced by the designer at all. It is useful to know where these control boundaries are so that

- Focus is applied to areas that are practical to change.
- Time is not wasted on system elements that cannot be influenced.
- A proper understanding of the environment is developed.

Even if an element is outside of control and influence, it may be circumvented or its effect nullified by creating a system that is robust in respect to that element.

For coding purposes, a control suffix to the entity number is used:

- "-C1" for entities under *direct* control- this is the highest level of items in our span of control. In these, we can *directly control* their value. For example, if the material of an item we are designing may be steel, lead or copper. Since we are designing the item, we can choose the material, so the material type would be coded as C1.
- "-C2" for entities under *indirect* control- like C1, these are in our span of control, but only through manipulation of other entities or the logic of the system can we change them. Still, we do not need to get authority from an outside agency to change their value. End effects of designs are usually C2 because changing their design is only possible through changing some other entity that controls it. For instance, if we want to design a car airbag to deploy in such a way that it will not be the cause of a fatality, we cannot directly control it, but we can indirectly control it by choosing things within the airbag system that we can directly control.
- "-C3" for entities that our controlled by an outside source or agency. Since someone controls these, they are by definition under our *sphere of influence*. All we need to do is influence the person or agency controlling these entities. Policies often fall into this group. The federal guidelines for when an airbag deploys is an instance of a C3 control. It is controlled by someone, but not by the designers of the airbag. It may be possible to influence these standards, but it is more likely to be outside the scope of the problem.
- "-C4" for entities that are controlled by nature or are "given" for the problem. These are outside of our sphere of influence, unless we are allowed to redefine the problem. For instance, in the airbag example, the existence of a driver who his under 5 feet tall is given. We cannot make the design exclude these

people, although we may be able to compensate for their height (if necessary) by changing the system in some way that negates the danger of short drivers in an accident.

- "-C5" for entities completely outside our sphere of influence. In some cases, we can still ignore them, but it is even more difficult than for C4 entities. In the airbag example, "an accident occurs" is such an entity. We cannot remove it from the problem. If we could redesign the safety system of an automobile to make an accident impossible, then we could circumvent even this problem. From a creative thinking standpoint, solutions that address the C5 control level are exciting because they will (by definition) change the entire complexion of both the problem and the solution.

Step 2.2.2 ASSIGN NUMBERS TO EACH ENTITY.

Assign a number to each of the terminal effects that starts with 101. (101, 102, 103....)

The next layer back (i.e. the immediate causes of the terminal effects) is assigned 200 series numbers (201, 202, 203 ...)

The causes of the 200 series entities are assigned 300 series numbers and so on.

Step 2.2.3 SUMMARY OF THE ENTITY CODE SCHEME

D-	101	Q	-C1
U-	102	L	-C2
N-	Etc.		-C3
			-C4
			-C5

Figure 17. Entity Scheme Variables

First position (desirability):

"D-" for desirable entities

"U-" for undesirable entities

"N-" for neutral entities.

Second position (Indenture):

First digit represents where it is in the logic of the system (100- terminal effect, 200- immediate causes of terminal effect and so on)

Second two digits are sequentially ordered (01, 02, 03...99)

Third position (variable type)-

Q- quantitative

L- logical or Boolean

Fourth Position (control)

-C1 for entities under *direct* control

-C2 for entities under *indirect* control

-C3 for entities that are controlled by an outside source or agency.

-C4 for entities that are controlled by nature or are "given" for the problem.

-C5 for entities completely outside of sphere of influence.

For example, "U-101L-C2" is the code for the terminal effect of the airbag logic diagram (figure 23), ***airbag causes a fatality***, it is coded-

U	An Undesirable entity
101	The first or primary terminal effect of the system
L	A logical variable
C2	Outside of direct control, but indirectly controllable by controlling input causes.

Figure 18. Entity Value Example

Step 2.2.4 TEST THE LOGIC DIAGRAM USING THE RULES OF LOGIC.

Once cause and effect relationships are incorporated into the logic diagram, they need to be tested for validity and completeness. In *Goldratt's Theory of Constraints*[10], Dettmer cites rules of logic developed for Theory of Constraints. These rules of logic are called, "Categories of Legitimate Reservation" (CLR). The method proposed in this dissertation uses a modified list of logical rules derived from TOC's CLR.

From Dettmer, the CLR is listed below:

1. Clarity (seeking to understand)
    a. Would I add any verbal explanation if reading the tree to someone else?
    b. Is the meaning/context of words unambiguous?
    c. Is the connection cause and effect convincing "at face value"?
    d. Are intermediate steps missing?
2. Entity Existence (Complete, properly structured, valid statements of cause and effect)
    a. Is it a complete sentence?
    b. Does it make sense?
    c. Is it free from "if-then" statements?
    d. Does it convey only one idea (i.e. not compound entity)?
    e. Does it exist in my reality?
3. Causality existence (Logical connection between cause and effect)
    a. Does an "if then" connection really exist, as written?
    b. Does the cause, in fact, result in the effect?
    c. Does it make sense when read aloud exactly as written?
    d. Is the cause intangible? (If so, look for additional predicted effect)
4. Cause insufficiency (A nontrivial dependent element missing)
    a. Can the cause, as written, result in the effect on its own?
    b. Are there any significant cause factors missing?
    c. Is/are the written cause(s) sufficient to justify all parts of the effect(s)?
    d. Is an ellipse *(an AND Gate)* required?
5. Additional cause (A separate, independent cause producing the same effect)

a. Is there anything else that might cause the effect on its own? *(Missing OR Gate)*

b. If the stated cause is eliminated, will the effect be almost completely eliminated?

6. Cause-effect reversal (Arrow pointing in the wrong direction)

   a. Is the stated effect really the cause and vice versa?

   b. Is the stated cause the reason why or just how we know the effect exists?

7. Predicted effect existence (Additional corroborating effect resulting from cause)

   a. Is the cause intangible?

   b. Do other unavoidable outcomes exist besides the stated effect?

8. Tautology (Circular logic)

   a. Is the cause intangible?

   b. Is the effect offered as a rationale for the existence of the cause?

   c. Do other unavoidable outcomes exist besides the stated effect?

In addition to these logical rules, a few more are required for this approach.

9. Check that all variables are of the right type, Boolean or Quantitative.
10. Check that Quantitative variables are converted to Boolean variables before entering a AND, OR, XOR or NOT gates.
11. Check that Boolean variables are converted to Quantitative variables before entering Converter gates.
12. Check that there is a "machinery" input entity for each entity that requires a piece of equipment to operate.

Step 2.2.5 COMPLETE THE LOGIC DIAGRAM

At this point, there will be some gaps in the logic of the system that the developer should consider. Since it is crucial to identify as few critical entities as possible, once the diagram is drawn, check to see that it goes deep enough to reveal the right entities. From Dettmer[10]:

1. First, look for intervening entities that are needed to solidify the cause and effect relationship.
2. Next look for ways to link together different branches of the logic diagram.
3. Build each branch to the left until a logical lateral connection presents itself.
4. Add entities as required to tighten logic.
5. Re-check all connections using rules of logic.
6. Look for connections that may actually be correlations, rather than cause and effect.

Step 3. ANALYZE LOGIC DIAGRAM TO FIND THE CONSTRAINTS OF THE SYSTEM

Develop a set of rules to work through a logic diagram:

Step 3.1 FIND THE SWITCHES FOR THE SYSTEM

Looking at the terminal effects, are they directly controllable (coded C1)? If they are and they are desirable, generate I-TRIZ solutions for Desirable entities (steps 4.2 and 4.4). If they are undesirable, generate I-TRIZ solutions for Undesirable entities (step 4.1).

If there is more than one terminal effect, look for the best place to force the system to turn all UDEs off and all DEs on, with a few exceptions.

To do this, find a directly controllable entity or a small group of directly controllable entities that can force the indirectly controllable entities to their desired states. These points are called "switches" for the system because they can be switched on and off to control the whole system.

There are instances where undesirable cause entities must be switched "on" in order to control downstream effects. Likewise, there are instances where desirable cause entities must be switched "off" in order to control downstream effects. Such instances are usually some form of engineering trade-off. In TRIZ theory, engineering trade-offs are called technical contradictions and are generally avoided in design. In TRIZ, a discipline has been developed to eliminate a technical contradiction that is very effective and useful. In such instances, TRIZ theory is used to eliminate the contradictions as described in step 4.3.

Step 3.2 FOR EACH DE, SEEK TO ENSURE THE LOGICAL VALUE OF THE ENTITY IS = 1.

In this case, switches that are DE and are Boolean in form are considered here. If the entity is quantitative, then set a target value and convert then it to 1 if it is reached or zero if it is not.

Once the logical DE switches are established, solve them using I-TRIZ methods described in step 4.2.

Step 3.3 FOR EACH UDE, SEEK TO CREATE THE VALUE OF THE NODE = 0

Perform the same analysis for switches that are UDE and are Boolean in form. If the switch is quantitative, then set a target value and convert then it to 1 if it is reached or zero if it is not.

Once the logical UDE switches are established, solve them using I-TRIZ methods described in step 4.1.

Step 3.4 IDENTIFY ANY TRADE-OFFS IN THE DESIGN

If there are known trade-offs in the current design (called technical contradictions in TRIZ), they are also a good place to begin.

Trade-offs represent:

- A "couple" where one effect entity is desirable and the other is undesirable (common)
- An undesirable entity that causes a desirable one (rare)
- A desirable entity that causes an undesirable one (common)
- A desirable entity that somehow limits another desirable entity (common)
- An undesirable entity that is the only way to limit another undesirable entity (rare)

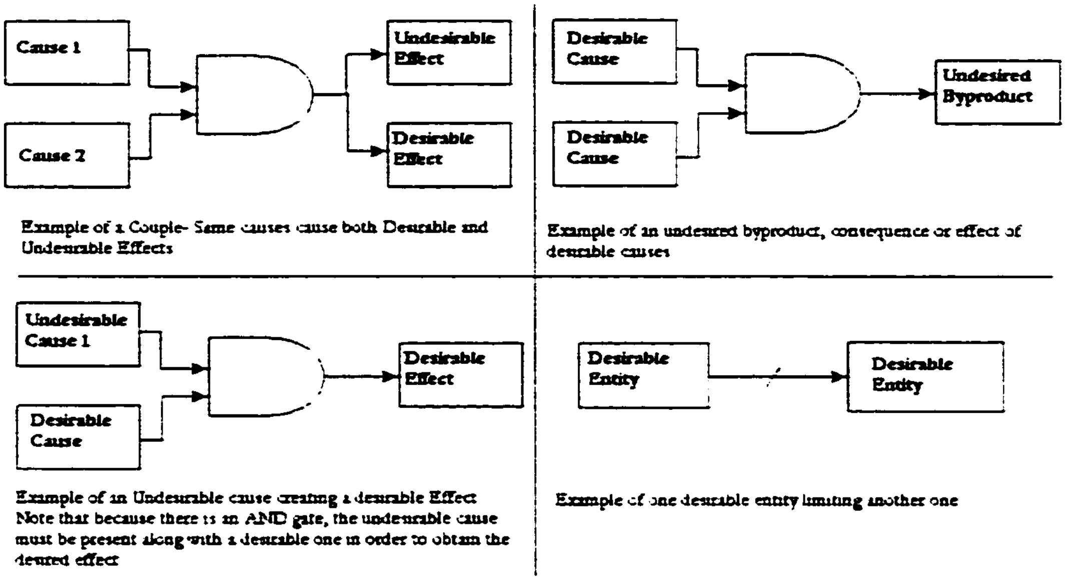


Figure 19. Examples of Trade-offs or Contradictions

Once the trade-off switches are established, solve them using i-TRIZ methods described in step 4.3.

Step 3.5 REVIEW TOTAL SYSTEM

In TOC, there are methods to find root causes and core problems established when such are not immediately visible in the original logic established for the system. As a check that the best entities for switches have been found, I recommend considering this process, reproduced below from Dettmer[10]:

1. Identify Root Causes and Core Problems

- Locate all root causes (entities with outbound arrows only)
- Determine how many UDEs each root cause produces
- Determine whether any root cause produces 70 percent or more of the UDEs. If so, designate it as the core problem. If not, go to the next step.
- Look for V-Shaped or missing connections to ensure diagram captures the true logic of the system
- Compare root causes; look for two that might be related
- Continue to build the logic diagram until you find a root cause
- Look for previously missed lateral connections above the root cause
- Determine core problem
- Decide which root cause to attack
- Draw your span of control to enclose all entities over which you have authority

- Draw your sphere of influence to enclose all entities outside of your span of control that you can influence
- Select the core problem, if it lies in your span of influence
- If the core problem is not within your sphere of influence, select one or more root causes within your sphere of influence

Table 4. How to Identify Root causes and Core Problems (from Dettmer[10])

Step 4. GENERATE SOLUTIONS AT THE CRITICAL ENTITIES AND TRADE-OFFS

A critical entity is an entity found in step 3 to be a switch that can control the final outcome of the design. Now there is enough information to focus on where the best application of the final solution should be and apply the principles of TRIZ to it.

The foundation of Ideation TRIZ is the simple yet profound notion that the objective of design and innovation is to increase Ideality. If entities can be described as either "useful" (desirable) or "harmful" (undesirable), then to increase ideality, one merely has to increase the beneficial effects of desirable entities and decrease the detrimental effects of the undesirable entities. At the onset, this sounds exactly like the Classical TRIZ contradiction resolution, but in fact it goes much further. Where Classical TRIZ only tries to eliminate trades between harmful and useful events, Ideation TRIZ goes further because it seeks to increase benefits and decrease detriments regardless of the presence of limiting factors.

One tool of Ideation TRIZ is Innovation Workbench 2000[7], a dynamic tool used to assist in the problem solving process. A user of this tool defines the problem with block entities that are coded as "Harmful" or "Useful." These entities are connected to each other as either causal or counteractive. Once the system model is constructed, a list of possible areas for solutions is generated. In studying the model, I noticed that the solutions created followed predictable patterns and these solutions patterns actually created a large number of possible solution types to investigate, more than any designer would want to address. The following discussion is my observation of how the tool works, after that is a suggestion of how I believe the tool can be more effectively used. I do not advocate creating a system model in IWB2000 because IWB2000 generates too many solution types and does not take into account logical operators or chief constraints.

How IWB2000 works

For consistency, let us rename the two different kinds of events, Harmful Events (HE) and Useful Events (UE), as Undesirable Entities (UDEs) and Desirable Entities (DEs), respectively. The relationship between entities may either be causal (→) or counteractive (⇸). Therefore, in a system with two or more entities, the smallest component of relationships between events can be manifested in eight configurations:

1. DE → DE
2. DE → UDE
3. DE ⇸ DE
4. DE ⇸ UDE
5. UDE → DE

6. UDE → UDE
7. UDE ↛ DE
8. UDE ↛ UDE

A system then can be drawn for any problem that consists of these eight building blocks.

The Ideation Software Tool, Innovation Workbench 2000[7] (IWB2000) from Ideation International has a Problem Formulator Module to analyze systems. To use this module, an inventor first converts a system to a diagram consisting of events coded as harmful or useful and relationships between these events that are either causal or counteractive. After completing the diagram, the inventor selects the "formulate" icon and solution types for relationships between the blocks are generated.

Problem formulator offers four solution types:

1. Solution types that target an undesirable entity (configurations 2, 4, 5, 6, 7 and 8)
2. Solution types that target a desirable entity (configurations 1, 2, 3, 4, 5 and 7)
3. Solution types aimed at resolving contradictions (configurations 2, 3, 5 and 8)
4. Solution types aimed at increasing the level of ideality of the system (configurations 1, 3, 5 and 7 where effect is not a cause to any subsequent effect)

Each of these four solution types, which called henceforth "parent relations," can be further expanded to from 2 to 9 different forms of solutions, which are called "child relations." Each child relation has between 1 and 13 different forms of solution, which called "grandchild relations." Each grandchild relation has between 1 and 40 different solution types called "operators." Some operators are further broken down into sub-operators. At the lowest level of operator or sub-operator, IWB2000[7] offers examples of the application of the particular principle.

The method proposed in this dissertation identifies the Parent relations that are the best logical choices by considering the degree of control, logic of the system and analysis of system switches. Once these parent relations are identified in step 3, only they are considered for analysis using TRIZ methods, thus limiting the number of solutions to consider.

Parent relationships

There are four different kinds of parent relationships, as described above. Using IWB2000[7]'s Problem Formulator, the following applies:

1. For each UDE, Problem formulator generates nine child relations.
2. For each DE, Problem formulator generates six child relations.
3. For each contradiction, Problem Formulator generates two child relations.
4. For each DE that is also a terminal effect (i.e. it does not cause any subsequent effects), Problem formulator generates seven child relations.

Once a model of a system is generated, then Problem formulator will create the following suggestions:

1. One for each UDE, plus
2. One for each DE, plus
3. One for each contradiction, plus
4. One for each terminal DE.

In the next sections, these suggestions are further broken down into child relations, grandchild relations and operators. Using I-TRIZ by itself causes even a very simple problem to generate a great deal of potential solutions, more than a reasonable design effort could afford to research.

Step 4.1 I-TRIZ Solution Recommendations for Undesirable Entities

If a particular critical entity must be "turned off," then follow I-TRIZ solution recommendations for UDE. TRIZ Problem Formulator generates the following problem statements. Substitute the name of the UDE or DE for "Harmful Cause," "Harmful Effect," "Useful Cause" and "Useful Effect."

UDE → DE	Find a way to eliminate, reduce or prevent Undesirable entity then think how to provide Desirable entity
UDE → UDE	Find a way to eliminate, reduce or prevent Undesirable entity cause in order to avoid Undesirable entity effect
	Find a way to eliminate, reduce or prevent Undesirable entity effect under the conditions of Undesirable entity cause
UDE ↛ DE	Find a way to eliminate, reduce or prevent Undesirable entity
UDE ↛ UDE	Find a way to eliminate, reduce or prevent Undesirable entity cause, then thinks how to eliminate, reduce or prevent Undesirable entity effect.
	Find a way to eliminate, reduce or prevent Undesirable entity cause
DE → UDE	Find a way to eliminate, reduce or prevent Undesirable entity under the conditions of Desirable entity
DE ↛ UDE	Find a way to eliminate, reduce or prevent Undesirable entity

Table 5. Problem statements generated for Undesirable Entities by IWB2000[7]

Regardless of the particular parent, there are 9 child relations for the UDE Parent. The 9 child relations have a total of 47 grandchild relations and 135 operators. The UDE child relations are:

1. Isolate the system or its part from the harmful effect.
2. Counteract the harmful effect.
3. Impact on the harmful action.
4. Reduce sensitivity of the system or its part to the harmful effect.
5. Eliminate the cause of the undesired action.
6. Reduce the harmful results produced.
7. Apply universal Operators to reduce the undesired factor.
8. Consider resources to reduce the undesired factor.
9. Try to benefit from the undesired factor.

Table 6. Child Relations of Undesirable Effects

Step 4.1.1 THE "ISOLATE THE SYSTEM OR ITS PART FROM THE HARMFUL EFFECT" UDE CHILD RELATION

The first UDE child relation, "Isolate the System or Its Part From the Harmful Effect," has 6 grandchildren and 19 operators:

1. Introduce an isolating substance
    1.1. Deformation
    1.2. Wear
    1.3. Overheating
    1.4. Ambient Oxygen
    1.5. Moisture
    1.6. Evaporation
    1.7. Low Temperature
    1.8. Fire, Explosion
2. Introduce a liquid
    2.1. Introduce a liquid
    2.2. Smart way to introduce a substance
3. Use a selectively-permeable isolation
    3.1. Employ selectively permeable isolation from thermal influence
    3.2. Employ selectively permeable isolation from pollution
    3.3. Employ selectively permeable isolation from noise
    3.4. Employ selectively permeable isolation from fire or explosion
4. Use an easily destroyed interlayer
    4.1. Use an easily destroyed interlayer
    4.2. Smart way to introduce a substance
5. Use the culprit of an undesired action is an operator with no subordinates
6. "Shelter" for a period of time
    6.1. "Shelter" for a period of time
    6.2. Smart way to introduce a substance

Step 4.1.2 THE "COUNTERACT THE HARMFUL EFFECT" UDE CHILD RELATION

The second UDE child relation, "Counteract the Harmful Effect," has 6 grandchildren and 18 operators:

1. Preliminary counteraction
    1.1. Preliminary counteraction
    1.2. Improve mechanical strength
2. Divide into compensating parts
    2.1. Divide into compensating parts
    2.2. Compensating bi-system
3. Combine with another undesired action
    3.1. Homogeneous "compensating" bi-system

3.2. Compensating bi-system

4. Counteraction by means of a similar action I an operator with no subordinates

5. Counteraction by means of another action

   5.1. Choose a field

   5.2. While choosing a countering action, consider:

   5.3. Readily available field resources

   5.4. Derived field resources

6. Counteraction of deformation or destruction

   6.1. Transform the shape of an object

   6.2. Transform an object's microstructure

   6.3. Transform the aggregate state

   6.4. Integration into a poly-system

   6.5. Introduce a strengthening element

   6.6. Anti-loading

   6.7. Introduce a strengthening additive

Step 4.1.3 THE "IMPACT ON THE HARMFUL ACTION" UDE CHILD RELATION

The third UDE child relation, "Impact On the Harmful Action," has 6 grandchildren and 12 operators:

1. "Draw off" an undesired action
   1.1. "Smart" ways to introduce a substance
   1.2. "Drawing off" an undesired action can be applied for protection from overheating
   1.3. "Drawing off" an undesired action can be applied for protection from destruction
2. Change the direction of an action is an operator with no subordinates.
3. Switch off an action
   3.1. Switch off an action
   3.2. Transform the aggregate state
   3.3. Change the environment
4. Enforce an action is an operator with no subordinates.
5. Local slackening of an action
   5.1. Local slackening of an action
   5.2. Rushing through
6. Weaken an action
   6.1. Weaken an action
   6.2. Divide into a set of operations

Step 4.1.4 THE "REDUCE SENSITIVITY OF THE SYSTEM OR ITS PART TO THE HARMFUL EFFECT" UDE CHILD RELATION

The fourth UDE child relation, "Reduce Sensitivity of the System or its Part to the Harmful Effect," has 2 grandchildren and 2 operators:

1. Exclude the sensitive portion is an operator with no subordinates
2. "Vaccination" is an operator with no subordinates

Step 4.1.5 THE "ELIMINATE THE CAUSE OF THE UNDESIRED ACTION" UDE CHILD RELATION

The fifth UDE child relation, "Eliminate the Cause of the Undesired Action," has 2 grandchildren and 3 operators:

1. Exclude the cause
    1.1. Exclude the cause
    1.2. Failure analysis
2. Exclude the source is an operator with no subordinates

Step 4.1.6 THE "REDUCE THE HARMFUL RESULTS PRODUCED" UDE CHILD RELATION

The sixth UDE child relation, "Reduce the Harmful Results Produced," has 4 grandchildren and 9 operators:

1. Isolate harmful product
    1.1. Isolate harmful product
    1.2. "Smart" ways to introduce a substance
2. Transient use of a harmful substance
    2.1. Introduce a substance for a time period
    2.2. Shelter inside another substance
    2.3. Mask a substance
    2.4. Apply a temporary mediator
3. Localize a harmful action is an operator with no subordinates
4. Provide for easy and timely detection
    4.1. Development of a system for measurement and / or control
    4.2. Immobilize the source of harmful action

Step 4.1.7 THE "APPLY UNIVERSAL OPERATORS TO REDUCE THE UNDESIRED FACTOR" UDE CHILD RELATION

The seventh UDE child relation, "Apply Universal Operators to Reduce the Undesired Factor," has 5 grandchildren and 22 operators:

1. Partial/excessive action
    1.1. Partial/excessive action
    1.2. Excessive action
    1.3. Partial action
    1.4. Alternative methods
2. Inversion
    2.1. Substitute an action by an opposing one
    2.2. Inversion of movable and immovable parts
    2.3. "Head over heels" (turned inside-out) object
3. Separation

3.1. Separate opposite requirements in space

3.2. Separate opposite requirements in time

3.3. Optimize characteristics in time

3.4. Separate opposite requirements between the whole object and its parts

3.5. Separate opposite requirements via changing conditions

3.6. Separate an impeding part from an object

3.7. Separate (remove) a required part from an object

4. Integration

4.1. Integrate to obtain new properties

4.2. Integrate to obtain opposite properties

4.3. Add an object with required properties

5. Segmentation

5.1. Make an object dismountable

5.2. Partition into simple-shaped parts

5.3. Pulverizing

5.4. Link degeneration during partitioning

5.5. Partitioning followed by integration

Step 4.1.8 THE "CONSIDER RESOURCES TO REDUCE THE UNDESIRED FACTOR" UDE CHILD RELATION

The eighth UDE child relation, "Consider Resources to Reduce the Undesired Factor," has 12 grandchildren and 44 operators:

1. Substance resources

1.1. Waste

1.2. Raw materials or unfinished products

1.3. System elements

1.4. Inexpensive substances

1.5. Substance flows

1.6. Substance properties

2. Field resources

2.1. Fields (energy) in a system

2.2. Fields (energy) from the environment

2.3. Sources of fields

2.4. Fields of dissipation - energy waste

3. Space resources

3.1. Occupy vacant space

3.2. Use another dimension

3.3. Arrange vertically

3.4. Use the reverse side

3.5. Nesting (matreshka)

3.6. Travel through

4. Time resources

4.1. Preliminary action

4.2. Partial preliminary action

4.3. Preliminary placement of an object

4.4. Create and use pauses

4.5. Eliminate idling

4.6. Concurrent operations

4.7. Group processing

4.8. Staggered processing

4.9. Use post-process time

5. Informational resources

5.1. Fields of dissipation

5.2. Substance properties

5.3. Substance flows from a system

5.4. Substance/field flows passing through

5.5. Alterable properties of substances

6. Functional resources

6.1. Resources - functions

6.2. Resources - super-effect

7. Derived substance resources

7.1. Transformed waste

7.2. Transformed raw materials or products

7.3. Other transformed substances

7.4. Modified water

8. Derived field resources

8.1. Transformed fields from a system

8.2. Transformed fields from the environment

8.3. Transformed fields from system sources

9. "Derived time resources" is an operator with no subordinates.

10. "Derived functional resources" is an operator with no subordinates.

11. Derived resource accumulation

11.1. Accumulate a resource:

11.2. Devices for energy accumulation

12. Derived resource concentration is an operator with no subordinates.

Step 4.1.9 THE "TRY TO BENEFIT FROM THE UNDESIRED FACTOR" UDE CHILD RELATION

The ninth UDE child relation, "Try to Benefit from the Undesired Factor," has 4 grandchildren and 6 operators:

1. New or useful application for a used substance is an operator with no subordinates.
2. Packaging utilization
   2.1. Packaging utilization
   2.2. Changing (masking)
   2.3. Functional resources
3. "Harm into benefit" is an operator with no subordinates.
4. "Coat the pill with sugar" is an operator with no subordinates.

Step 4.2 I-TRIZ SOLUTION RECOMMENDATIONS FOR DESIRABLE ENTITIES.

If a particular critical entity must be "turned on," then follow I-TRIZ solution recommendations for DE. TRIZ Problem Formulator generates the following problem statements. Substitute the name of the UDE or DE for "Harmful Cause," "Harmful Effect," "Useful Cause" and "Useful Effect."

DE → DE	Find an alternative way to obtain the useful cause that provides or enhances the other useful effect
	Find an alternative way to obtain Useful effect that does not require the useful cause
DE → UDE	Find an alternative way to obtain the useful cause that does not cause the harmful effect.
DE ↛ DE	Find an alternative way to obtain the useful cause that does not influence the useful effect
	Find an alternative way to obtain the useful effect that is not influenced by the useful cause.
DE ↛ UDE	Find an alternative way to obtain the useful cause that eliminates, reduces or prevents the harmful effect
UDE → DE	Find an alternative way to obtain the useful effect that does not require the harmful cause
UDE ↛ DE	Find an alternative way to obtain the useful effect that is not influenced by the harmful cause.

Table 7. Problem statements generated for Desirable Entities by IWB2000[7]

There are 6 child relations for the DE parent. The six child relations have a total of 50 grandchild relations and 211 operators. The DE child relations are:

1.	Improve the useful factor.
2.	Obtain the useful result without the use of Useful Effect (Idealization)
3.	Increase effectiveness of the useful action.
4.	Synthesize the new system to provide Useful Effect.
5.	Apply universal Operators to provide the useful factor.
6.	Consider resources to provide the useful factor.

Table 8. Child Relations for Desirable Entities

Step 4.2.1 THE "IMPROVE THE USEFUL FACTOR" DE CHILD RELATION

The first DE child relation, Improve the useful factor, has 13 grandchildren:

They are:

1. Reliability. Reliability has 5 operators:
   1.1. Duplication of critical elements
   1.2. Improve the mechanical strength of an element
   1.3. Substitute a set of inexpensive objects
   1.4. Apply the module principle
   1.5. Eliminate stressful operation
2. Action speed. Action Speed has two operators:
   2.1. Readily-available time resources
   2.2. Improve functional efficiency
3. Mechanical strength. Mechanical strength has 8 operators:
   3.1. Transform the shape of an object
   3.2. Transform an object's micro-structure
   3.3. Transform the aggregate state
   3.4. Integration into a poly-system
   3.5. Introduce a strengthening element
   3.6. Anti-loading
   3.7. Introduce a strengthening additive
   3.8. Eliminate a stressful operation
4. Composition stability. Composition stability has 7 operators. They are:
   4.1. Introduce negative feedback
   4.2. Rushing through
   4.3. Restoration
   4.4. Mask a substance
   4.5. Apply the "binary" principle
   4.6. Transform the aggregate state
   4.7. Eliminate a disturbing operation
5. Convenience. Convenience has 19 operators:
   5.1. Make an object dismountable
   5.2. Self-service
   5.3. Apply a model or copy
   5.4. Apply disposable objects
   5.5. Vary optical characteristics
   5.6. Vary transparency
   5.7. Apply a mediator
   5.8. Apply inflatable constructions
   5.9. Optimize characteristics
   5.10. Adapt a tool to a person

5.11. Divide into "heavy" and "light" parts

5.12. Move a heavy object

5.13. Optimize characteristics

5.14. Apply inflatable constructions

5.15. Anti-weight 1

5.16. Anti-weight 2

5.17. Compensate by means of other forces

5.18. "Retain the available" principle

5.19. Transient use of a substance

6. Productivity. Productivity has 4 operators:

6.1. Simultaneous operation

6.2. Specialization

6.3. Increase the effectiveness of an action

6.4. Improve the speed of an action

7. Manufacturing accuracy. Manufacturing accuracy has 13 operators:

7.1. Group machining

7.2. Substitute for an action

7.3. Introduce negative feedback

7.4. Add an object for a period of time

7.5. Vary optical characteristics

7.6. Vary transparency

7.7. Introduce a mediator

7.8. Preliminary action

7.9. Partial preliminary action

7.10. Apply a physical effect

7.11. Adjustment of parameters (tuning)

7.12. Selection

7.13. Improve dispensing accuracy

8. Dispensing accuracy. Dispensing accuracy has 11 operators:

8.1. Add a carrier

8.2. Dissolve into a liquid carrier

8.3. Shape transformation

8.4. Transform the aggregate state

8.5. Crush for dispensing

8.6. Integration

8.7. Precise control of a metering device

8.8. Apply a physical effect

8.9. Partial/excessive action

8.10. Preliminary dispensing

8.11. Selective mode

9. Shape. Shape has 9 operators:

9.1. Apply asymmetry

9.2. Apply curvilinear forms

9.3. Add an object

9.4. Apply physical effects

9.5. Preliminary anti-action

9.6. Restoration

9.7. Apply physical effects

9.8. Change to a variable shape

9.9. Eliminate a disturbing operation

10. Universality. Universality has 4 operators:

10.1. Introduce elements that can be interchanged

10.2. Introduce elements that automatically interchanged

10.3. Introduce elements with dynamic features

10.4. Introduce adjusting elements and links

11. Controllability. Controllability has 10 operators:

11.1. Introduce a control field

11.2. Introduce an additive

11.3. Introduce a dynamic device

11.4. Introduce an anti-process

11.5. Introduce combined control

11.6. Introduce a controlled section

11.7. Transformation of a primary process

11.8. Self-control

11.9. Introduce negative feedback

11.10. Shift to another principle of operation

12. Degree of adaptability. Degree of adaptability has 2 operators:

12.1. Dynamization

12.2. Adapt a tool to a person

13. Selective mode. Selective mode has 4 operators:

13.1. Selective slackening

13.2. Selective amplification

13.3. Selective changes of properties

13.4. Apply standing waves

There are therefore 13 great grandchildren and 98 possible operators for the DE child relation, "Improve the Useful Factor." Each operator contains a description that is an analogy and at least one example. A few operators have sub-operators as well.

To give an idea of how difficult it is to apply an operator, the first one, "Duplication of critical elements" is reproduced below:

Duplication of critical elements Operator

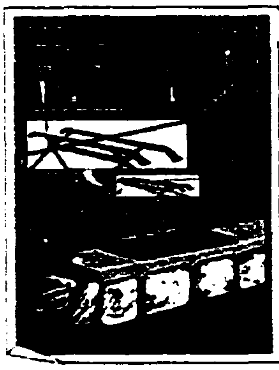
To increase reliability, consider using redundancy for the most important (or the most unreliable) subsystems or components.

Illustration:
Avoiding contact breaks between a trolley and a wire

Redundancy usually increases a system's weight, overall dimensions, and other expense related characteristics.

To handle these secondary drawbacks, see:
Reduce undesired factors

Example: Avoiding contact breaks between a trolley and a wire



When the current collector of an electrically-driven vehicle slides along a contact wire, breaks can occur in the contact due to vibration. This produces sparking, which is harmful to the vehicle and wire.

The use of more than one contact region, e.g. a double trolley, neutralizes this effect. If one of the regions is disconnected, the second maintains contact with the wire. Simultaneous disconnection of both regions is unlikely. In an improved version of this solution, contacts in different regions of the vehicle are connected to each other by a bar with a pivot point in the middle, so that if one of them lowers, the other rises, restoring the broken contact.

Reduce undesired factors Related Operator (suboperator):
Choose a factor you wish to reduce:

- Weight
- Overall dimensions
- Energy consumption
- Object complexity
- Energy wasted
- Time wasted (utilize time resources)
- Cost
- Deformation, displacement, shock, vibration, destruction
- Mechanical obstacles
- Wear
- Noise

Figure 20. Duplication of Critical Elements Operator

Note: From this illustration, it is clear that looking up an analogous solution requires time and patience. Although the 18 sub-operators are not reproduced, they also have files and examples associated with them. Also, the other 97 operators associated with this particular grandchild are not reproduced. Since there are a total of six grandchildren with 50 great grandchildren and 211 operators for this one child, there is a tremendous amount of time required if the inventor/designer were to thoughtfully consider each operator. This problem is compounded further by most systems because most systems cannot be modeled with only two blocks.

Step 4.2.2 THE "IDEALIZATION" DE CHILD RELATION

The second DE child relation, Idealization, has 7 grandchildren:

They are:

1. Exclude duplicate elements has two operators:
   1.1. If your system contains duplicate elements (subsystems), consider replacing them with a single general element. The system will be simplified considerably
   1.2. If removing the duplicate elements results in a decrease in reliability, consider: Improving reliability
2. "Use more highly integrated subsystems" is an operator with no subordinates.
3. Exclude auxiliary functions has 6 operators:
   3.1. Exclude correcting functions
   3.2. Exclude preliminary functions
   3.3. Exclude protective functions
   3.4. Exclude housing functions
   3.5. Exclude other auxiliary functions
   3.6. For measurement/control systems, also see: Eliminate the need for measurement
4. Self-service has two operators:
   4.1. Self service
   4.2. Functional resources
5. Exclude elements has 5 operators:
   5.1. Apply foam or empty space
   5.2. Restoration
   5.3. Self-interaction
   5.4. Readily-available substance resources
   5.5. Derived substance resources
6. Consolidation of discrete subsystems is an operator with no subordinates.
7. Simplify through total replacement has two operators:
   7.1. Simplify through total replacement
   7.2. Smart substances

The seven great grandchildren of "Idealization" have 19 operators associated with them.

Step 4.2.3 THE "INCREASE EFFECTIVENESS" DE CHILD RELATION

The third DE child relation, Increase Effectiveness, has 8 grandchildren and 18 operators. They are:

1. Intensify a field
    1.1. Accumulate energy, then later release the energy.
    1.2. Introducing additives.
    1.3. Devices for energy accumulation
2. Apply multiple actions
    2.1. Use repetitive actions or multiple actions
    2.2. Divide into a set of operations
3. Introduce a field-intensifier is an operator with no subordinates.
4. Concentrate energy
    4.1. Concentrate the action at a specific location
    4.2. Create unidirectional action
5. Introduce an additional field
    5.1. Choose a field
    5.2. Transit to a varying field
    5.3. Transit to a pulsed field
    5.4. Complementary bi-system
6. Substitute a field with a more effective one
    6.1. Replace the field that produces the existing function with a more effective field.
    6.2. Field transformation
7. "Make a road" is an operator with no subordinates.
8. Transform the environment
    8.1. Transform the properties of the system or process or of transform the properties of the environment in which it operates
    8.2. Transform the aggregate state
    8.3. Vary optical characteristics

Step 4.2.4 THE "SYNTHESIZE A NEW SYSTEM" DE CHILD RELATION

The fourth DE child relation, Synthesize a new system, has 5 grandchildren and 10 operators. They are:

1. Look for a prototype to improve is an operator with no subordinates.
2. Use other systems
    2.1. Use other systems
    2.2. Utilization of resources
3. Combine known systems
    3.1. Combine systems having the same functions
    3.2. Combine systems having opposite functions
    3.3. Create a system from homogeneous elements
4. System for obtaining information

4.1. Bypass the problem of measurement / control

4.2. Direct ways of improving measurement / control

4.3. Indirect ways of improving measurement / control

5. Step-by-step synthesis is an operator with no subordinates.

Step 4.2.5 THE "APPLY UNIVERSAL OPERATORS" DE CHILD RELATION

The fifth DE child relation, Apply Universal Operators, has 5 grandchildren and 22 operators. They are:

1. Partial/excessive action
   1.1. Partial/excessive action
   1.2. Excessive action
   1.3. Partial action
   1.4. Alternative methods
2. Inversion
   2.1. Substitute an action by an opposing one
   2.2. Inversion of movable and immovable parts
   2.3. "Head over heels" (turned inside-out) object
3. Separation
   3.1. Separate opposite requirements in space
   3.2. Separate opposite requirements in time
   3.3. Optimize characteristics in time
   3.4. Separate opposite requirements between the whole object and its parts
   3.5. Separate opposite requirements via changing conditions
   3.6. Separate an impeding part from an object
   3.7. Separate (remove) a required part from an object
4. Integration
   4.1. Integrate to obtain new properties
   4.2. Integrate to obtain opposite properties
   4.3. Add an object with required properties
5. Segmentation
   5.1. Make an object dismountable
   5.2. Partition into simple-shaped parts
   5.3. Pulverizing
   5.4. Link degeneration during partitioning
   5.5. Partitioning followed by integration

Step 4.2.6 THE "RESOURCES" DE CHILD RELATION

The sixth grandchild, resources, has 12 grandchildren and 44 operators. They are:

1. Substance resources
   1.1. Waste

   1.2. Raw materials or unfinished products
   1.3. System elements
   1.4. Inexpensive substances
   1.5. Substance flows
   1.6. Substance properties
2. Field resources
   2.1. Fields (energy) in a system
   2.2. Fields (energy) from the environment
   2.3. Sources of fields
   2.4. Fields of dissipation - energy waste
3. Space resources
   3.1. Occupy vacant space
   3.2. Use another dimension
   3.3. Arrange vertically
   3.4. Use the reverse side
   3.5. Nesting (matreshka)
   3.6. Travel through
4. Time resources
   4.1. Preliminary action
   4.2. Partial preliminary action
   4.3. Preliminary placement of an object
   4.4. Create and use pauses
   4.5. Eliminate idling
   4.6. Concurrent operations
   4.7. Group processing
   4.8. Staggered processing
   4.9. Use post-process time
5. Informational resources
   5.1. Fields of dissipation
   5.2. Substance properties
   5.3. Substance flows from a system
   5.4. Substance/field flows passing through
   5.5. Alterable properties of substances
6. Functional resources
   6.1. Resources - functions
   6.2. Resources - super-effect
7. Derived substance resources
   7.1. Transformed waste

7.2. Transformed raw materials or products

7.3. Other transformed substances

7.4. Modified water

8. Derived field resources

8.1. Transformed fields from a system

8.2. Transformed fields from the environment

8.3. Transformed fields from system sources

9. "Derived time resources" is an operator with no subordinates.

10. "Derived functional resources" is an operator with no subordinates.

11. Derived resource accumulation

11.1. Accumulate a resource:

11.2. Devices for energy accumulation

12. Derived resource concentration is an operator with no subordinates.

Step 4.3 I-TRIZ SOLUTION RECOMMENDATIONS FOR CONTRADICTIONS

If there is a contradiction, then follow the I-TRIZ solution recommendations for contradictions. TRIZ Problem Formulator generates the following problem statements. Substitute the name of the UDE or DE for "Harmful Cause," "Harmful Effect," "Useful Cause" and "Useful Effect."

DE → UDE	Try to resolve the following contradiction: The useful cause should be in place in order to fulfill useful purpose and should not exist in order to avoid harmful effect.
DE ↛ DE	Try to resolve the following contradiction: The useful cause should be in place in order to fulfill useful purpose and should not exist in order to avoid hindering resultant useful effect.
UDE → DE	Try to resolve the following contradiction: The harmful cause should not exist in order to avoid harmful results and should be in place in order to provide or enhance the useful effect.
UDE ↛ UDE	Try to resolve the following contradiction: The harmful cause should not exist and should be in place in order to eliminate, reduce or prevent the harmful effect.

Table 9. Problem statements generated for Contradictions by Problem Formulator

Regardless of the wording of the problem statement, there are two Child relations for Contradictions Parent and 47 operators. The contradictions Child relations are:

1.	Apply separation principles to satisfy contradictory requirements.
2.	Apply 40 Innovation Principles to resolve contradiction

Table 10. Child Relations for Contradictions

Step 4.3.1 THE "SEPARATION PRINCIPLES" CONTRADICTION CHILD RELATION.

The "Separation Principles" Contradiction child relation has 7 operators:

1.1. Separate opposite requirements in space

1.2. Separate opposite requirements in time
1.3. Optimize characteristics in time
1.4. Separate opposite requirements between the whole object and its parts
1.5. Separate opposite requirements via changing conditions
1.6. Separate an impeding part from an object
1.7. Separate (remove) a required part from an object

Step 4.1.1 THE "40 INNOVATION PRINCIPLES" CONTRADICTION CHILD RELATION

The "40 Innovation Principles" Contradiction child relation has 40 operators:

2.1. Segmentation
2.2. Extraction
2.3. Local conditions
2.4. Asymmetry
2.5. Combining
2.6. Universality
2.7. Nesting
2.8. Anti-Weight
2.9. Prior counter-action
2.10. Prior action
2.11. Cushion in advance
2.12. Equipotentiality
2.13. Inversion
2.14. Spheroidality
2.15. Dynamicity
2.16. Partial-excessive action
2.17. Shift to a new dimension
2.18. Mechanical vibration
2.19. Periodic action
2.20. Continuity of useful action
2.21. Rushing through
2.22. Convert harm into benefit
2.23. Feedback
2.24. Mediator
2.25. Self-service
2.26. Copying
2.27. Disposable object
2.28. Replacement of a mechanical system
2.29. Use a pneumatic or hydraulic construction
2.30. Flexible film or thin membranes

2.31. Use of porous material
2.32. Changing the color
2.33. Homogeneity
2.34. Rejecting and regenerating parts
2.35. Transformation of physical and chemical states
2.36. Phase transition
2.37. Thermal expansion
2.38. Use strong oxidizers
2.39. Inert environment
2.40. Composite materials

Step 4.4 I-TRIZ SOLUTION RECOMMENDATIONS FOR INCREASING IDEALITY

If the design only has desirable entities, then consider the I-TRIZ solution recommendations for increasing the level of ideality of the system. TRIZ Problem Formulator generates the following problem statements. Substitute the name of the UDE or DE for "Harmful Cause," "Harmful Effect," "Useful Cause" and "Useful Effect."

DE → DE DE ↛ DE UDE → DE UDE ↛ DE	Consider transitioning to the next generation of the system that will provide useful effect in a more effective way and/or will be free of existing problems.

Table 11. Problem statements for Increasing Ideality by IWB2000[7]

This relationship could also be considered another focus on useful effect since it only operates on the effect side of relationships whose effects are useful. Regardless of the wording of the problem statement, there are 7 Child relations, 32 grandchild relations and 90 operators for the Terminal Desirable Effect Parent.

The seven child relations of Terminal DE Parent are:

1. Improve Ideality of your system that provides the Useful effect.
2. Consider the possibility to transform the existing system that provides the Useful effect into bi- or poly-system.
3. Consider segmentation of the existing system that provides the Useful effect.
4. Consider restructuring the existing system that provides the Useful effect.
5. Increase dynamism of the existing system that provides the Useful effect.
6. Increase controllability of the existing system that provides [the Useful effect.
7. Make the existing system that provides the Useful effect and/or its elements more universal.

Table 12. Child Relations of Increase System Ideality Parent

Step 4.4.1 THE "IMPROVE IDEALITY" TERMINAL DE CHILD RELATION

The "Improve Ideality" Terminal DE Child Relation has 2 grandchildren and 49 operators. They are:

1. Enhance useful Features

1.1. Useful function (functional efficiency)
1.2. Reliability
1.3. Action speed
1.4. Mechanical strength
1.5. Composition stability
1.6. Convenience
1.7. Productivity
1.8. Manufacturing accuracy
1.9. Dispensing accuracy
1.10. Shape
1.11. Universality
1.12. Controllability
1.13. Degree of adaptability
1.14. Enhance Mechanical characteristic (pressure, force, etc.)
1.15. Enhance Spatial characteristic (shape, dimension, etc.)
1.16. Enhance Characteristic of vibration, sound, oscillation
1.17. Enhance Thermal characteristic (heating, cooling, etc.)
1.18. Enhance Molecular characteristic (adhesion, diffusion, etc.)
1.19. Enhance Chemical characteristic
1.20. Enhance Electrical characteristic (charge, current, etc.)
1.21. Enhance Magnetic characteristic
1.22. Enhance Optical characteristic

2. Reduce undesired features
2.1. Reduce undesired action: Deformation, shock, vibration, destruction
2.2. Reduce undesired action: Mechanical obstacles
2.3. Reduce undesired action: Wear
2.4. Reduce undesired action: Noise
2.5. Reduce undesired action: Contamination
2.6. Reduce undesired action: Overheating
2.7. Reduce undesired action: Undesired adhesion
2.8. Reduce undesired action: Fire or explosion
2.9. Reduce undesired action: Interaction with the environment
2.10. Reduce undesired action: Person's potentially harmful acts
2.11. Reduce undesired action: Incompatible useful actions
2.12. Reduce undesired action of characteristic: Weight
2.13. Reduce undesired action of characteristic: Overall dimensions
2.14. Reduce undesired action of characteristic: Energy consumption
2.15. Reduce undesired action of characteristic: Object complexity

2.16. Reduce undesired action of characteristic: Energy wasted

2.17. Reduce undesired action of characteristic: Time wasted

2.18. Reduce undesired action of characteristic: Cost

2.19. Isolation

2.20. Counteraction

2.21. Impact on a harmful action

2.22. Reduce sensitivity

2.23. Eliminate the cause of an undesired action

2.24. Reduce harmful results produced by an undesired action

2.25. Benefit from harmful results

2.26. General Operators

2.27. Effects of an undesired action

Step 4.4.2 THE "MONO-BI-POLY" TERMINAL DE CHILD RELATION

The "Mono-Bi-Poly" Terminal DE Child Relation has 3 grandchildren and 16 operators. They are:

1. Build a bi-system:
    - 1.1. Build a homogeneous bisystem
    - 1.2. Build a homogeneous "compensating" bisystem
    - 1.3. Build a bisystem with shifted characteristics
    - 1.4. Build a bisystem composed of competing systems
    - 1.5. Build a "towing" bisystem
    - 1.6. Build a "compensating" bisystem
    - 1.7. Build an alternative bisystem
    - 1.8. Build a symbiotic bisystem
    - 1.9. Combine systems with opposite functions
    - 1.10. Apply the "binary" principle
2. Build a poly-system:
    - 2.1. Build a homogeneous polysystem
    - 2.2. Build a polysystem with shifted characteristics
    - 2.3. Build a polysystem composed of bi-systems
    - 2.4. Build a dynamic polysystem
3. Enhance a bi- or poly-system:
    - 3.1. Enhance the links in a bi- or poly-system
    - 3.2. Increase the differences between elements

Step 4.4.3 THE "SEGMENTATION" TERMINAL DE CHILD RELATION

The "Segmentation" Terminal DE Child Relation has 4 operators. They are:

1. Make an object dismountable

1. Partition into simple-shaped parts
2. "Pulverize" an object
3. Provide the degeneration of links during partitioning

Step 4.4.4 THE "RESTRUCTURING" TERMINAL DE CHILD RELATION

The "Restructuring" Terminal DE Child Relation has 4 operators. They are:

1. Redistribute a substance
2. Modify a part of a substance
3. Substitute for a part of a substance
4. Apply contact phenomena

Step 4.4.5 THE "INCREASE DYNAMISM" TERMINAL DE CHILD RELATION

The "Increase Dynamism" Terminal DE Child Relation has 5 operators. They are:

1. Decrease the degree of stability
2. Transit from stationary condition to movable
3. Divide a system into mobile parts
4. Introduce a mobile object
5. Apply physical effects

Step 4.4.6 THE "INCREASE CONTROLLABILITY" TERMINAL DE CHILD RELATION

The "Increase Controllability" Terminal DE Child Relation has 10 operators. They are:

1. Introduce a control field
2. Introduce additives
3. Introduce dynamic devices
4. Introduce an anti-process
5. Introduce combined control
6. Introduce a controlled section
7. Transform a primary process
8. Provide self-control
9. Introduce negative feedback
10. Shift to another principle of operation

Step 4.4.7 THE "MAKE SYSTEM MORE UNIVERSAL" TERMINAL DE CHILD RELATION

The "Make System More Universal" Terminal DE Child Relation has 4 operators. They are:

1. Introduce elements that can be interchanged
2. Introduce elements that interchange automatically
3. Introduce elements with dynamic features
4. Introduce adjustable elements and links

CHAPTER 4. AIRBAG CASE STUDY

4.1 OVERVIEW OF THE AIRBAG PROBLEM AND RESULTS

Airbags are safety devices that have been used in automobiles extensively since the mid-1970s. Airbags are a passive restraint system that is designed to be deployed during an accident. The purpose of the airbag is to provide a soft barrier between the occupant of a vehicle and hard surfaces within the vehicle, such as the dashboard, the windshield and the steering column.

The airbag cannot be extended while the vehicle is in operation, so it must be deployed during a crash before an occupant has the opportunity to strike a hard surface. The deployment must be very fast in order to intercept the occupant because forward inertia will cause the occupant to move forward very quickly. The airbag must also stop deploying before the occupant strikes the airbag so that the speed of the airbag does not become a secondary hazard.

The problem at hand is that deploying airbags during accidents have killed people. A solution must be devised so that the airbag may continue to save lives in the way it was intended while not causing any additional lives to be lost as a result of its existence. No trade-offs in human lives are acceptable.

The design methodology of this research provided some very surprising results for the airbag problem. Intuitive solutions offered before the application of the method were incomplete, proving that the method brought a level of understanding that was not present without it. The method yielded results that neither TRIZ not TOC could have provided on their own, also proving the merit of the proposed method. A few of the surprising results were:

- In step 1, the act of defining the problem revealed that the conventional understanding of the problem was flawed. Conventionally, it was believed that drivers were being killed by airbags because they were of small stature and that a design solution that compensated for small-statured people was necessary to sole the problem. In fact, it is not the size of the driver or the passenger that causes airbag fatalities, but rather the distance between the person and the airbag at the time of the airbag deployment. This clearer understanding of the problem led to an entirely different solution approach.
- Despite the fact that a great deal of effort and designs have already been applied to this problem, none of them solve the chief cause of driver fatality because none properly identify the problem as the driver being too close to the airbag at the time of impact. This problem ***cannot*** be solved with the airbag stowed in the steering column, yet every other design offered in the US Patent database stows the driver's airbag in the steering column. Only through proper problem identification could the nature of the problem be established and the nature of the solution determined.
- In step 2, the logic was developed. The logic diagram developed a clear picture of the true problem, how it could be solved and (more importantly) how it could ***not*** be solved. Another important feature of the logic diagram is that it provides a model to be discussed by a team working on the problem before a design solution is offered. The underlying assumptions of the model, as well as the actual construction of causal relations can be discussed and resolved using a common, easily understood picture of the process.

- Step 3 continued the work of step 2, analyzing the logic diagram until a plan of action was developed. Four different changes to the system were discovered to be necessary and sufficient to eradicate the problem.
- Step 4 offered innovative solutions to the problem. The radical idea of making a change to the steering column, (not the airbag) became very evident as this step developed. It led to a study of patents that offer retractable and breakaway steering columns as well as to alternate steering arrangements. Even if these steering designs were not available, the principles of TRIZ, such as the *Nesting Principle* could easily be discovered and implemented.

The solution offered maintains all the safety features of airbags without the side effects of driver and passenger fatalities, it does not appreciably increase the complexity of the system and is not expensive to implement on new vehicles. No other solution to the airbag problem encountered in patent library could be found that met of all these objectives.

Problem: Identify the weaknesses in the design of a vehicle Airbag, Apply the Design Algorithm to it and Improve it.

Step 1. GATHER INFORMATION ABOUT THE AIRBAG PROBLEM

Step 1.1 DESCRIBE THE AIRBAG PROBLEM IN NON-TECHNICAL TERMS

The problem is that there are fatalities due directly to the force from the airbag when the airbag encounters the driver or passenger within the airbag risk zone. The airbag risk zone is within 2 - 3 inches from the airbag.

Step 1.2 DEFINE AND DESCRIBE THE AIRBAG SYSTEM

Driver's Airbag system consists of a vehicle, a steering wheel, a driver, a seatbelt and an airbag.

Passenger Airbag system consists of a passenger, a vehicle, a seatbelt and an airbag.

Step 1.2.1 NAME THE AIRBAG SYSTEM

Common or Technical name of System being improved

1. Air Bag system

Step 1.2.2 DEFINE THE AIRBAG SYSTEM STRUCTURE

To solve the problem, the following were considered:

1. Steering column
2. Driver's Airbag
3. Passenger's Airbag
4. Airbag deployment settings
5. Vehicle
6. Driver
7. Passenger
8. Seatbelt

Supersystem in which the system resides:

1. Vehicle

Other Systems in the Supersystem:

- Steering Column
- Driver
- Seatbelt
- Passenger

Component	Problem
Steering column	If the steering column encases the airbag, the edge of the steering column must be greater than 3 inches away from the driver at the time of airbag deployment.
Driver's airbag	The driver's airbag must be at least 3 inches away from the driver at the time of airbag deployment.
Passenger's airbag	The passenger's airbag must be greater than 3 inches away from the passenger at the time of airbag deployment.
Airbag deployment system	The airbag must deploy with enough speed and force to inhibit the driver or passenger from colliding with the vehicle or steering column but must not deploy with force sufficient to kill the driver or passenger.
Vehicle	The vehicle must not come in direct contact with the driver or passenger during an impact.
Driver	The driver must not be within 3 inches of the airbag at the time of deployment.
Passenger	The passenger must not be within 3 inches of the airbag at the time of deployment.
Seatbelt	The seatbelt must prevent the driver or passenger from being within three inches of the airbag at the time of deployment

Table 13. Problem Statements for Airbag Problem

Step 1.2.3 DEFINE THE SPHERE OF INFLUENCE AND SPAN OF CONTROL ON THE AIRBAG SYSTEM

The entire system is considered to be level "-C3" because it is controlled by an outside source or agency. The components of the system are generally coded C2- under indirect control. Component control level is developed in greater detail in Step 2.2.1.4.

Step 1.2.4 DEFINE THE WAY THE SYSTEM FUNCTIONS

Primary useful function:

The primary useful function of the airbag is to intercept the occupant before the occupant strikes the vehicle during a crash.

Reason to perform the primary useful function:

To protect the occupant from injury

Functioning of the system:

Upon impact, the airbag deploys with force great enough to encounter the occupant before the occupant's forward inertia causes the occupant to strike the interior of the vehicle

Step 1.2.5 DEFINE THE AIRBAG SYSTEM BOUNDARIES AND ENVIRONMENT

Other parts of the supersystem (the same systemic level as that mentioned earlier):

- Tires
- Windows
- Engine

Other systems nearby the supersystem or those that might often be nearby

- Other vehicles
- Road

Other systems interacting with the system and its supersystem, especially sources of energy, substances, receivers of waste, etc.

- Road
- Other Vehicles
- Obstacles in car's path
- Car falling from height such as a cliff
- Dashboard

Requirements for the functioning of the system and its supersystem

- Car must react to sudden change in speed (rapid deceleration)
- Car must stop very rapidly to avoid accident

Conditions around the system and its supersystem, both artificial and natural (indoor or outdoor conditions, temperature, humidity, medium, etc.)

- Imminent impact
- High rates of speed
- Children or short adults in car
- People not wearing seatbelts

Requirements for interactions between the system/supersystem and the environment mentioned above

- Car can be destroyed by impact with other cars, ground or objects, but occupants of car must be kept alive in the widest variety of circumstances.
- Under no circumstances should the safety devices of the vehicle kill the occupants of the vehicle.

In extreme circumstances, the occupant may die due to the severity of impact. In other words, if the accident is bad enough the airbag will not save the life of the occupant. However, the airbag should never cause death and should minimize death of occupants to the greatest extent possible.

Step 1.3 REFINE THE DEFINITION OF THE AIRBAG PROBLEM

Step 1.3.1 IDENTIFY THE AIRBAG PROBLEM TO BE RESOLVED

A drawback must be eliminated: Airbags must not encounter vehicle occupants with enough impact to kill them.

Step 1.3.2 ESTABLISH THE MECHANISM CAUSING THE AIRBAG PROBLEM.

An airbag causes a fatality if the airbag deploys and a person is too close to the airbag.

Step 1.3.3 DESCRIBE THE UNDESIRED CONSEQUENCES OF AN UNRESOLVED AIRBAG PROBLEM.

Occupant dies.

Step 1.3.4 BRIEFLY DESCRIBE THE HISTORY OF THE AIRBAG PROBLEM

See paragraph 2.3.1 of the Literature review.

Step 1.3.5 IDENTIFY OTHER SYSTEMS IN WHICH A SIMILAR PROBLEM EXISTS

See paragraph 2.3.2 of the Literature review.

Step 1.3.6 OTHER PROBLEMS TO BE SOLVED IN THE COURSE OF SOLVING THE AIRBAG PROBLEM.

Alternative to given system. Remove the steering column so driver is not sitting so close to the driver's airbag. Use another steering mechanism.

Step 1.4 DEFINE THE AIRBAG SOLUTION SPACE

The Airbag that produces a required useful effect [deploys on impact] is not necessary any more.

The Airbag that causes a harmful effect [strikes occupant] is removed from the system.

A harmful effect [airbag strikes occupant] withdraws itself.

Step 1.5 DEFINE AIRBAG AVAILABLE RESOURCES

Substance Resources

Waste-

- Exhaust from the airbag on deployment
- Airbag cover
- Airbag itself

System Elements

- Tires
- Vehicle
- Seatbelt
- Airbag

Steering Column

Inexpensive substances

Airbag cover

Airbag

Field Resources

Chemical

Airbag propellant

Electrical

Signal to deploy airbag
Signal to detect occupant conditions
Rear facing child restraint
Low weight occupant
Distance from Driver to Steering column

Mechanical

Breakaway cover
Steering column construction

Thermal

Friction from tires
Heat from engine
Heat from propellant

Space Resources

Space between occupant and airbag

Time Resources

Time to deploy the airbag

Informational resources

Signal that crash is imminent (sudden deceleration)

Step 1.6 CONSIDER ALLOWABLE CHANGES TO THE AIRBAG SYSTEM

Drastic changes are acceptable.

The speed of deployment of the airbag cannot be decreased because it represents an unacceptable trade off-more lives will be lost due to accidents because the airbag did not deploy quickly enough.

Disabling the airbag with a manual switch is unacceptable because it allows human error in judgment to foolishly remove a life saving option.

The effectiveness of the solution should not be dependant on personal choices of the operator/passenger. Since no one knows when an accident will occur, it is very easy to disable or ignore the airbag, which is only intended to be used in drastic situations.

Step 1.7 FURTHER REFINE AIRBAG SOLUTION SPACE

Proper distance between the vehicle occupant and the airbag is maintained regardless of the size of the driver or the proclivity to wear seatbelts.

All other characteristics of the airbag are maintained

Step 2. CONSTRUCT A LOGIC DIAGRAM FOR AIRBAG SYSTEM

Step 2.1 IDENTIFY CHIEF UNDESIRABLE EFFECTS OF AIRBAG SYSTEM

An airbag causes a fatality. In other words, someone dies in a vehicle equipped with an airbag who would not have died in the same circumstances except the vehicle does not have an airbag.

Step 2.2 DRAW THE LOGIC DIAGRAM OF AIRBAG SYSTEM

The following entities have been identified:

1. "Occupant of vehicle dies"
2. "The airbag deploys"
3. "A Person is too close to the airbag"
4. "The airbag is on"
5. "There is a signal to deploy the airbag"
6. "The Driver is too close to airbag"
7. "The Passenger is too close to airbag"
8. "The Mechanical Sensor gives a signal to deploy"
9. "The Accelerometer Sensor gives a signal to deploy"
10. "The Driver's Seat is moved forward"
11. "The Driver is 'slumped' forward"
12. "There is a Child in a RFCSS in the front seat"
13. "The Driver's Feet can't reach the pedals"
14. "The passenger is too far forward"
15. "The Driver likes to sit up close"
16. "Impact from an accident causes forward motion"
17. "Occupant (Driver or Passenger) is not wearing a seatbelt"
18. "Occupant's shoulder harness is improperly positioned behind his back"
19. "The Driver has passed out"
20. "The passenger is under 1 year old or weighs less than 40 pounds"
21. "An infant passenger is in the front seat"
22. "An Accident Occurs"
23. "The shoulder harness is too high to be comfortable"
24. "The driver is short (60 inches tall or less)"
25. "The shoulder harness is not adjustable"
26. "Infant should be in back seat"
27. "There is no back seat in the vehicle"
28. "Driver is within 10 inches of steering column"
29. "Airbag is stowed in steering column"

Step 2.2.1 CONNECTING AIRBAG ENTITIES

Step 2.2.1.1 CODE THE ENTITIES

All of the entities identified above are Boolean.

Step 2.2.1.2 IDENTIFY CONNECTIONS BETWEEN ENTITIES

The following are the cause/effect relationships between the entities identified above:

"(1) Occupant of vehicle dies" is caused by

"(2) The airbag deploys" **and**

"(3) A Person is too close to the airbag"

(2)*(3)→(1) **(22)**

"(2) The airbag deploys" is caused by

"(4) The airbag is on" **and**

"(5) There is a signal to deploy the airbag"

(4)*(5)→(2) **(23)**

"(3) A Person is too close to the airbag" is caused by

"(6) The Driver is too close to airbag" **or**

"(7) The Passenger is too close to airbag"

(6)+(7)→(3) **(24)**

"(4) The airbag is on" is a root cause

"(5) There is a signal to deploy the airbag" is caused by

"(8) The Mechanical Sensor gives a signal to deploy" **and**

"(9) The Accelerometer Sensor gives a signal to deploy"

(8)*(9)→(5) **(25)**

"(6) The Driver is too close to airbag" is caused by

"(28) Driver is within 10 inches of steering column" and

"(29) Airbag is stowed in steering column"

(28)*(29)→(6) **(26)**

"(28) Driver is within 10 inches of steering column" is caused by

"(10) The Driver's Seat is moved forward" **or**

"(11) The Driver is 'slumped' forward"

(10)+(11)→(28) **(27)**

"(7) The Passenger is too close to airbag" is caused by

"(14) The passenger is too far forward" **or**

"(12) There is a Child in a RFCSS in the front seat"

(12)+(14)→(7) **(28)**

"(8) The Mechanical Sensor gives a signal to deploy" is caused by

"(22) An Accident Occurs" (root cause)

(22)→(8) **(29)**

"(9) The Accelerometer Sensor gives a signal to deploy" is caused by

"(22) An Accident Occurs" (root cause)

(22)→(9) **(30)**

"(10) The Driver's Seat is moved forward" is caused by

"(13) The Driver's Feet can't reach the pedals" **or**

"(15) The Driver likes to sit up close"

(13)+(15) →(10) **(31)**

"(11) The Driver is 'slumped' forward" is caused by

"(16) Impact from an accident causes forward motion" **and**

["(17) Occupant (Driver or Passenger) is not wearing a seatbelt" **or**

"(18) Occupant's shoulder harness is improperly positioned behind his back" **or**

"(19) The Driver has passed out"]

(16)*[(17)+(18)+(19)] →(11) **(32)**

"(14) The passenger is too far forward" is caused by

"(16) Impact from an accident causes forward motion" **and**

["(17) Occupant (Driver or Passenger) is not wearing a seatbelt" **or**

"(18) Occupant's shoulder harness is improperly positioned behind his back"]

(16)*[(17)+(18)] →(14) **(33)**

"(12) There is a Child in a RFCSS in the front seat" is caused by

"(20) The passenger is under 1 year old or weighs less than 40 pounds" **and**

"(21) An infant passenger is in the front seat"

(20)*(21) → (12) **(34)**

"(13) The Driver's Feet can't reach the pedals" is a root cause

"(15) The Driver likes to sit up close" is a root cause

"(16) Impact from an accident causes forward motion" is caused by

"(22) An Accident Occurs" (root cause)

(22) →(16) **(35)**

"(17) Occupant (Driver or Passenger) is not wearing a seatbelt" is a root cause

"(18) Occupant's shoulder harness is improperly positioned behind his back" is caused by

"(23) The shoulder harness is too high to be comfortable" **and**

"(24) The driver is short (60 inches tall or less)" and

"(25) The shoulder harness is not adjustable"

(23)*(24)*(25) →(18) **(36)**

"(19) The Driver has passed out" is a root cause

"(20) The passenger is under 1 year old or weighs less than 40 pounds" is a root cause

"(21) An infant passenger is in the front seat" is caused by

"(26) Infant should be in back seat" **or**

"(27) There is no back seat in the vehicle"

(26)*(27) →(21) **(37)**

Summarizing the Boolean Logic:

First, combine equations 22, 23 and 24:

(4)*(5)*[(6)+(7)]→(1) **(38)**

Combining Equation 38 with equations 25, 26 and 28:

(4)*(8)*(9)*[(28)*(29)+(12)+(14)]→(1) **(39)**

Combining equation 39 with equations 27, 29, 30, 33 and 34:

(4)*(22)*[{(10)+(11)}*(29)+(20)*(21)+(16)*{(17)+(18)}] →(1) **(40)**

Combining equation 40 with equations 31, 32 and 37:

$$(4)*(22)*[\{(13)+(15)+(16)*[(17)+(18)+(19)]\}*(29)+(20)*(26)*(27)+(16)*\{(17)+(18)\}] \rightarrow (1) \quad (41)$$

Combining equation 41 with equations 35 and 36:

$$(4)*(22)*[\{(13)+(15)+(22)*[(17)+ (23)*(24)*(25)+(19)]\}*(29)+(20)*(26)*(27)+(22)*\{(17)+ (23)*(24)*(25)\}] \rightarrow (1) \quad (42)$$

Simplifying Equation 42:

$$(4)*(22)*[\{(13)+(15)+(17)+ (23)*(24)*(25)+(19)\}*(29)+(20)*(26)*(27)+\{(17)+ (23)*(24)*(25)\}] \rightarrow (1)(43)$$

The beauty of this equation will be evident after the entities are coded and we begin to analyze the system.

Already we have a logical basis for our problem solution and we have not even coded the entities yet. Once the entities are properly coded, we can decide how to go about setting the right values to false so that we can create a system where fatalities will not occur due to the airbag.

These cause and effect relationships would look like this in an uncoded logic diagram:

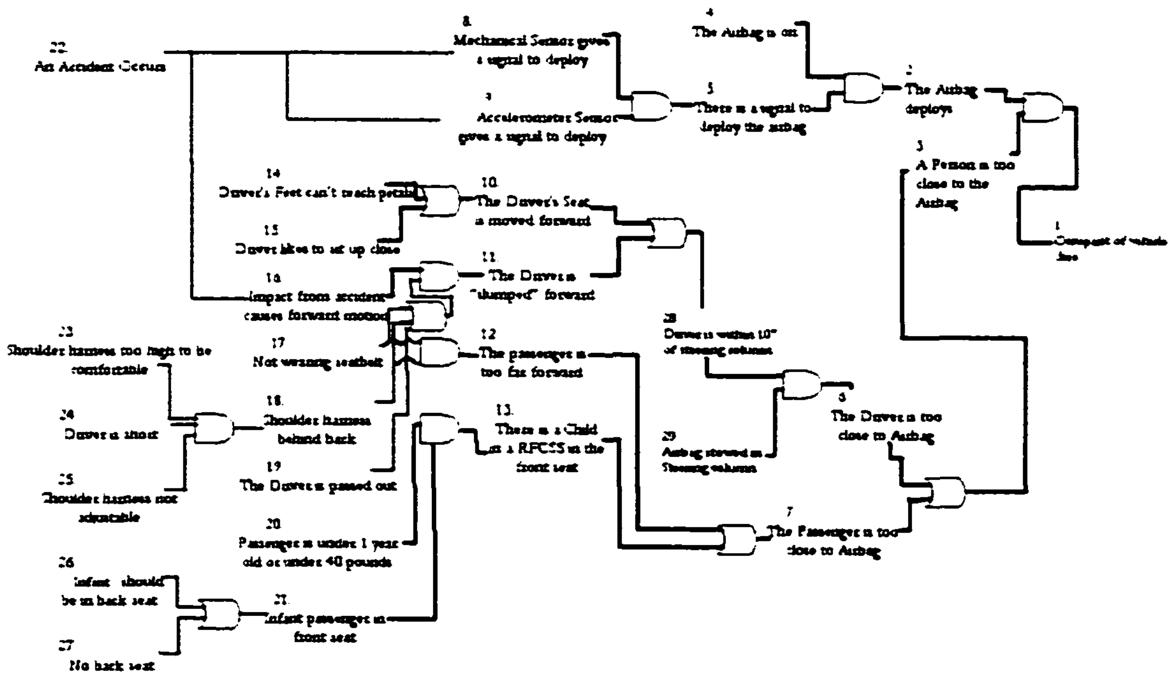


Figure 21. Logic Diagram for Airbag Problem

Step 2.2.1.3 CODE ENTITIES AS DESIRABLE, UNDESIRABLE OR NEUTRAL

Desirable, Undesirable and Neutral are from the perspective of the manufacturer. Although the idea that the airbag deploys may be undesirable from the perspective of the occupant, it is the desired effect after an accident occurs. For this problem, there are two Desirable Entities-

"The airbag deploys." To the manufacturer, it is desirable for the airbag to deploy when it is called upon. This design does not consider the possibility of an airbag deployment when not desired.

"The airbag is on." Although many operators would rather turn their airbags off, for the maximum life saving potential, the airbag should be on.

For this problem, the following are Undesirable Entities-

1. **"Occupant of vehicle dies."** The purpose of this design change is to keep the airbag from causing a fatality. Airbags are designed to reduce fatalities by intercepting passengers and drivers before they hit the steering wheel or the dashboard directly following a collision. Airbags reduce the number of deaths due to accidents, but they do not eliminate deaths due to accidents. This design is only concerned with fatalities that can be attributed to the airbag, not fatalities attributed to the accident itself.
2. **"A Person is too close to the airbag."** A person too close to the airbag at the time of collision is the only cause of death due to airbag deployment.
3. **"The Driver is too close to airbag."** Either the driver is too close to the airbag or the passenger is too close to the airbag. The two situations are profoundly different because the driver must be in the front seat and because the driver's airbag is already closer to most drivers because it is stowed in the steering column.
4. **"The Passenger is too close to airbag."** There are unique causes for a passenger being too close to an airbag. Of greatest concern is the increased risk to children who are fidgeting in their seats or infants who are in Rear Facing Child Safety Seats.
5. **"The Driver's Seat is moved forward."** This is a judgment call. It could as easily be considered "neutral." If the driver positions himself too close to the airbag, then the driver exposes himself to increased risk of death due to airbag deployment.
6. **"The Driver is 'slumped' forward."** Even a seat-belted driver who has not moved his seat forward can place himself too close to the airbag if he is slumped forward. There were two fatalities cited in airbag accident statistics where the driver fainted due to low blood sugar level complications from diabetes.
7. **"The passenger is too far forward."** A passenger being too far forward is different than a driver being too far forward because the passenger is naturally farther away from the airbag.
8. **"There is a Child in a RFCSS in the front seat."** RFCSS units in the front seat have claimed the lives of many infants. Manufacturers of RFCSS units recommend that they only be placed in the back seat. The only time when it is appropriate to place a RFCSS in the front seat is when in a vehicle that has no backseat. In this instance, the airbag should be turned off. Current practice is to have a manual switch to turn off the airbag mechanism, but such a practice opens up the possibility of user error. A user could turn the airbag off when the RFCSS is not in the front seat and thereby not protect the passenger or the user could forget to turn the airbag off when an infant is in the front seat in a RFCSS, causing a fatality. There is at least one instance where the latter has occurred and the driver was accused of manslaughter.

9. **"Occupant (Driver or Passenger) is not wearing a seatbelt."** The seatbelt is the primary safety restraint device in any vehicle. Individuals often neglect to use their safety belt because they have an airbag, but doing so could actually increase the chance of a fatality. Occupants should always use their seatbelts whether or not there is an airbag present.
10. **"Occupant's shoulder harness is improperly positioned behind his back."** Car manufacturers no longer produce cars with just a lap belt and have never done so with cars equipped with airbags. Even if restrained by a lap belt, if the shoulder harness is not in place the occupant's torso will pitch forward at the time of an accident due to inertia and will encounter the airbag precipitously.
11. **"The Driver has passed out."** Although there is nothing that can be done about a passed out driver, it is certainly an unsafe and undesirable situation.
12. **"An Accident Occurs."** It is interesting that a problem formulated using TRIZ software or TOC methods will first identify this entity as the best place to address the airbag fatality problem. If the accident did not occur, the airbag would not deploy and no one would be killed by the airbag. Solving the accident problem can be a bit of a fool's errand because there are so many possible causes of an accident. For this design problem, the possibility of an accident occurring is given and this design will focus on the ways in which we can mitigate the loss of life after an accident occurs.
13. **"The shoulder harness is too high to be comfortable."** If the shoulder harness is too high, it can be very uncomfortable, especially for short drivers and child passengers. I have experienced discomfort in cars where the harness is not adjustable and I am above the lower limits of height used in ergonomic analysis (I'm 64 inches tall). If the shoulder harness is uncomfortable, an individual is likely to put it behind his back, making it useless to restrain in the time of an accident.
14. **"The driver is short (60 inches tall or less)."** This is another judgment call. A designer cannot do anything about a driver being less than 60 inches tall, but it is undesirable for the purposes of airbag safety for a driver to be less than 60 inches tall. Any design offered should be insensitive to the height of the driver.
15. **"The shoulder harness is not adjustable."** Currently, new cars have adjustable shoulder harnesses. If a shoulder harness is not adjustable and it is uncomfortable, it is more likely that an individual will place it behind his back.

The remaining entities are considered "neutral":

1. **"There is a signal to deploy the airbag."** The presence of a signal to deploy is good if there is an accident that warrants it, but bad if not.
2. **"The Mechanical Sensor gives a signal to deploy."** If there is an accident, then it is desirable for the sensor to give a signal to deploy. If there is not accident, then it is undesirable to give a signal to deploy the airbag.
3. **"The Accelerometer Sensor gives a signal to deploy."** If there is an accident, then it is desirable for the sensor to give a signal to deploy. If there is not accident, then it is undesirable to give a signal to deploy the airbag.

4. **"The Driver's Feet can't reach the pedals."** This entity could also be considered undesirable in some instances. It is not a controllable entity, so it really is not important whether it is considered "neutral" or "undesirable."
5. **"The Driver likes to sit up close."** This entity could also be considered undesirable in some instances. It is not a controllable entity, so it really is not important whether it is considered "neutral" or "undesirable."
6. **"Impact from an accident causes forward motion."** The physical law of inertia states that a body in motion tends to stay in motion unless acted on by an outside force. Inertia forces will cause contents of a vehicle to continue to move forward when the car frame is brought to an abrupt stop due to an accident.
7. **"The passenger is under 1 year old or weighs less than 40 pounds."** This entity could also be considered undesirable in some instances. It is not a controllable entity, so it really is not important whether it is considered "neutral" or "undesirable."
8. **"An infant passenger is in the front seat."** This entity could also be considered undesirable in some instances. It is not a controllable entity, so it really is not important whether it is considered "neutral" or "undesirable."
9. **"Infant should be in back seat."** This entity could also be considered undesirable in some instances. It is not a controllable entity, so it really is not important whether it is considered "neutral" or "undesirable."
10. **"There is no back seat in the vehicle."** This entity could also be considered undesirable in some instances. It is not a controllable entity, so it really is not important whether it is considered "neutral" or "undesirable."
11. **"Driver is within 10 inches of steering column."** Proximity to the airbag is dangerous but proximity to the steering wheel is not
12. **"Airbag is stowed in steering column"**

Step 2.2.1.4 CODE CONTROL OF ENTITIES

The following entities are coded "-C1," under *direct* control- this is the highest level of items in our span of control. In these, we can *directly control* their value. For the purposes of the airbag design, our perspective is that of the automobile manufacturer. Simple decisions of the vehicle occupants, like the decision to place the seat too close to the steering wheel are therefore considered not under direct control.

1. **"The airbag is on"**- since the manufacturer turns the airbag controls on and leaves them on, it may seem that this is outside of the manufacturer's control once it leaves the factory. But, if the manufacturer can place control circuitry to disable the airbag under certain circumstances, then the control is under the manufacturer's influence, at least as far as the control circuitry is concerned. In those automobiles where the airbag can be manually turned off, the operator overrides the control of the manufacturer.

2. **"The shoulder harness is not adjustable"**- the manufacturer can make the shoulder harness adjustable by putting in a different design of shoulder harness. In older vehicles that are not adjustable, after market kits can be purchased to hold the shoulder harness away from the neck f the occupant.
3. **"Occupant (Driver or Passenger) is not wearing a seatbelt"**- it may be far-fetched to believe that a manufacturer can "make" a person wear their seat belt, but it can be done using sensors to identify if there is a person in the seat and the seat belt is clasped. Typically, cars have an alarm to let the operator know that someone has failed to connect their seatbelt. These alarms can often be overridden or ignored, but the controls exist to make overriding and ignoring the alarm very difficult.
4. **"Airbag is stowed in steering column."** Although this is not easy to fix, it is under the designer's control.

The following entities are coded "C2," under *indirect* control. Like C1, these are in our span of control, but only through manipulation of other entities or the logic of the system can we change them. Still, we do not need to get authority from an outside agency to change their values.

1. **"Occupant of vehicle dies"**- although we cannot control whether or not a fatality occurs directly, by manipulating the input variables we can make it nearly impossible for the airbag itself to cause a fatality. The goal of this study is to do precisely that.
2. **"A Person is too close to the airbag"**- a person being too close to an airbag at the time of an airbag deployment is the only identified mechanism for an airbag to kill a person. If we can keep drivers and passengers away from airbags at the time of a deployment, then we can negate this entity.
3. **"The Driver is too close to airbag"**- Actually, this could be coded as C1, under direct control. The reason that drivers are too close to airbags is generally because the airbag is deployed through the steering column and the steering column is by definition very close to the driver. If a driver was properly seated and the airbag came from the dashboard (as it does on the passenger side), the driver would be a safe distance from the airbag.
4. **"The Passenger is too close to airbag"**- there are many reasons why a passenger may be too close to an airbag. Most notable are the ones surrounding children who are not strapped in seatbelts or are not properly strapped in seatbelts. Another notable cause is infants in the front seat, either in an adult's arms or in a Rear Facing Child Safety Seat. To eliminate this cause, we need to have several different interventions to address each one.
5. **"The Driver's Seat is moved forward"**- we can indirectly control how far forward the driver's seat is moved, although the driver may protest.
6. **"Occupant's shoulder harness is improperly positioned behind his back"**- If we recommended a type of shoulder harness that could not be placed behind the back, this would be coded C1. Instead, we will suggest that an adjustment mechanism be added to the shoulder harness.

The following entities are coded "C3" for entities that our controlled by an outside source or agency. Since someone controls these, they are by definition under our *sphere of influence*. All we need to do is influence the person or agency controlling these entities. Policies often fall into this group.

1. **"The airbag deploys"**- airbag deployment specifications are set at the factory to values determined by a regulatory agency. It has been suggested that changing the required impact or the force of airbag deployment would save some people from being killed by airbags in low speed collisions. This option is deemed unacceptable for this case study because it requires making an additional trade-off in human lives. It is doubtful that the number of lives saved from the direct effects of the airbag would be greater than the number of lives that would be lost due to accidents that do not meet the lower thresholds for actuation.
2. **"There is a Child in a RFCSS in the front seat"**- RFCSS are not designed to be placed in a front seat because they place an infant's head only inches from the airbag and the windshield. Tragically, many of the lives lost are infants in these child safety seats. This is used as an indirect control of **"The airbag is on"** because sensors can be put into the front seat to disable the passenger side airbag when a RFCSS is used.
3. **"The shoulder harness is too high to be comfortable"**- the exact placement of shoulder harnesses is set using ergonomic studies of the range of body sizes and shapes likely to sit in a particular seat. Often, these ergonomic values are set using adults only and fail to take into account very small adults of children. There are two simple solutions to adjusting the harness height: one is to design all vehicles to have an adjustable shoulder harness height. The other is to buy an after-market kit to hold the shoulder harness away from an occupant's neck and throat. Since this problem has been defined as being for manufacturers of new automobiles, the after-market kit is not a viable option.
4. **"Infant should be in back seat"**- safety advice today dictates that all children sit in the back seat in an age-appropriate restraint, ranging from RFCSS for infants to regular seat belts for older children. Since society has laws governing the mandatory use of seatbelts, it also could adopt laws to govern the mandatory placement of children under a certain size or age in the back seat. Enforcement of such laws would be difficult, though.

The following entities are coded "C4" for entities that are controlled by nature or are "given" for the problem. These are outside of our sphere of influence, unless we are allowed to redefine the problem. For instance, in the airbag example, the existence of a driver who is under 5 feet tall is given. We cannot make the design exclude these people, although we may be able to compensate for their height (if necessary) by changing the system in some way that negates the danger of short drivers in an accident.

1. **"The Driver is 'slumped' forward."** The solution offered must be insensitive to the physical impairment of the driver. If a driver falls asleep, is drunk or passes out for any other reason (heart attack, diabetic problem, etc.); not only is it likely that the driver will get into an accident but it is also likely the driver will lean forwards towards the airbag. This is less applicable to the passenger side because the passenger is already farther away from the airbag because the airbag originates in the dashboard for the passenger side but in the steering column for the driver's side.
2. **"The passenger is too far forward."** The solution offered must be insensitive to the passenger. Accidents have been cited where elderly passengers have passed out or child passengers have been moving in their seats or leaning forward to pick up something at the instant an accident occurs

making them too close to the airbag, although they are wearing the proper safety equipment. This is not as serious as the driver's side because the passenger is already farther away from the airbag because the airbag originates in the dashboard for the passenger side but in the steering column for the driver's side.

3. "**The Driver's Feet can't reach the pedals.**" The solution offered must be insensitive to the length from the driver's torso to the driver's feet. This is often related to the height of the driver cited above, but would be a separate problem in the case of a deformed or missing leg. This anatomical feature does not affect the mechanisms for a passenger being killed by an airbag. The reason a driver's leg length comes into play is because the driver must take steps to be able to reach the controls to drive. These steps force the driver to move toward the airbag.
4. "**The passenger is under 1 year old or weighs less than 40 pounds.**" These are the criteria for using a RFCSS.
5. "**The driver is short (60 inches tall or less).**" The solution offered must be insensitive to the height of the driver. The mechanisms for a passenger being killed by an airbag are not affected by the height of the passenger. The reason a driver's height comes into play is because the driver takes steps to be able to see and reach the controls to drive. These steps force the driver to move toward the airbag. The passenger, on the other hand, is already farther away from the airbag because the airbag originates in the dashboard for the passenger side but in the steering column for the driver's side.
6. "**There is no back seat in the vehicle.**" Some sports cars and light trucks do not have back seats, so infants in these vehicles must be carried in the front seat. If we do not represent a manufacturer of these particular vehicles, this is not an issue. By law, a driver is supposed to manually disable a passenger side airbag when transporting a child in a RFCSS in the front seat and manufacturers are supposed to provide a switching mechanism in these vehicles. The law did not save the life of a newborn infant whose father transported him in a RFCSS in the front of a light truck. The law may also lead careless drivers to turn off airbags when not necessary to do so because they forgot it was disabled or because they distrust the device in general. There are safety switches that can sense the presence of a RFCSS and automatically disable the airbag, thus taking individual human error out of the equation.

The remaining entities are coded "C5" as they are completely outside our sphere of influence. In some cases, we can still ignore them, but it is even more difficult than for C4 entities. In the airbag example, "an accident occurs" is such an entity. We cannot remove it from the problem because it is the reason for having an airbag in the first place. If we could redesign the safety system of an automobile to make an accident impossible, then we could circumvent even this problem. From a creative thinking standpoint, solutions that address the C5 control level are exciting because they will by definition change the entire complexion of both the problem and the solution.

1. "**There is a signal to deploy the airbag.**" Although we could save lives from airbag deployment by disabling the sensors and thus disabling the airbag, to do so would cost lives that would have been saved by airbags and is unacceptable.

2. **"The Mechanical Sensor gives a signal to deploy."** Arguably, the sensor could be coded as C4 because we could design a system without a mechanical sensor, but that is clearly out of the acceptable design space of the problem. The two sensors (mechanical and accelerometer) provide independent redundant indications that an accident occurs, minimizing false deployment of airbags.
3. **"The Accelerometer Sensor gives a signal to deploy."** Arguably, the sensor could be coded as C4 because we could design a system without an accelerometer sensor, but that is clearly out of the acceptable design space of the problem. The two sensors (mechanical and accelerometer) provide independent redundant indications that an accident occurs, minimizing false deployment of airbags.
4. **"The Driver likes to sit up close."** This is a poor driving habit of mine which I did not even realize until I started performing this study. Although I am over the height considered dangerous by 4 inches, I still prefer to sit as close to the steering wheel as possible with the seat pushed all the way forward and the steering column pointing straight towards me. I do not sit at the end of the seat however. As this is a driving habit that cannot be controlled by an outside source, any design solution must be robust to a proclivity to sit up close.
5. **"Impact from an accident causes forward motion."** Inertia is a fact of nature and we cannot control it.
6. **"The Driver has passed out."** We must design around the possibility that a driver is passed out. There is no way to control whether or not a driver will pass out.
7. **"An infant passenger is in the front seat."** The choice to put an infant in the front seat of a vehicle is ill advised, but it is a personal choice and outside of the control of the automobile manufacturer. A proper solution should be insensitive to the presence of an infant in the front seat of the automobile.
8. **"An accident occurs."** Some design solutions actually operate on this level. If we could eliminate the possibility of an accident, then there is no need for an airbag and thus no danger from it causing a fatality. A solution of this magnitude is considered outside of the scope of this problem, but should not necessarily be rejected out of hand in the future.
9. **"Driver is within 10 inches of steering column."** With the current design of the steering column, we will not be able to control the distance between the driver and the steering column.

Step 2.2.2 ASSIGN NUMBERS TO EACH AIRBAG ENTITY.

The following numbers are assigned:

101. "Occupant of vehicle dies"
201. "The airbag deploys"
202. "A Person is too close to the airbag"
301. "The airbag is on"
302. "There is a signal to deploy the airbag"
303. "The Driver is too close to airbag"
304. "The Passenger is too close to airbag"
401. "The Mechanical Sensor gives a signal to deploy"
402. "The Accelerometer Sensor gives a signal to deploy"

403. "The Driver's Seat is moved forward"

404. "The Driver is 'slumped' forward"

405. "The passenger is too far forward"

406. "There is a Child in a RFCSS in the front seat"

407. "Driver is within 10 inches of steering column"

408. "Airbag is stowed in steering column"

501. "The Driver's Feet can't reach the pedals"

502. "The Driver likes to sit up close"

503. "Impact from an accident causes forward motion"

504. "Occupant (Driver or Passenger) is not wearing a seatbelt"

505. "Occupant's shoulder harness is improperly positioned behind his back"

506. "The Driver has passed out"

507. "The passenger is under 1 year old or weighs less than 40 pounds"

508. "An infant passenger is in the front seat"

601. "An Accident Occurs"

602. "The shoulder harness is too high to be comfortable"

603. "The driver is short (60 inches tall or less)"

604. "The shoulder harness is not adjustable"

605. "Infant should be in back seat"

606. "There is no back seat in the vehicle"

Step 2.2.3 **SUMMARY OF THE ENTITY CODE SCHEME**

1. U-101-L-C2 "Occupant of vehicle dies"
2. D-201-L-C3 "The airbag deploys"
3. U-202-L-C2 "A Person is too close to the airbag"
4. D-301-L-C1 "The airbag is on"
5. N-302-L-C5 "There is a signal to deploy the airbag"
6. U-303-L-C2 "The Driver is too close to airbag"
7. U-304-L-C2 "The Passenger is too close to airbag"
8. N-401-L-C5 "The Mechanical Sensor gives a signal to deploy"
9. N-402-L-C5 "The Accelerometer Sensor gives a signal to deploy"
10. U-403-L-C2 "The Driver's Seat is moved forward"
11. U-404-L-C4 "The Driver is 'slumped' forward"
12. U-405-L-C4 "The passenger is too far forward"
13. U-406-L-C3 "There is a Child in a RFCSS in the front seat"
14. N-501-L-C4 "The Driver's Feet can't reach the pedals"
15. N-502 -L-C5 "The Driver likes to sit up close"
16. N-503-L-C5 "Impact from an accident causes forward motion"

17. U-504-L-C1 "Occupant (Driver or Passenger) is not wearing a seatbelt"
18. U-505-L-C2 "Occupant's shoulder harness is improperly positioned behind his back"
19. U-506-L-C5 "The Driver has passed out"
20. N-507-L-C4 "The passenger is under 1 year old or weighs less than 40 pounds"
21. N-508-L-C5 "An infant passenger is in the front seat"
22. U-601-L-C5 "An Accident Occurs"
23. U-602-L-C3 "The shoulder harness is too high to be comfortable"
24. U-603-L-C4 "The driver is short (60 inches tall or less)"
25. U-604-L-C1 "The shoulder harness is not adjustable"
26. N-605-L-C3 "Infant should be in back seat"
27. N-606-L-C4 "There is no back seat in the vehicle"
28. N-407-L-C5 "Driver is within 10 inches of steering column"
29. N-408-L-C1 "Airbag is stowed in steering column"

Step 2.2.4 TEST THE AIRBAG LOGIC DIAGRAM USING THE RULES OF LOGIC.

From Dettmer[10], the eight laws of the CLR are listed below:

1) Clarity (seeking to understand)
   - Would I add any verbal explanation if reading the tree to someone else? ***No***
   - Is the meaning/context of words unambiguous? ***Yes***
   - Is the connection cause and effect convincing "at face value"? ***Yes***
   - Are intermediate steps missing? ***No***
2) Entity Existence (Complete, properly structured, valid statements of cause and effect)
   - Is it a complete sentence? ***Yes***
   - Does it make sense? ***Yes***
   - Is it free from "if-then" statements? ***Yes***
   - Does it convey only one idea (i.e. not compound entity)? ***Yes***
   - Does it exist in my reality? ***Yes***
3) Causality existence (Logical connection between cause and effect)
   - Does an "if then" connection really exist, as written? ***Yes***
   - Does the cause, in fact, result in the effect? ***Yes***
   - Does it make sense when read aloud exactly as written? ***Yes***
   - Is the cause intangible? (If so, look for additional predicted effect) ***No***
4) Cause insufficiency (A nontrivial dependent element missing)
   - Can the cause, as written, result in the effect on its own? ***No***
   - Are there any significant cause factors missing? ***No***
   - Is/are the written cause(s) sufficient to justify all parts of the effect(s)? ***Yes***

- Is an ellipse *(an AND Gate)* required? ***No***

5) Additional cause (A separate, independent cause producing the same effect)
   - Is there anything else that might cause the effect on its own? *(Missing OR Gate)* ***No***
   - If the stated cause is eliminated, will the effect be almost completely eliminated? ***Yes***
6) Cause-effect reversal (Arrow pointing in the wrong direction)
   - Is the stated effect really the cause and vice versa? ***No***
   - Is the stated cause the reason why or just how we know the effect exists? ***No***
7) Predicted effect existence (Additional corroborating effect resulting from cause)
   - Is the cause intangible? ***No***
   - Do other unavoidable outcomes exist besides the stated effect? ***No***
8) Tautology (Circular logic)
   - Is the cause intangible? ***No***
   - Is the effect offered as a rationale for the existence of the cause? ***No***
   - Do other unavoidable outcomes exist besides the stated effect? ***No***

In addition to these logical rules, a few more are required for this approach.

9) Check that all variables are of the right type, Boolean or Quantitative. ***All variables are Boolean, as they should be in this problem.***
10) Check that Quantitative variables are converted to Boolean variables before entering a AND, OR, XOR or NOT gates. ***Not applicable***
11) Check that Boolean variables are converted to Quantitative variables before entering MAG AND gates. ***Not applicable***
12) Check that there is a "machinery" input entity for each entity that requires a piece of equipment to operate. ***Yes***

Step 2.2.5 **COMPLETE THE AIRBAG LOGIC DIAGRAM**

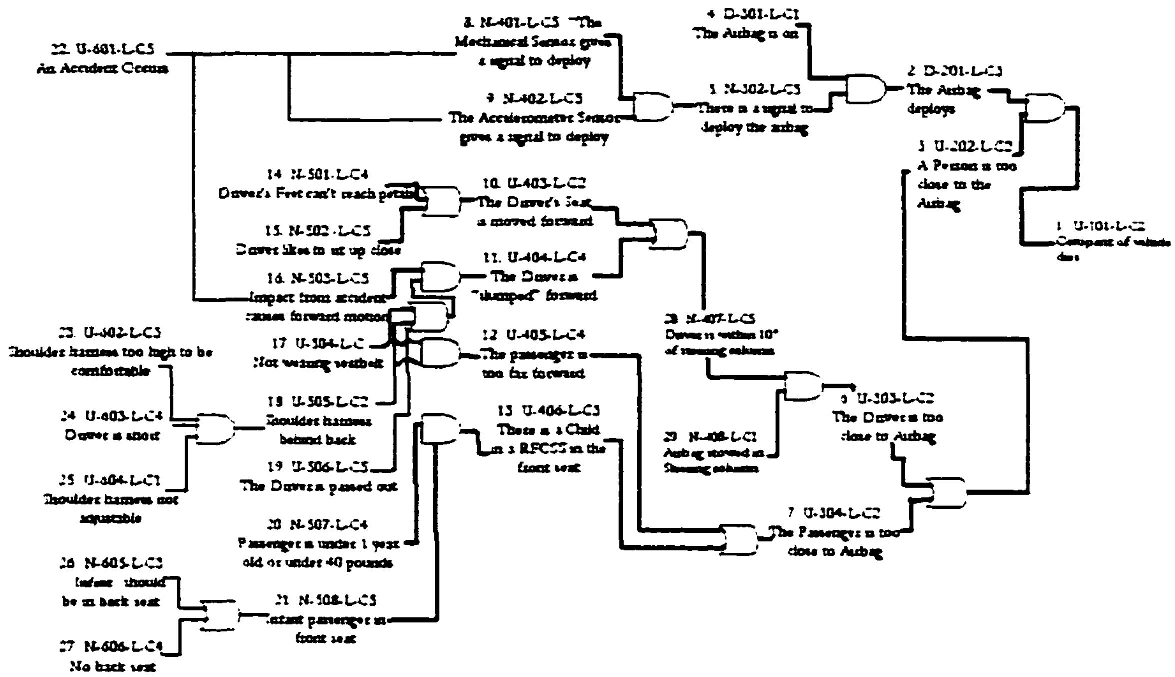


Figure 22. Completed Logic Diagram

Step 3. ANALYZE LOGIC DIAGRAM TO FIND THE CONSTRAINTS OF THE AIRBAG SYSTEM

Step 3.1 FIND THE SWITCHES FOR THE AIRBAG SYSTEM

Step 3.1.1 ARE ANY AIRBAG TERMINAL EFFECTS CODED AS C1?

No. There is only one terminal effect, U-101-L-C2 ("Occupant of vehicle dies") and it is coded as C2.

Step 3.1.2 WHAT ARE THE SWITCHES IN THE AIRBAG SYSTEM?

Before the entities were coded, the logical expression for the entire system was:

(4)·(22)·[{(13)+(15)+(17)+ (23)·(24)·(25)+(19)}·(29)+(20)·(26)·(27)+{(17)+ (23)·(24)·(25)}] →(1) (44)

With the codes developed, that same expression becomes:

(D-301-L-C1)·(U-601-L-C5)·[{(U-406-L-C3)+(N-502 -L-C5)+(U-504-L-C1)+ (U-602-L-C3)·(U-603-L-C4)·(U-604-L-C1)+(U-506-L-C5)}·(N-408-L-C1)+(N-507-L-C4)·(N-605-L-C3)·(N-606-L-C4)+{(U-504-L-C1)+ (U-602-L-C3)·(U-603-L-C4)·(U-604-L-C1)}] →(U-101-L-C2) (45)

Since the entity on the right side of the equation is Undesirable, our goal is to make U-101-L-C2 false.

On the right side of the equation are several C4 and C5 entities that are true because we cannot control them. They can be removed from all AND Gates and be replaced by their logical value of "1" on all OR gates:

(D-301-L-C1)· [{(U-406-L-C3)+1+1+ (U-602-L-C3)·(U-603-L-C4)·(U-604-L-C1)+1}·(N-408-L-C1)+ (N-605-L-C3) +{(U-504-L-C1)+ (U-602-L-C3)· (U-604-L-C1)}] →(U-101-L-C2) (46)

Looking at this equation, there hare 2 ways to make the expression on the left false

Make D-301-L-C1 "The airbag is on" False. This is unacceptable because it negates a Desirable entity that saves lives

Make the following entities false:

1. N-408-L-C1 "airbag is stowed in steering column"
2. N-605-L-C3 "Infant should be in back seat"
3. U-504-L-C1 "Occupant (Driver or Passenger) is not wearing a seatbelt"
4. U-602-L-C3 "The shoulder harness is too high to be comfortable"
5. U-604-L-C1 "The shoulder harness is not adjustable"

These are the five switches for the system. In the rest of Step 3, we'll verify that if these can be adjusted, the system will give us the proper response. In Step 4, we'll devise innovative solutions (if necessary) to adjust the system switches.

Step 3.2 FOR EACH AIRBAG DE, SEEK TO ENSURE THE LOGICAL VALUE OF THE ENTITY IS = 1.

Making the 5 proposed changes of step 3.1 should ensure all DE are "true." Assuming these changes can be made:

D-201-L-C3 "The airbag deploys"- If an accident occurs, the sensors will give a signal to deploy. When the sensors give a signal to deploy, then there will a signal to the airbag to deploy. If the airbag is on and there is a signal to deploy, the airbag will deploy.

D-301-L-C1 "The airbag is on"- This is a first order control. The passive value of this logical entity is set to one.

Step 3.3 FOR EACH AIRBAG UDE, SEEK TO CREATE THE VALUE OF THE NODE = 0

Making the 5 proposed changes of step 3.1 should ensure all UDEs are "true." Assuming these changes can be made and the logic of the diagram adequately models the system, all of the following will be false:

U-101-L-C2 "Occupant of vehicle dies"

U-202-L-C2 "A Person is too close to the airbag"

U-303-L-C2 "The Driver is too close to airbag"

U-304-L-C2 "The Passenger is too close to airbag"

U-405-L-C4 "The passenger is too far forward"

U-505-L-C2 "Occupant's shoulder harness is improperly positioned behind his back"

The following UDEs are from the proposed changes:

U-602-L-C3 "The shoulder harness is too high to be comfortable"

U-604-L-C1 "The shoulder harness is not adjustable"

U-504-L-C1 "Occupant (Driver or Passenger) is not wearing a seatbelt"

The remainder of the UDEs are not controlled but no longer influence the terminal UDE that an occupant of the vehicle dies:

U-403-L-C2 "The Driver's Seat is moved forward"

U-404-L-C4 "The Driver is 'slumped' forward"

U-406-L-C3 "There is a Child in a RFCSS in the front seat"

U-506-L-C5 "The Driver has passed out"

U-601-L-C5 "An Accident Occurs"

U-603-L-C4 "The driver is short (60 inches tall or less)"

Step 3.4 IDENTIFY ANY TRADE-OFFS IN THE DESIGN OF THE AIRBAG SYSTEM

It is not possible to control entity N-605-L-C3 "Infant should be in back seat" (note it is coded as C3). In order to preclude an infant being in the front seat in a RFCSS, recommend sensing that a RFCSS is in the front seat and turning off the passenger airbag in such a case.

Therefore, the only remaining trade-off is that the passenger airbag is turned off when a RFCSS is in the passenger seat. There is therefore no airbag protection for this position when the vehicle is in an accident.

Step 3.5 REVIEW TOTAL AIRBAG SYSTEM

At this point, the system design approach is complete.

Step 4. GENERATE AIRBAG SOLUTIONS AT THE CRITICAL ENTITIES AND TRADE-OFFS

The method has led to a simple solution that uses four Sub-solutions:

Sub-solution 1. Make it impossible to start the car without the seatbelt fastened. This sets the following entity to false:

U-504-L-C1 "Occupant (Driver or Passenger) is not wearing a seatbelt"

Sub-solution 2. Add a simple adjustment mechanism to the shoulder harness assembly. This sets the following entities to false:

U-602-L-C3 "The shoulder harness is too high to be comfortable"

U-604-L-C1 "The shoulder harness is not adjustable"

Sub-solution 3. Add a sensor to turn the airbag off when a RFCSS is in the passenger seat. This sets the following entity to false:

N-605-L-C3 "Infant should be in back seat"

Sub-solution 4. Eliminate the steering wheel or stow the driver side airbag in the dashboard. This sets the following entity to false:

N-408-L-C1 "Airbag is stowed in steering column"

4.1.1.1. Undesirable Entities

Three of the switches of the system are UDEs. They are addressed in sub-solutions 1 and 2.

4.1.1.2. Desirable Entities

None of the switches of the system are DEs.

4.1.1.3. Contradiction Relationships

Note that the first Contradictory relationship is suggested by sub-solution 4:

C-001. The steering wheel should exist (to steer the car) and not exist (when there is an accident)

C-002. Short passengers should be seated up close (to see and to reach the foot pedals) and far away (from the airbag).

4.1.1.4. Increasing Ideality Entities

None

Note that we do not have to deal with every one of the above parent relationships. By working through the logic of the system in Step 3 above, we only need to solve the 4 Sub-solutions using TRIZ which is good because with the number of parent relationships identified, we would have 2,541 possible operators to address (15 UDE * 135 operators + 2 DE * 211 operators +2 CON * 47 operators = 2,541 operators).

Of the four Sub-solutions we have to consider, Sub-solutions 1 through 3 deal with entities that must be "turned off" and their solutions are self-evident.

The last one requires an understanding of physical contradictions.

- C-001. The steering wheel should exist (to steer the car) and not exist (when there is an accident)
- C-002. Short passengers should be seated up close (to see and to reach the foot pedals) and far away (from the airbag).

Every single UDE and DE is addressed using the logic diagram, but consideration of operators is not necessary for each one.

Step 4.1 I-TRIZ SOLUTION RECOMMENDATIONS FOR AIRBAG UNDESIRABLE ENTITIES

The following are UDEs:

4.1.1.5. Undesirable Entity Parent relationships

U-101-L-C2 "Occupant of vehicle dies" is neutralized by **Sub-solutions 1, 2, 3 and 4.**

U-202-L-C2 "A Person is too close to the airbag" is neutralized by **Sub-solutions 1, 2, 3 and 4.**

U-303-L-C2 "The Driver is too close to airbag" is neutralized by **Sub-solutions 1, 2 and 4.**

U-304-L-C2 "The Passenger is too close to airbag" is neutralized by **Sub-solutions 1, 2 and 3.**

U-403-L-C2 "The Driver's Seat is moved forward" is neutralized by **Sub-solution 4.**

U-404-L-C4 "The Driver is 'slumped' forward" is neutralized by **Sub-solutions 1, 2 and 4.**

U-405-L-C4 "The passenger is too far forward" is neutralized by **Sub-solutions 1 and 2.**

U-406-L-C3 "There is a Child in a RFCSS in the front seat" is neutralized by **Sub-solution 3**

U-504-L-C1 "Occupant (Driver or Passenger) is not wearing a seatbelt" =0 by **Sub-solution 1.**

U-505-L-C2 "Occupant's shoulder harness is improperly positioned behind his back"=0 by **Sub-solution 2.**

U-506-L-C5 "The Driver has passed out" is neutralized by **Sub-solution 4.**

U-601-L-C5 "An Accident Occurs" is not controlled or neutralized but the harmful effect of an accident occurring is neutralized by **Sub-solutions 1 through 4.**

U-602-L-C3 "The shoulder harness is too high to be comfortable" =0 by **Sub-solution 2.**

U-603-L-C4 "The driver is short (60 inches tall or less)" is neutralized by **Sub-solution 4.**

U-604-L-C1 "The shoulder harness is not adjustable"= 0 by **Sub-solution 2.**

Step 4.2 I-TRIZ SOLUTION RECOMMENDATIONS FOR AIRBAG DESIRABLE ENTITIES.

The following are DEs:

4.1.1.6. Desirable Entity Parent relationships

D-201-L-C3 "The airbag deploys" is not controlled.

D-301-L-C1 "The airbag is on" is controlled by **Sub-solution 3** only when a child is in RFCSS.

Step 4.3 I-TRIZ SOLUTION RECOMMENDATIONS FOR AIRBAG CONTRADICTIONS.

The following are considered contradictions that must be solved in order to establish **Sub-solution 4**:

4.1.1.7. Contradiction Parent relationships

C-001. The steering wheel should exist (to steer the car) and not exist (when there is an accident)

C-002. Short passengers should be seated up close (to see and to reach the foot pedals) and far away (from the airbag).

Step 4.3.1 THE "SEPARATION PRINCIPLES" CONTRADICTION CHILD RELATION.

In order to resolve physical contradictions (a characteristic is self-opposing), Altshuller recommends using separation principles:

- Separation of opposite requirements in space
- Separation of opposite requirements in time

In fact, these separation principles are both satisfied if ten inches is maintained between the occupant, whether driver or passenger and the airbag. The problem is to control the distance between the occupant and the airbag to be greater than or equal to ten inches, regardless of the size of the driver or personal habits of the driver or passenger.

4.1.1.8. Further solutions using separation principles

One solution is the following:

- For the driver's airbag, 1) cause the steering column to retract in reaction to the seat being moved closer to the dashboard.
- For the both airbags, 2) use a sensor to detect the presence of a seated occupant. Do not allow the vehicle to be placed in gear if an occupant is not using a seatbelt. Requiring the seatbelt to be fastened removes any requirement to adjust deployment for non-belted occupants.
- For both sides of the car, 3) install an adjustable shoulder harness that can be adjusted too lay across the shoulder of seat occupants within a range of height from 36 inches to 80 inches (most cars already have this feature).
- For cars without back seats, the airbag on the passenger side should continue to be deactivated in the presence of a rear facing child safety seat.

Another solution is to remove the steering wheel and put in its place a joystick, located to the right of the driver (in cars where the driver is seated on the left). Once the steering wheel is eliminated, there is no problem with moving the seat up because the airbag can be located in the console.

Step 4.3.2 THE "40 INNOVATION PRINCIPLES" CONTRADICTION CHILD RELATION

As the problem has already been solved, there is no need to pursue the 40 Innovation Principles.

Step 4.4 I-TRIZ SOLUTION RECOMMENDATIONS FOR INCREASING AIRBAG IDEALITY

This is not applicable to the airbag problem.

4.2 CONCLUSION FOR AIRBAG PROBLEM

The airbag design problem is solved using the method of this research. The method has led to a simple solution that uses four Sub-solutions:

Sub-solution 1. Make it impossible to start the car without the seatbelt fastened.

Sub-solution 2. Add a simple adjustment mechanism to the shoulder harness assembly.

Sub-solution 3. Add a sensor to turn the airbag off when a RFCSS is in the passenger seat.

Sub-solution 4. Eliminate the steering wheel or stow the driver side airbag in the dashboard.

CHAPTER 5. AIRLIFT LOADING SYSTEM CASE STUDY

5.1 OVERVIEW OF AIRLIFT LOADING SYSTEM

The airlift loading system is the current system used to load cargo aircraft and transport it to various parts of the world. The need for a more efficient loading system stemmed from the observation that aircraft were being loaded to less than 20% of their volumetric capacity because cargo could not be stacked.

Due to client confidentiality concerns, the exact names of aircraft used as well as part names and numbers has been withheld. Representative values and case scenarios are used to illustrate the problem and quantify the solution.

Large Cargo Planes are being used to transport material across large distances. Because the material is not stackable, it is being placed one-box high on pallets. It was noted that a great deal of volumetric capacity of the airplane was being wasted. This case study uses the methods developed in this dissertation to define and solve this problem. The solution is simple and seems intuitive: create a loading system with removable shelves for greatest flexibility.

This study exemplifies the need for a disciplined approach because it can be compared to an identical design effort that was based on the traditional "flash of insight" undisciplined approach. The group that solved the original problem had a brilliant idea - to increase the volumetric capacity by adding a second pallet position to the loading system. Immediately, a study ensued because the design was considered a great idea, born in a flash of insight. The study that ensued did not define the problem or the system it was in, it immediately started on the development of a solution.

The designers generated hundreds of drawings. They also created prototypes and tested them destructively. Millions of research dollars were spent over a greater than two year period. A cost study comparing the new 2-level solution with the old method of loading pallets was conducted and this study demonstrated substantial savings.

Had the developers defined the problem with the method described in this dissertation beforehand, they would have saved a great deal more with virtually no additional development costs by realizing that they could have added many more loading options by creating multiple pallet positions that can be reconfigured in any way the cargo loader need to configure it.

The solution to this problem is shown is found in Chapter 5. A detailed cost analysis is performed in Appendix C.

Step 1. GATHER INFORMATION ABOUT THE AIRLIFT LOADING PROBLEM

Step 1.1 DESCRIBE THE AIRLIFT LOADING PROBLEM IN NON-TECHNICAL TERMS

Extra aircraft are being used to airlift supplies because the cargo is not stackable.

Step 1.2 DEFINE AND DESCRIBE THE AIRLIFT LOADING SYSTEM

Step 1.2.1 NAME THE AIRLIFT LOADING SYSTEM

Airlift Loading System

Step 1.2.2 DEFINE THE AIRLIFT LOADING SYSTEM STRUCTURE

There are four types of aircraft available for airlifting cargo. They can be described in terms of cost of aircraft per flight hour and number of pallet positions available. They are identified throughout this report as follows:

Aircraft	Number of pallets	Cost per flight hour
Plane 1	5	$ 3,570
Plane 2	11	$ 6,000
Plane 3	15	$ 6,460
Plane 4	30	$ 14,600

Table 14. Aircraft Load Constraints

There is only one kind of pallet available. Because of considerable capital investment and compatibility with cargo hold securing units, it must be used. Each pallet is 96 inches wide by 96 inches deep. Each pallet weighs 300 pounds. Each pallet position has a capacity of 12,000 pounds.

The cargo hold area is 120 inches tall.

There are ten airlift missions per year, ranging from 15 to 25 flight hours each. Some missions can use any combination of the four aircraft, while others may only certain types of aircraft, as shown below:

Mission	One-way flight time	Aircraft used
Mission 1	15 hrs	Planes 1 and 3
Mission 2	16 hrs	Planes 3 and 4
Mission 3	17 hrs	Plane 4
Mission 4	18 hrs	Plane 4
Mission 5	19 hrs	Mixed
Mission 6	20 hrs	Planes 3 and 4
Mission 7	21 hrs	Plane 1
Mission 8	22 hrs	Planes 2 and 3
Mission 9	23 hrs	Planes 3 and 4
Mission 10	24 hrs	Mixed

Table 15. Mission Definitions

Cargo is not stackable. Different kinds of cargo may not be mixed on a pallet. Ten cargo configuration scenarios are defined:

Scenario 1	Size 1	Size 2
Number of Pallets	32 pallets	40 pallets
Number of Boxes per Pallet	2	1
Number of Boxes	64 boxes	40 boxes
Size of box-width	48.0 in	96.0 in
Size of box-depth	96.0 in	96.0 in
Size of box-height	24.0 in	24.0 in

Volume per box	64.0 ft3	128.0 ft3
Total Volume	4096.0 ft3	5120.0 ft3
Weight per box	1,088 lb	2,176 lb
Total Weight	69,632 lb	87,040 lb

Scenario 2	Size 1	Size 2	Size 3
Number of Pallets	12 pallets	40 pallets	40 pallets
Number of Boxes per Pallet	9	3	1
Number of Boxes	108 boxes	120 boxes	40 boxes
Size of box-width	32.0 in	32.0 in	96.0 in
Size of box-depth	32.0 in	80.0 in	88.0 in
Size of box-height	30.0 in	36.0 in	20.4 in
Volume per box	17.8 ft3	53.3 ft3	99.7 ft3
Total Volume	1920.0 ft3	6400.0 ft3	3989.3 ft3
Weight per box	302 lb	907 lb	1,695 lb
Total Weight	32,640 lb	108,800 lb	67,819 lb

Scenario 3	Size 1
Number of Pallets	140 pallets
Number of Boxes per Pallet	1
Number of Boxes	140 boxes
Size of box-width	50.0 in
Size of box-depth	60.0 in
Size of box-height	40.0 in
Volume per box	69.4 ft3
Total Volume	9722.2 ft3
Weight per box	1,181 lb
Total Weight	165,278 lb

Scenario 4	Size 1	Size 2	Size 3
Number of Pallets	32 pallets	40 pallets	12 pallets
Number of Boxes per Pallet	1	2	3
Number of Boxes	32 boxes	80 boxes	36 boxes
Size of box-width	90.0 in	48.0 in	50.0 in
Size of box-depth	88.0 in	88.0 in	32.0 in
Size of box-height	20.4 in	88.0 in	36.0 in
Volume per box	93.5 ft3	215.1 ft3	33.3 ft3
Total Volume	2992.0 ft3	17208.9 ft3	1200.0 ft3
Weight per box	1,590 lb	3,657 lb	567 lb

Total Weight	50,864 lb	292,551 lb	20,400 lb
Scenario 5	**Size 1**	**Size 2**	**Size 3**
Number of Pallets	32 pallets	120 pallets	55 pallets
Number of Boxes per Pallet	2	3	1
Number of Boxes	64 boxes	360 boxes	55 boxes
Size of box-width	54.0 in	32.0 in	96.0 in
Size of box-depth	40.0 in	40.0 in	88.0 in
Size of box-height	20.4 in	40.0 in	30.0 in
Volume per box	25.5 ft3	29.6 ft3	146.7 ft3
Total Volume	1632.0 ft3	10666.7 ft3	8066.7 ft3
Weight per box	434 lb	504 lb	2,493 lb
Total Weight	27,744 lb	181,333 lb	137,133 lb
Scenario 6	**Size 1**	**Size 2**	**Size 3**
Number of Pallets	35 pallets	35 pallets	40 pallets
Number of Boxes per Pallet	2	2	1
Number of Boxes	70 boxes	70 boxes	40 boxes
Size of box-width	50.0 in	50.0 in	88.0 in
Size of box-depth	40.0 in	30.0 in	88.0 in
Size of box-height	10.0 in	30.0 in	30.0 in
Volume per box	11.6 ft3	26.0 ft3	134.4 ft3
Total Volume	810.2 ft3	1822.9 ft3	5377.8 ft3
Weight per box	197 lb	443 lb	2,286 lb
Total Weight	13,773 lb	30,990 lb	91,422 lb
Scenario 7	**Size 1**	**Size 2**	
Number of Pallets	15 pallets	70 pallets	
Number of Boxes per Pallet	2	1	
Number of Boxes	30 boxes	70 boxes	
Size of box-width	48.0 in	96.0 in	
Size of box-depth	96.0 in	96.0 in	
Size of box-height	24.0 in	24.0 in	
Volume per box	64.0 ft3	128.0 ft3	
Total Volume	1920.0 ft3	8960.0 ft3	
Weight per box	1,088 lb	2,176 lb	
Total Weight	32,640 lb	152,320 lb	
Scenario 8	**Size 1**	**Size 2**	**Size 3**
Number of Pallets	15 pallets	12 pallets	20 pallets

Number of Boxes per Pallet	9	3	1
Number of Boxes	135 boxes	36 boxes	20 boxes
Size of box-width	32.0 in	32.0 in	96.0 in
Size of box-depth	32.0 in	80.0 in	88.0 in
Size of box-height	30.0 in	36.0 in	20.4 in
Volume per box	17.8 ft3	53.3 ft3	99.7 ft3
Total Volume	2400.0 ft3	1920.0 ft3	1994.7 ft3
Weight per box	302 lb	907 lb	1,695 lb
Total Weight	40,800 lb	32,640 lb	33,909 lb
Scenario 9		**Size 1**	
Number of Pallets		95 pallets	
Number of Boxes per Pallet		1	
Number of Boxes		95 boxes	
Size of box-width		50.0 in	
Size of box-depth		60.0 in	
Size of box-height		40.0 in	
Volume per box		69.4 ft3	
Total Volume		6597.2 ft3	
Weight per box		1,181 lb	
Total Weight		112,153 lb	
Scenario 10	**Size 1**	**Size 2**	**Size 3**
Number of Pallets	68 pallets	21 pallets	45 pallets
Number of Boxes per Pallet	1	2	3
Number of Boxes	68 boxes	42 boxes	135 boxes
Size of box-width	90.0 in	48.0 in	50.0 in
Size of box-depth	88.0 in	88.0 in	32.0 in
Size of box-height	20.4 in	88.0 in	36.0 in
Volume per box	93.5 ft3	215.1 ft3	33.3 ft3
Total Volume	6358.0 ft3	9034.7 ft3	4500.0 ft3
Weight per box	1,590 lb	3,657 lb	567 lb
Total Weight	108,086 lb	153,589 lb	76,500 lb

Table 16. Scenario Definitions

Step 1.2.3 DEFINE THE SPHERE OF INFLUENCE AND SPAN OF CONTROL ON A SYSTEM

We cannot change the aircraft, the pallets or the defined missions. We can design a loading system that incorporates the existing system of planes, pallets and missions.

Step 1.2.4 DEFINE THE WAY THE SYSTEM FUNCTIONS

Primary useful function of the system

To deliver cargo on pallets using available aircraft in predefined airlift missions.

Reason to perform the primary useful function:

To deliver cargo in a cost efficient manner

Functioning of the system:

Cargo is loaded on pallets onto aircraft and sent overseas on predefined missions.

Step 1.2.5 **DEFINE THE SYSTEM BOUNDARIES AND ENVIRONMENT**

In the system are the aircraft, the pallets, the cargo and anything we design to be used within the cargo hold area.

Step 1.3 **REFINE THE DEFINITION OF THE PROBLEM**

Step 1.3.1 **IDENTIFY THE PROBLEM TO BE RESOLVED**

The cargo loading process must be improved to more efficiently use the volumetric capacity of the aircraft.

Step 1.3.2 **ESTABLISH THE MECHANISM CAUSING THE PROBLEM.**

Because the boxes are not stackable, the aircraft cannot be loaded to volumetric capacity.

Step 1.3.3 **DESCRIBE THE UNDESIRED CONSEQUENCES OF AN UNRESOLVED PROBLEM.**

Cost is unnecessarily escalated due to extra aircraft being used in each airlift.

Step 1.3.4 **BRIEFLY DESCRIBE THE HISTORY OF THE PROBLEM**

The problem has been noted in the past but never resolved.

Step 1.3.5 **IDENTIFY OTHER SYSTEMS IN WHICH A SIMILAR PROBLEM EXISTS**

None noted

Step 1.3.6 **OTHER PROBLEMS TO BE SOLVED IN THE COURSE OF SOLVING THE PRIMARY PROBLEM.**

None noted

Step 1.4 **DEFINE THE SOLUTION SPACE**

The aircraft use all of the available volumetric capacity.

Step 1.5 **DEFINE AVAILABLE RESOURCES**

Aircraft, pallets, cargo and design cargo holding apparatus.

Step 1.6 **CONSIDER ALLOWABLE CHANGES TO THE SYSTEM**

Only the pallet loading system may be changed

Step 1.7 **FURTHER REFINE SOLUTION SPACE**

Not applicable

Step 2. CONSTRUCT AN AIRLIFT LOADING LOGIC DIAGRAM

Step 2.1 IDENTIFY AIRLIFT LOADING CHIEF UNDESIRABLE EFFECTS

This problem does not have an undesirable effect. The objective is to enhance an existing system, not to overcome an undesirable effect.

It may be tempting to that the undesirable effect is that the cargo is not loaded to capacity, but this is not an undesirable effect in the purest sense of the word because it is only a matter of degree between an undesirable effect and a desirable effect.

Step 2.2 DRAW THE AIRLIFT LOADING LOGIC DIAGRAM

The following entities have been identified:

"Cost is minimized"

"Cost of Mission"

"Weight is minimized"

"Empty space is minimized"

"The right mix of aircraft are used"

"The cargo is kept segregated on the pallets"

"The mission is defined"

"A mixture of planes 1, 2, 3 and 4 is allowed"

"Only Plane 1s are allowed"

"Only Plane 2s are allowed"

"Only Plane 3s are allowed"

"Only Plane 4s are allowed"

"Only Planes 1 and 2 are allowed"

"Only Planes 1 and 3 are allowed"

"Only Planes 1 and 4 are allowed"

"Only Planes 2 and 3 are allowed"

"Only Planes 2 and 4 are allowed"

"Only Planes 3 and 4 are allowed"

"Only Planes 1, 2 and 3 are allowed"

"Only Planes 2, 3 and 4 are allowed"

"Number of Plane 1s used"

"Number of Plane 2s used"

"Number of Plane 3s used"

"Number of Plane 4s used"

"Planes are loaded to capacity"

"Planes are loaded to volumetric capacity"

"Planes are loaded to weight capacity"

"Cargo is stacked to the ceiling"

"Cargo is not stacked"

"Weight of pallets is 300 lbs each"

"Weight of cargo is 17 lbs per ft^3"

"Height of the cargo area is 120 inches (10 feet)"

"Width of the pallet is 96 inches (8 feet)"

"Depth of the pallet is 96 inches (8 feet)"

"Plane 1 has 5 pallet positions"

"Plane 2 has 11 pallet positions"

"Plane 3 has 15 pallet positions"

"Plane 4 has 30 pallet positions"

"Plane 1 costs $3,750 per flight hour to fly"

"Plane 2 costs $6,000 per flight hour to fly"

"Plane 3 costs $6,460 per flight hour to fly"

"Plane 4 costs $14,600 per flight hour to fly"

"Number of pallet positions used"

"Number of boxes"

"Number of boxes per pallet"

"One way flight time"

"Weight capacity"

"Total weight"

"Weight component of cost"

"Cost per lb."

"Weight of Cargo and Loading System"

"Weight of Aircraft"

"Weight of boxes"

"Weight capacity of pallets is 12,000 lb per pallet position"

"Dimensions of boxes"

Step 2.2.1 CONNECTING ENTITIES

Step 2.2.1.1 CODE THE ENTITIES

The following are Boolean entities:

1. "Cost is minimized"
2. "Weight is minimized"
3. "Empty space is minimized"
4. "The right mix of aircraft are used"
5. "The cargo is kept segregated on the pallets"
6. "The mission is defined"
7. "A mixture of planes 1, 2, 3 and 4 is allowed"

8. "Only Plane 1s are allowed"
9. "Only Plane 2s are allowed"
10. "Only Plane 3s are allowed"
11. "Only Plane 4s are allowed"
12. "Only Planes 1 and 2 are allowed"
13. "Only Planes 1 and 3 are allowed"
14. "Only Planes 1 and 4 are allowed"
15. "Only Planes 2 and 3 are allowed"
16. "Only Planes 2 and 4 are allowed"
17. "Only Planes 3 and 4 are allowed"
18. "Only Planes 1, 2 and 3 are allowed"
19. "Only Planes 2, 3 and 4 are allowed"
20. "Planes are loaded to capacity"
21. "Planes are loaded to volumetric capacity"
22. "Planes are loaded to weight capacity"
23. "Cargo is stacked to the ceiling"
24. "Cargo is not stacked"

The following are quantitative variables:

1. "Cost of Mission"
2. "Number of Plane 1s used"
3. "Number of Plane 2s used"
4. "Number of Plane 3s used"
5. "Number of Plane 4s used"
6. "Weight of pallets is 300 lbs each"
7. "Weight of cargo is 17 lbs per ft^3"
8. "Height of the cargo area is 120 inches (10 feet)"
9. "Width of the pallet is 96 inches (8 feet)"
10. "Depth of the pallet is 96 inches (8 feet)"
11. "Plane 1 has 5 pallet positions"
12. "Plane 2 has 11 pallet positions"
13. "Plane 3 has 15 pallet positions"
14. "Plane 4 has 30 pallet positions"
15. "Plane 1 costs $3,750 per flight hour to fly"
16. "Plane 2 costs $6,000 per flight hour to fly"
17. "Plane 3 costs $6,460 per flight hour to fly"
18. "Plane 4 costs $14,600 per flight hour to fly"
19. "Number of pallet positions used"
20. "Number of boxes"

21. "Number of boxes per pallet"
22. "One way flight time"
23. Weight capacity"
24. "Total weight"
25. "Weight component of cost"
26. "Cost per lb."
27. "Weight of Cargo and Loading System"
28. "Weight of Aircraft"
29. "Weight of boxes"
30. "Weight capacity of pallets is 12,000 lb per pallet position"
31. "Dimensions of boxes"

Step 2.2.1.2 IDENTIFY CONNECTIONS BETWEEN ENTITIES

Many of the entities are variables that are related to each other by equations. The methodology was able to handle this very nicely. The equations given below are in *Excel* spreadsheet format. Three functions may not be familiar to the reader and are defined here for clarity:

MOD (x, y) is the remainder in whole numbers after x is divided by y.

FLOOR (x, y) is the value of x rounded to the next lower value, rounded to y significance. If y is 1, then the value is rounded down to the next lower integer.

CEILING (x, y) is the value of x rounded to the next higher value, rounded to y significance. If y is 1, then the value is rounded up to the next higher integer.

For instance:

MOD (100, 30) = 10 because 100 ÷ 30 = 3 +10/30

FLOOR (100/30, 1) = 3, because 100 ÷ 30 = 3.33, round down to 3

CEILING (100/30, 1) = 4, because 100 ÷ 30 = 3.33, round up to 4

"Cost is minimized" is caused by

"Cost of Mission"

"Cost of mission" is caused by

"Cost of mission"= {(Number of Plane 1s)* $3,750 + (Number of Plane 2s)* $6,000 + (Number of Plane 3s)* $6,460 + (Number of Plane 4s)* $14,600}* (One way flight time) * 2 **(47)**

"One way flight time"

"The right mix of aircraft are used"

"Empty space is minimized"

"Weight component of cost"

"The right mix of aircraft are used" is made up of

Number of Plane 1s

Number of Plane 2s

Number of Plane 3s

Number of Plane 4s

Number of Plane 1s, 2s, 3s and 4s are made up of

"Number of pallet positions used"

"Plane 1 costs $3,750 per flight hour to fly"

"Plane 2 costs $6,000 per flight hour to fly"

"Plane 3 costs $6,460 per flight hour to fly"

"Plane 4 costs $14,600 per flight hour to fly"

"Plane 1 has 5 pallet positions"

"Plane 2 has 11 pallet positions"

"Plane 3 has 15 pallet positions"

"Plane 4 has 30 pallet positions"

"The mission is defined"

"Number of pallet positions used" is made up of

"Number of pallet positions used"= $n = \Sigma$ (number of boxes * number of boxes per pallet) **(48)**

"Number of boxes"

"Number of boxes per pallet"

"The cargo is kept segregated on the pallets"

To find- Number of Plane 1s, Number of Plane 2s, Number of Plane 3s and Number of Plane 4s

Use "The mission is defined"

For "A mixture of planes 1, 2, 3 and 4 is allowed"

Number of Plane 1s = IF (MOD (n, 15) = 0, 0, IF (MOD (n, 15) < 6, 1, 0)) **(49)**

Number of Plane 2s = IF (MOD (n, 15) <6, 0, IF (MOD (n, 15) < 12, 1, 0)) **(50)**

Number of Plane 3s = IF (MOD (n, 15) <12, 0, 1) + FLOOR (n/15,1) **(51)**

Number of Plane 4s = 0 **(52)**

For "Only Plane 1s are allowed"

Number of Plane 1s = CEILING (n/5,1) **(53)**

For "Only Plane 2s are allowed"

Number of Plane 2s = CEILING (n/11,1) **(54)**

For "Only Plane 3s are allowed"

Number of Plane 3s = CEILING (n/15,1) **(55)**

For "Only Plane 4s are allowed"

Number of Plane 4s = CEILING (n/30,1) **(56)**

For "Only Planes 1 and 2 are allowed"

Number of Plane 1s = IF (MOD (n, 11) = 0, 0, IF (MOD (n, 11) < 6,1, 0)) **(57)**

Number of Plane 2s = IF (MOD (n, 11) >5, 1,0) + FLOOR (n/11, 1) **(58)**

For "Only Planes 1 and 3 are allowed"

Number of Plane 1s = IF (MOD (n, 15) = 0, 0, IF (MOD (n, 15) < 6,1, 0)) **(59)**

Number of Plane 3s = IF (MOD (n, 15) >5, 1,0) + FLOOR (n/15, 1) **(60)**

For "Only Planes 1 and 4 are allowed"

Number of Plane 1s = IF (MOD (n, 30) = 0, 0, IF (MOD (n, 30) < 21,CEILING (MOD (n, 30)/5,1), 0)) **(61)**

Number of Plane 4s = IF (MOD (n, 30) >20, 1,0) + FLOOR (n/30, 1) **(62)**

For "Only Planes 2 and 3 are allowed"

Number of Plane 2s = IF (MOD (n, 15) = 0, 0, IF (MOD (n, 15) < 12,1, 0)) **(63)**

Number of Plane 3s = IF (MOD (n, 15) >11, 1,0) + FLOOR (n/15, 1) **(64)**

For "Only Planes 2 and 4 are allowed"

Number of Plane 2s = IF (MOD (n, 30) = 0, 0, IF (MOD (n, 30) < 23,CEILING (MOD (n, 30)/11,1), 0)) **(65)**

Number of Plane 4s = IF (MOD (n, 30) >22, 1,0) + FLOOR (n/30, 1) **(66)**

For "Only Planes 3 and 4 are allowed"

Number of Plane 3s = CEILING (n/15,1) **(67)**

Number of Plane 4s = 0 **(68)**

For "Only Planes 1, 2 and 3 are allowed"

Number of Plane 1s = IF (MOD (n, 15) = 0, 0, IF (MOD (n, 15) < 6, 1, 0)) **(69)**

Number of Plane 2s = IF (MOD (n, 15) <6, 0, IF (MOD (n, 15) < 12, 1, 0)) **(70)**

Number of Plane 3s = IF (MOD (n, 15) <12, 0, 1) + FLOOR (n/15,1) **(71)**

For "Only Planes 2, 3 and 4 are allowed"

Number of Plane 2s = IF (MOD (n, 15) = 0, 0, IF (MOD (n, 15) < 12,1, 0)) **(72)**

Number of Plane 3s = IF (MOD (n, 15) >11, 1,0) + FLOOR (n/15, 1) **(73)**

Number of Plane 4s = 0 **(74)**

"Number of boxes per pallet" is made up of

- "Width of the pallet is 96 inches (8 feet)"
- "Depth of the pallet is 96 inches (8 feet)"
- "Dimensions of boxes"

"The mission is defined" is made up of

- "A mixture of planes 1, 2, 3 and 4 is allowed"
- "Only Plane 1s are allowed"
- "Only Plane 2s are allowed"
- "Only Plane 3s are allowed"
- "Only Plane 4s are allowed"
- "Only Planes 1 and 2 are allowed"
- "Only Planes 1 and 3 are allowed"
- "Only Planes 1 and 4 are allowed"

"Only Planes 2 and 3 are allowed"

"Only Planes 2 and 4 are allowed"

"Only Planes 3 and 4 are allowed"

"Only Planes 1, 2 and 3 are allowed"

"Only Planes 2, 3 and 4 are allowed"

"Empty space is minimized" is caused by

"Planes are loaded to capacity"

"Planes are loaded to capacity" is caused by

"Planes are loaded to volumetric capacity"

"Planes are loaded to weight capacity"

"Planes are loaded to volumetric capacity" is caused by

"Height of the cargo area is 120 inches (10 feet)"

"Width of the pallet is 96 inches (8 feet)"

"Depth of the pallet is 96 inches (8 feet)"

"Cargo is stacked to the ceiling"

"Cargo is not stacked"

"The cargo is kept segregated on the pallets"

"Planes are loaded to weight capacity" is caused by

"Weight capacity"

"Total weight"

"Weight is minimized" is caused by

"Total weight"

"Total weight" is caused by

"Weight of Cargo and Loading System"

"Weight of Aircraft"

"Weight of Cargo and Loading System" is caused by

"Weight of Cargo and Loading System" $= n * 300$ **lbs** $+ \Sigma$ **(# boxes) * (weight per box)** **(75)**

"Weight of boxes"

"Weight of pallets is 300 lbs each"

"Number of pallet positions used"

"Weight of boxes" is caused by

"Number of boxes"

"Number of boxes per pallet"

"Weight of cargo is 17 lbs per ft^3"

Step 2.2.1.3 CODE ENTITIES AS DESIRABLE, UNDESIRABLE OR NEUTRAL

See Summary of the Entity Coding Scheme below.

Step 2.2.1.4 CODE CONTROL OF ENTITIES

See Summary of the Entity Coding Scheme below.

Step 2.2.2 **ASSIGN NUMBERS TO EACH ENTITY.**

See Summary of the Entity Coding Scheme below.

Step 2.2.3 **SUMMARY OF THE ENTITY CODE SCHEME**

D-101-L-C2	"Cost is minimized"
N-201-Q-C2	"Cost of Mission"
D-102-L-C2	"Weight is minimized"
D-301-L-C2	"Empty space is minimized"
D-302-L-C2	"The right mix of aircraft are used"
N-601-L-C5	"The cargo is kept segregated on the pallets"
N-501-L-C5	"The mission is defined"
N-602-L-C5	"A mixture of planes 1, 2, 3 and 4 is allowed"
N-603-L-C5	"Only Plane 1s are allowed"
N-604-L-C5	"Only Plane 2s are allowed"
N-605-L-C5	"Only Plane 3s are allowed"
N-606-L-C5	"Only Plane 4s are allowed"
N-607-L-C5	"Only Planes 1 and 2 are allowed"
N-608-L-C5	"Only Planes 1 and 3 are allowed"
N-609-L-C5	"Only Planes 1 and 4 are allowed"
N-610-L-C5	"Only Planes 2 and 3 are allowed"
N-611-L-C5	"Only Planes 2 and 4 are allowed"
N-612-L-C5	"Only Planes 3 and 4 are allowed"
N-613-L-C5	"Only Planes 1, 2 and 3 are allowed"
N-614-L-C5	"Only Planes 2, 3 and 4 are allowed"
D-401-Q-C1	"Number of Plane 1s used"
D-402-Q-C1	"Number of Plane 2s used"
D-403-Q-C1	"Number of Plane 3s used"
D-404-Q-C1	"Number of Plane 4s used"
D-405-L-C3	"Planes are loaded to capacity"
D-502-L-C3	"Planes are loaded to volumetric capacity"
D-503-L-C2	"Planes are loaded to weight capacity"
D-615-L-C3	"Cargo is stacked to the ceiling"
U-616-L-C1	"Cargo is not stacked"
N-409-Q-C5	"Weight of pallets is 300 lbs each"
N-515-Q-C5	"Weight of cargo is 17 lbs per ft^3"
N-617-Q-C5	"Height of the cargo area is 120 inches (10 feet)"
N-618-Q-C5	"Width of the pallet is 96 inches (8 feet)"

N-619-Q-C5	"Depth of the pallet is 96 inches (8 feet)"
N-504-Q-C5	"Plane 1 has 5 pallet positions"
N-505-Q-C5	"Plane 2 has 11 pallet positions"
N-506-Q-C5	"Plane 3 has 15 pallet positions"
N-507-Q-C5	"Plane 4 has 30 pallet positions"
N-508-Q-C5	"Plane 1 costs $3,750 per flight hour to fly"
N-509-Q-C5	"Plane 2 costs $6,000 per flight hour to fly"
N-510-Q-C5	"Plane 3 costs $6,460 per flight hour to fly"
N-511-Q-C5	"Plane 4 costs $14,600 per flight hour to fly"
N-512-Q-C2	"Number of pallet positions used"
N-620-Q-C5	"Number of boxes"
N-621-Q-C5	"Number of boxes per pallet"
N-303-Q-C5	"One way flight time"
N-622-Q-C5	"Weight capacity"
N-202-Q-C4	"Total weight"
N-304-Q-C2	"Weight component of cost"
N-406-Q-C5	"Cost per lb."
N-407-Q-C2	"Weight of Cargo and Loading System"
N-408-Q-C5	"Weight of Aircraft"
N-513-Q-C5	"Weight of boxes"
N-514-Q-C5	"Weight capacity of pallets is 12,000 lb per pallet position"
N-623-Q-C5	"Dimensions of boxes"

Table 17. Entities Defined for Airlift Loading System

Step 2.2.4 TEST THE LOGIC DIAGRAM USING THE RULES OF LOGIC.

There are three basic objectives to this problem:

1) Minimize cost,
2) Minimize weight and
3) Maximize volumetric utilization.

As it will be shown, these three objectives are all controlled by one constraint (N-621-Q-C5, "Number of boxes per pallet"). Constraint N-621-Q-C5 will be broken using the theories of TRIZ and then the system will be further improved using the I-TRIZ concept of Directed Evolution.

Cost minimization

Taking the equation for N-201-Q-C2 and working downwards:

N-201-Q-C2		"Cost of Mission" is a function of
	N-303-Q-C5	"One way flight time"
	N-304-Q-C2	"Weight component of cost"
	D-401-Q-C1	"Number of Plane 1s used"
	D-402-Q-C1	"Number of Plane 2s used"

D-403-Q-C1	"Number of Plane 3s used"
D-404-Q-C1	"Number of Plane 4s used"
N-508-Q-C5	"Plane 1 costs $3,750 per flight hour to fly"
N-509-Q-C5	"Plane 2 costs $6,000 per flight hour to fly"
N-510-Q-C5	"Plane 3 costs $6,460 per flight hour to fly"
N-511-Q-C5	"Plane 4 costs $14,600 per flight hour to fly"

201Q = 2*303Q*(401Q*508Q+402Q*509Q+403Q*510Q+404Q*511Q)+304Q (76)

Working from 201Q to its components,

N-303-Q-C5 "One way flight time" is defined for the mission

N-304-Q-C2 "Weight component of cost" is a function of

N-202-Q-C4 "Total weight"

N-406-Q-C5 "Cost per lb."

304Q = 202Q * 406Q (77)

Note that 304Q is assumed to be very small when compared to 201Q and that weight is already considered in variables 508Q through 511Q. So long as total weight of cargo and loading system (407Q) is greater than pallet weight capacity (514Q), cost component of weight is neglected.

N-202-Q-C4 "Total weight" is a function of

N-407-Q-C2 "Weight of Cargo and Loading System"

N-408-Q-C5 "Weight of Aircraft"

202Q = 407Q + 408Q (78)

N-407-Q-C2 "Weight of Cargo and Loading System" is a function of

N-409-Q-C5 "Weight of pallets is 300 lbs each"

N-512-Q-C2 "Number of pallet positions used"

N-513-Q-C5 "Weight of boxes"

407Q = 409Q*512Q + 513Q (79)

N-409-Q-C5 "Weight of pallets is 300 lbs each" is a constant

N-512-Q-C2 "Number of pallet positions used" is a function of

N-620-Q-C5 "Number of boxes"

N-621-Q-C5 "Number of boxes per pallet"

512Q = Σ 620Q * 621Q (80)

N-620-Q-C5 "Number of boxes" is given for a particular mission

N-621-Q-C5 "Number of boxes per pallet" is a function of

N-618-Q-C5 "Width of the pallet is 96 inches (8 feet)"

N-619-Q-C5 "Depth of the pallet is 96 inches (8 feet)"

N-623-Q-C5 "Dimensions of boxes"

621Q=MAX (FLOOR ($623Q_{width}$ ÷ 618Q, 1), FLOOR ($623Q_{depth}$ ÷ 618Q, 1) (81)

N-618-Q-C5 "Width of the pallet is 96 inches (8 feet)" is a constant

N-619-Q-C5 "Depth of the pallet is 96 inches (8 feet)" is a constant

N-623-Q-C5 "Dimensions of boxes" is given for a mission

N-513-Q-C5 "Weight of boxes" is a function of

- N-620-Q-C5 "Number of boxes" is given for a particular mission
- N-515-Q-C5 "Weight of cargo is 17 lbs per ft³"
- N-623-Q-C5 "Dimensions of boxes"

$$\mathbf{513Q = 620Q*515Q*623Q_{width}*623Q_{depth}*623Q_{height}} \tag{82}$$

N-515-Q-C5 "Weight of cargo is 17 lbs per ft3" is given for the problem

N-623-Q-C5 "Dimensions of boxes" is given for the mission

N-408-Q-C5 "Weight of Aircraft" is addressed in the next section (weight minimization)

N-406-Q-C5 "Cost per lb." is unknown but its value is neglected

D-401-Q-C1 "Number of Plane 1s used," D-402-Q-C1 "Number of Plane 2s used," D-403-Q-C1 "Number of Plane 3s used" andD-404-Q-C1 "Number of Plane 4s used" are all functions of

- N-501-L-C5 "The mission is defined"
- N-504-Q-C5 "Plane 1 has 5 pallet positions"
- N-505-Q-C5 "Plane 2 has 11 pallet positions"
- N-506-Q-C5 "Plane 3 has 15 pallet positions"
- N-507-Q-C5 "Plane 4 has 30 pallet positions"
- N-508-Q-C5 "Plane 1 costs $3,750 per flight hour to fly"
- N-509-Q-C5 "Plane 2 costs $6,000 per flight hour to fly"
- N-510-Q-C5 "Plane 3 costs $6,460 per flight hour to fly"
- N-511-Q-C5 "Plane 4 costs $14,600 per flight hour to fly"
- N-512-Q-C2 "Number of pallet positions used"

Note- an equation cannot be written from these because 501L needs to change to 501Q. First, change to N-501-L-C5 "The mission is defined" to N-501-Q-C5 "Mission definition." N-501-Q-C5 "Mission definition" takes on integer values of 1 through 13.

D-401-Q-C1 "Number of Plane 1s used," D-402-Q-C1 "Number of Plane 2s used," D-403-Q-C1 "Number of Plane 3s used" andD-404-Q-C1 "Number of Plane 4s used" are all functions of

- N-501-Q-C5 "Mission definition"
- N-504-Q-C5 "Plane 1 has 5 pallet positions"
- N-505-Q-C5 "Plane 2 has 11 pallet positions"
- N-506-Q-C5 "Plane 3 has 15 pallet positions"
- N-507-Q-C5 "Plane 4 has 30 pallet positions"
- N-508-Q-C5 "Plane 1 costs $3,750 per flight hour to fly"
- N-509-Q-C5 "Plane 2 costs $6,000 per flight hour to fly"
- N-510-Q-C5 "Plane 3 costs $6,460 per flight hour to fly"
- N-511-Q-C5 "Plane 4 costs $14,600 per flight hour to fly"
- N-512-Q-C2 "Number of pallet positions used"

401Q=

IF (501Q=1, IF (MOD (512Q, 506Q) = 0, 0, IF (MOD (512Q, 506Q) ≤ 504Q, 1, 0))

IF (501Q=2, CEILING (512Q/504Q, 1)

IF (501Q=3, 0

IF (501Q=4, 0

IF (501Q=5, 0

IF (501Q=6, IF (MOD (512Q, 505Q) = 0, 0, IF (MOD (512Q, 505Q) ≤ 504Q, 1, 0))

IF (501Q=7, IF (MOD (512Q, 506Q) = 0, 0, IF (MOD (512Q, 506Q) ≤ 504Q, 1, 0))

IF (501Q=8, IF (MOD (512Q, 507Q) = 0, 0, IF (MOD (512Q, 507Q) ≤ 4*504Q, CEILING (MOD (512Q, 507Q)/505Q, 1), 0))

IF (501Q=9, 0

IF (501Q=10, 0

IF (501Q=11, 0

IF (501Q=12, IF (MOD (512Q, 506Q) = 0, 0, IF (MOD (512Q, 506Q) ≤ 504Q, 1, 0))

IF (501Q=13, 0, "Undefined") **(83)**

402Q =

IF (501Q=1, IF (MOD (512Q, 506Q) ≤ 504Q, 0, IF (MOD (512Q, 506Q) < 12, 1, 0))

IF (501Q=2, 0

IF (501Q=3, CEILING (512Q/505Q, 1)

IF (501Q=4, 0

IF (501Q=5, 0

IF (501Q=6, IF (MOD (512Q, 505Q) >504Q, 1,0) + FLOOR (512Q÷505Q, 1)

IF (501Q=7, 0

IF (501Q=8, 0

IF (501Q=9, IF (MOD (512Q, 506Q) = 0, 0, IF (MOD (512Q, 506Q) ≤ 505Q, 1, 0))

IF (501Q=10, IF (MOD (512Q, 507Q) = 0, 0, IF (MOD (512Q, 507Q) ≤ 2*505Q, CEILING (MOD (512Q, 507Q)÷505Q, 1), 0))

IF (501Q=11, 0

IF (501Q=12, IF (MOD (512Q, 506Q) ≤ 504Q, 0, IF (MOD (512Q, 506Q) < 12, 1, 0))

IF (501Q=13, IF (MOD (512Q, 506Q) = 0, 0, IF (MOD (512Q, 506Q) ≤ 505Q, 1, 0)) **(84)**

403Q =

IF (501Q=1, IF (MOD (512Q, 506Q) ≤ 505Q, 0, 1) + FLOOR (512Q÷506Q, 1)

IF (501Q=2, 0

IF (501Q=3, 0

IF (501Q=4, CEILING (512Q/506Q, 1)

IF (501Q=5, 0

IF (501Q=6, 0

IF (501Q=7, IF (MOD (512Q, 506Q) >504Q, 1,0) + FLOOR (512Q÷506Q, 1)

IF (501Q=8, 0

IF (501Q=9, IF (MOD (512Q, 506Q) >505Q, 1,0) + FLOOR (512Q÷506Q, 1)

IF (501Q=10, 0

IF (501Q=11, CEILING (512Q/506Q, 1)

IF (501Q=12, IF (MOD (512Q, 506Q) ≤ 505Q, 0, 1) + FLOOR (512Q÷506Q, 1)

IF (501Q=13, IF (MOD (512Q, 506Q) >505Q, 1,0) + FLOOR (512Q÷506Q, 1) **(85)**

404Q =

IF (501Q=1, 0

IF (501Q=2, 0

IF (501Q=3, 0

IF (501Q=4, 0

IF (501Q=5, CEILING (512Q/507Q, 1)

IF (501Q=6, 0

IF (501Q=7, 0

IF (501Q=8, IF (MOD (512Q, 507Q) >4*504Q, 1,0) + FLOOR (512Q÷507Q, 1)

IF (501Q=9, 0

IF (501Q=10, IF (MOD (512Q, 507Q) >2*505Q, 1,0) + FLOOR (512Q÷507Q, 1)

IF (501Q=11, 0

IF (501Q=12, 0

IF (501Q=13, 0, Else "undefined") **(86)**

Note that the values of 508Q through 511Q define the forms of these equations implicitly.

N-501-Q-C5 "Mission definition" is function of

N-602-L-C5 "A mixture of planes 1, 2, 3 and 4 is allowed"

N-603-L-C5 "Only Plane 1s are allowed"

N-604-L-C5	"Only Plane 2s are allowed"
N-605-L-C5	"Only Plane 3s are allowed"
N-606-L-C5	"Only Plane 4s are allowed"
N-607-L-C5	"Only Planes 1 and 2 are allowed"
N-608-L-C5	"Only Planes 1 and 3 are allowed"
N-609-L-C5	"Only Planes 1 and 4 are allowed"
N-610-L-C5	"Only Planes 2 and 3 are allowed"
N-611-L-C5	"Only Planes 2 and 4 are allowed"
N-612-L-C5	"Only Planes 3 and 4 are allowed"
N-613-L-C5	"Only Planes 1, 2 and 3 are allowed"
N-614-L-C5	"Only Planes 2, 3 and 4 are allowed"

Note although 602 through 614 are logical functions, they can be used as in input to 501Q because they only need to take on vales of 1 (TRUE) or 0 (FALSE).

$$501Q = 602L + 2*603L + 3*604L = 4*605L + 5*606L + 6*607L + 7*608L + 8*609L + 9*610L + 10*611L + 11*612L + 12*613L + 13*614L \tag{87}$$

N-602-L-C5 through N-614-L-C5 is given for the mission (TRUE/FALSE). Only one may be TRUE: the rest are FALSE.

N-504-Q-C5	"Plane 1 has 5 pallet positions" is a constant
N-505-Q-C5	"Plane 2 has 11 pallet positions" is a constant
N-506-Q-C5	"Plane 3 has 15 pallet positions" is a constant
N-507-Q-C5	"Plane 4 has 30 pallet positions" is a constant
N-508-Q-C5	"Plane 1 costs $3,750 per flight hour to fly" is a constant
N-509-Q-C5	"Plane 2 costs $6,000 per flight hour to fly" is a constant
N-510-Q-C5	"Plane 3 costs $6,460 per flight hour to fly" is a constant
N-511-Q-C5	"Plane 4 costs $14,600 per flight hour to fly" is a constant

Cost minimization flowchart

The cost relationships are illustrated in a flowchart.

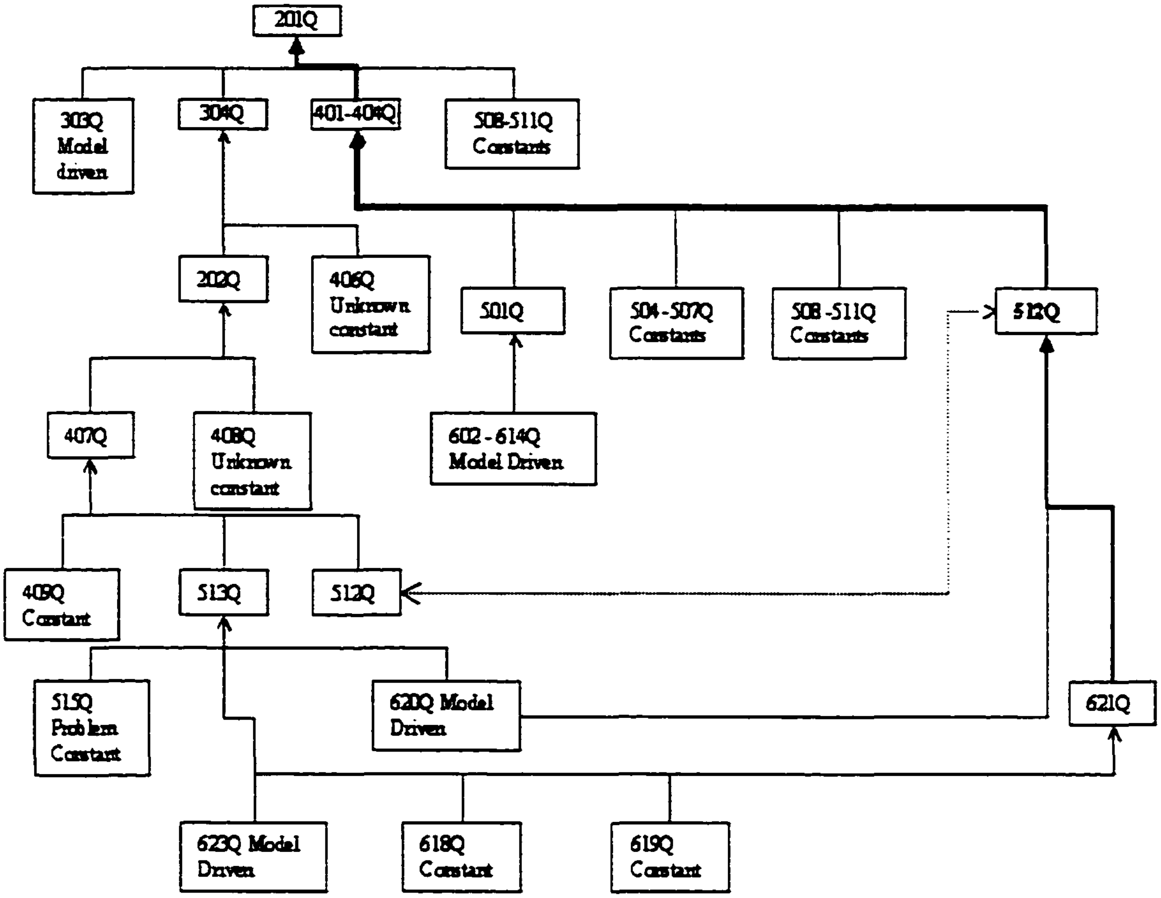


Figure 23. Cost Flowchart for Airlift Loading System

From the diagram, if N-621-Q-C5, "Number of boxes per pallet," can be increased, then total cost will decrease because total number of planes will decrease. With the current design, it cannot be increased because it is made up of N-618-Q-C5 "Width of the pallet is 96 inches (8 feet)," N-619-Q-C5 "Depth of the pallet is 96 inches (8 feet)" and N-623-Q-C5 "Dimensions of boxes," all of which are either constant or given. But if the boxes could be stacked two boxes high, then the value of 621Q is doubled. Using the TRIZ concept of physical contradiction, I will double the value of 621Q, but first I'll continue the discussion of weight minimization and volumetric utilization maximization.

Weight minimization

N-202-Q-C4		"Total weight" is a function of
	N-407-Q-C2	"Weight of Cargo and Loading System"
	N-408-Q-C5	"Weight of Aircraft"

202Q = 407Q + 408Q **(88)**

Note that 408Q >> 407Q. Reducing the number of aircraft has more effect on reducing total weight that reducing the weight of the cargo and pallets.

N-407-Q-C2 "Weight of Cargo and Loading System" has been defined earlier (equation 79).

N-408-Q-C5 "Weight of Aircraft" is a function of

D-401-Q-C1 "Number of Plane 1s used"
D-402-Q-C1 "Number of Plane 2s used"
D-403-Q-C1 "Number of Plane 3s used"
D-404-Q-C1 "Number of Plane 4s used"
N-410-Q-C5 "Weight of Plane 1" (new entity)
N-411-Q-C5 "Weight of Plane 2" (new entity)
N-412-Q-C5 "Weight of Plane 3" (new entity)
N-413-Q-C5 "Weight of Plane 4" (new entity)

408Q = 401Q*410Q + 402Q*411Q + 403Q*412Q + 404Q*413Q **(89)**

D-401-Q-C1 "Number of Plane 1s used," D-402-Q-C1 "Number of Plane 2s used," D-403-Q-C1 "Number of Plane 3s used" andD-404-Q-C1 "Number of Plane 4s used" were defined in equations (83), through (86)

N-510-Q-C5 "Plane 3 costs $6,460 per flight hour to fly" is a constant
N-511-Q-C5 "Plane 4 costs $14,600 per flight hour to fly" is a constant
N-410-Q-C5 "Weight of Plane 1" is an unknown constant
N-411-Q-C5 "Weight of Plane 2" is an unknown constant
N-412-Q-C5 "Weight of Plane 3" is an unknown constant
N-413-Q-C5 "Weight of Plane 4" is an unknown constant

Weight minimization flowchart

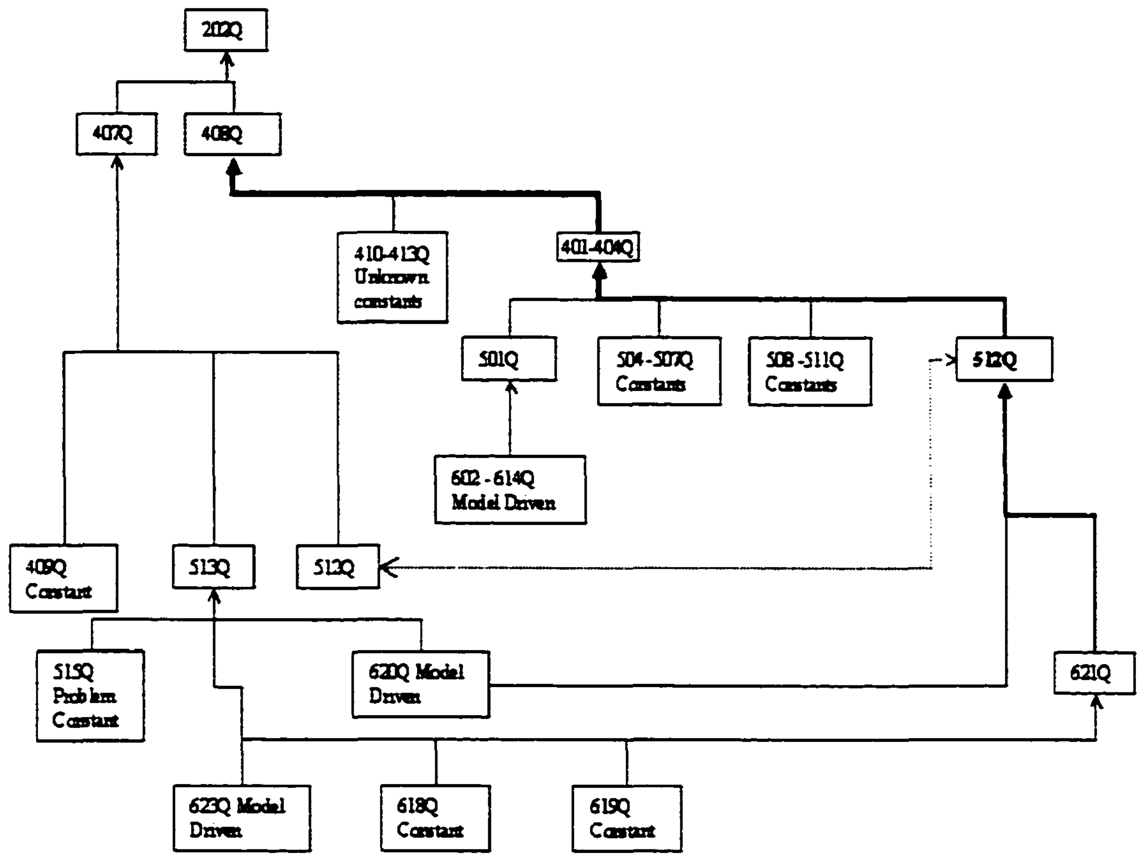


Figure 24. Weight Flowchart for Airlift Loading System

From the diagram, if N-621-Q-C5 ("Number of boxes per pallet") can be increased, then total weight will decrease because total number of planes will decrease. With the current design, it cannot be increased because it is made up of N-618-Q-C5 "Width of the pallet is 96 inches (8 feet)," N-619-Q-C5 "Depth of the pallet is 96 inches (8 feet)" and N-623-Q-C5 "Dimensions of boxes," all of which are either constant or given. But if the boxes could be stacked two boxes high, then the value of 621Q is doubled. Using the TRIZ concept of physical contradiction, I will double the value of 621Q, but first I'll continue the discussion of volumetric utilization maximization.

Volumetric utilization maximization

N-203-Q-C2	"Volumetric utilization" (new entity) is a function of
N-305-Q-C2	"Volume available" (new entity)
N-306-Q-C4	"Volume of load" (new entity)

203Q = 306Q ÷ 305Q **(90)**

N-305-Q-C2	"Volume available" is a function of
D-401-Q-C1	"Number of Plane 1s used"
D-402-Q-C1	"Number of Plane 2s used"
D-403-Q-C1	"Number of Plane 3s used"
D-404-Q-C1	"Number of Plane 4s used"

N-504-Q-C5	"Plane 1 has 5 pallet positions"
N-505-Q-C5	"Plane 2 has 11 pallet positions"
N-506-Q-C5	"Plane 3 has 15 pallet positions"
N-507-Q-C5	"Plane 4 has 30 pallet positions"
N-617-Q-C5	"Height of the cargo area is 120 inches (10 feet)"
N-618-Q-C5	"Width of the pallet is 96 inches (8 feet)"
N-619-Q-C5	"Depth of the pallet is 96 inches (8 feet)"

$$305Q = (401Q*504Q + 402Q*505Q + 403Q*506Q + 404Q*507Q) * 617Q*618Q*619Q \quad (91)$$

D-401-Q-C1 "Number of Plane 1s used," D-402-Q-C1 "Number of Plane 2s used," D-403-Q-C1 "Number of Plane 3s used" and D-404-Q-C1 "Number of Plane 4s used" were defined in equations (83), through (86)

N-617-Q-C5	"Height of the cargo area is 120 inches (10 feet)" is a constant
N-618-Q-C5	"Width of the pallet is 96 inches (8 feet)" is a constant
N-619-Q-C5	"Depth of the pallet is 96 inches (8 feet)" is a constant
N-306-Q-C4	"Volume of load" is a function of
N-620-Q-C5	"Number of boxes" is given for a particular mission
N-623-Q-C5	"Dimensions of boxes"

$$306Q = \Sigma\,(620Q*623Q_{width}*623Q_{depth}*623Q_{height})_i \quad (92)$$

N-623-Q-C5	"Dimensions of boxes" is given for a mission

Volumetric utilization flowchart

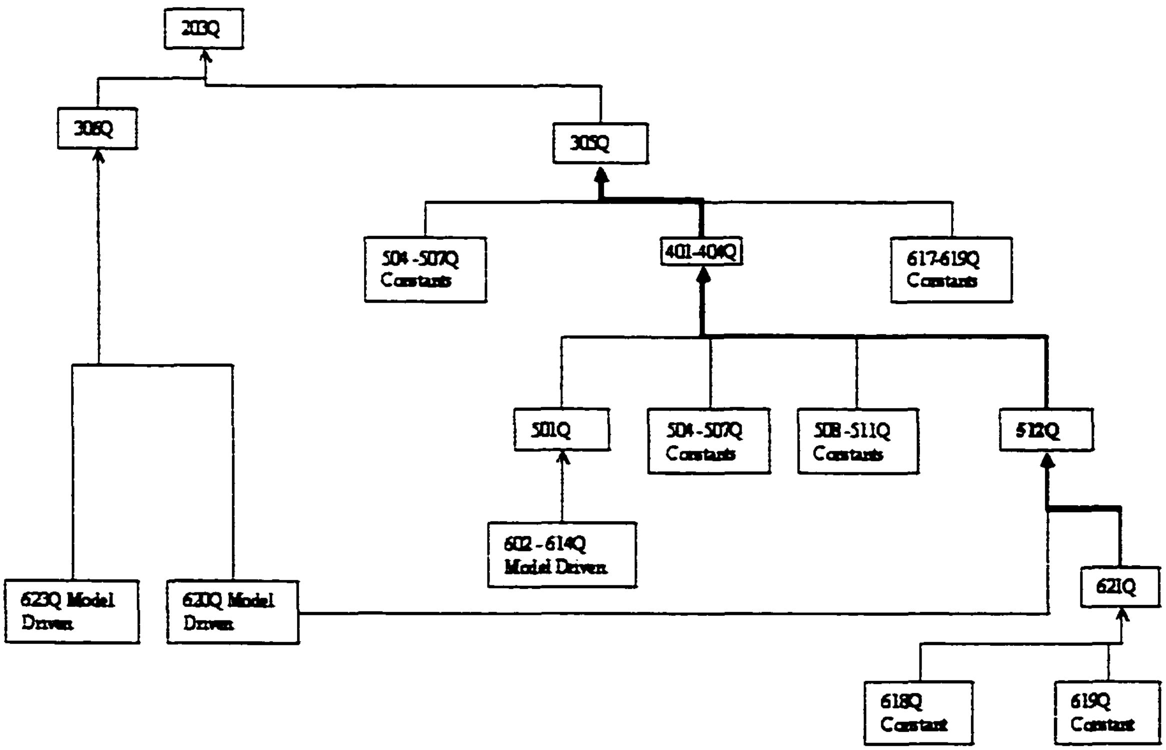


Figure 25. Volumetric Utilization Flowchart for Airlift Loading System

From the diagram, if N-621-Q-C5 ("Number of boxes per pallet") can be increased, then total volumetric utilization will increase because total number of planes will decrease while the volume of the load remains constant. With the current design, it cannot be increased because it is made up of N-618-Q-C5 "Width of the pallet is 96 inches (8 feet)," N-619-Q-C5 "Depth of the pallet is 96 inches (8 feet)" and N-623-Q-C5 "Dimensions of boxes," all of which are either constant or given. But if the boxes could be stacked two boxes high, then the value of 621Q is doubled. Using the TRIZ concept of physical contradiction, I will double the value of 621Q in Step 4.

Step 2.2.5 COMPLETE THE AIRLIFT SYSTEM LOGIC DIAGRAM

The ultimate system objective is "The system is optimal." Defining a new entity for this objective,

D-103-L-C2	"The system is optimal" is caused by
D-101-L-C2	"Cost is minimized" **and**
D-102-L-C2	"Weight is minimized" **and**
D-104-L-C2	"Volumetric utilization is maximized" (new entity)
D-101-L-C2	"Cost is minimized" is caused by
N-204-L-C4	"Existing system is used (new entity) **and**
D-615-L-C3	"Cargo is stacked to the ceiling"
N-204-L-C4	"Existing system is used is a problem constraint
D-615-L-C3	"Cargo is stacked to the ceiling" is opposed by
U-616-L-C1	"Cargo is not stacked"
D-102-L-C2	"Weight is minimized" is caused by
N-204-L-C4	"Existing system is used (new entity) **and**
D-615-L-C3	"Cargo is stacked to the ceiling"
N-204-L-C4	"Existing system is used is a problem constraint
D-615-L-C3	"Cargo is stacked to the ceiling" is opposed by
U-616-L-C1	"Cargo is not stacked"
D-104-L-C2	"Volumetric utilization is maximized" is caused by
N-204-L-C4	"Existing system is used (new entity) **and**
D-615-L-C3	"Cargo is stacked to the ceiling"
N-204-L-C4	"Existing system is used is a problem constraint
D-615-L-C3	"Cargo is stacked to the ceiling" is opposed by
U-616-L-C1	"Cargo is not stacked"

System logic diagram

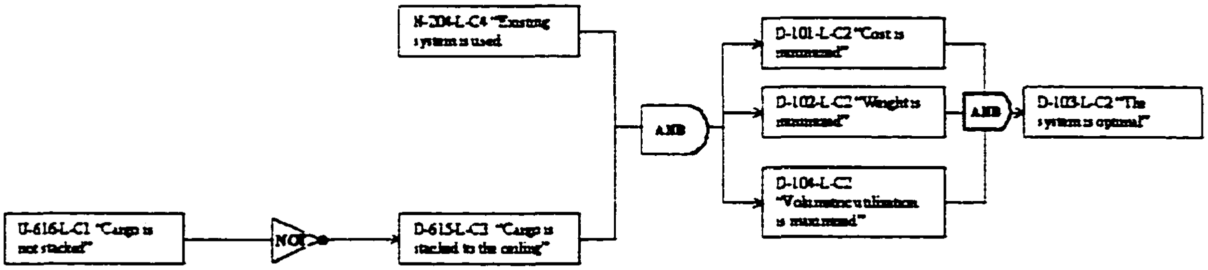


Figure 26. Overall Simplified Logic Diagram for Airlift Loading System

Step 3. ANALYZE AIRLIFT LOADING LOGIC DIAGRAM TO FIND THE CONSTRAINTS OF THE SYSTEM

There is only one constraint in the system to be resolved, that is the conflict between

D-615-L-C3 "Cargo is stacked to the ceiling" and

U-616-L-C1 "Cargo is not stacked"

This conflict is called a "physical contradiction" because the characteristic must both exist and not exist simultaneously. *Physical contradictions* are among the simplest problems to solve in TRIZ.

Step 3.1 FIND THE SWITCHES FOR THE AIRLIFT LOADING SYSTEM

The only switch in the system is a "physical contradiction" between

D-615-L-C3 "Cargo is stacked to the ceiling" and

U-616-L-C1 "Cargo is not stacked"

Step 3.2 FOR EACH DE, SEEK TO ENSURE THE LOGICAL VALUE OF THE ENTITY IS = 1.

If physical contradiction were resolved, all DEs would achieve the value of 1.

Step 3.3 FOR EACH UDE, SEEK TO CREATE THE VALUE OF THE NODE = 0

There is one UDE, U-616-L-C1. Resolving the physical contradiction would neutralize its effect on the system.

Step 3.4 IDENTIFY ANY TRADE-OFFS IN THE AIRLIFT LOADING DESIGN

The main trade-off is the contradiction inherent in the inability to stack cargo with the current system.

Step 3.5 REVIEW TOTAL AIRLIFT LOADING SYSTEM

The root cause is U-616-L-C1. The physical contradiction driving this root cause is the conflict between U-616-L-C1 and D-615-L-C3.

Step 4. GENERATE AIRLIFT LOADING SOLUTIONS AT THE CRITICAL ENTITIES AND TRADE-OFFS

Although it can be argued that the critical entity is U-616-L-C1 and it should be selected, the real critical entity is the physical contradiction between U-616-L-C1 and D-615-L-C3.

This problem has yielded one critical entity, a contradiction. Proceed to Step 4.3 to resolve the physical contradiction, then to step 4.4 to optimize the system further since it has a terminal useful effect.

Step 4.1 I-TRIZ SOLUTION RECOMMENDATIONS FOR AIRLIFT LOADING UDEs

None

Step 4.2 I-TRIZ SOLUTION RECOMMENDATIONS FOR AIRLIFT LOADING DEs.

None

Step 4.3 I-TRIZ SOLUTION RECOMMENDATIONS FOR AIRLIFT LOADING CONTRADICTIONS.

Since the contradiction is a *physical contradiction*, proceed to Step 4.3.1.

Step 4.3.1 THE "SEPARATION PRINCIPLES" CONTRADICTION CHILD RELATION.

The "Separation Principles" Contradiction child relation has 7 operators:

1. Separate opposite requirements in space
2. Separate opposite requirements in time
3. Optimize characteristics in time
4. Separate opposite requirements between the whole object and its parts
5. Separate opposite requirements via changing conditions
6. Separate an impeding part from an object
7. Separate (remove) a required part from an object

I expanded on the first separation principle, separate opposite requirements in space. According to the Innovation Workbench 2000[7], "If a system is required to perform contradictory functions or operate under contradictory conditions, try to (actually or theoretically) partition the system. Then assign each contradictory function or condition to a different subsystem."

The two contradictory functions are:

D-615-L-C3 "Cargo is stacked to the ceiling" and

U-616-L-C1 "Cargo is not stacked"

If the cargo were separated in space by placing it on a loading system with two pallet positions, then the effective footprint would be doubled so long as the height of the cargo still fit within loading system. I created a two-level loading system with one pallet at floor level and the other at 50 inches over the ground. There are now approximately 50 inches of clearance for the lower position and 70 inches of clearance in the upper position.

The second consideration is the fact that some cargo is too large to fit within the clearance limitations. This is also a physical contradiction between two mutually contradictory characteristics:

"There must be a center pallet position in order to accommodate twice as many cargo containers."

"There must not be a center pallet position in order to accommodate larger containers."

For this contradiction, the second contradiction principle is applicable, "separate opposite requirements in time." This is accomplished by making the center pallet position optional. The loading system should have a bracket for the center position and the center pallet should be easily removable with quick disconnects. In this way, sometimes there is a center pallet position and sometimes there is not a center pallet position according to the needs of a particular mission.

This is a solution to the design problem, but now we must ask, "Does it go far enough?" The terminal effect of the new process is a useful effect, making the new system eligible for Step 4.4, which states, "If the design only has desirable entities, then consider the I-TRIZ solution recommendations for increasing the level of ideality of the system."

Step 4.4 RECOMMENDATIONS FOR INCREASING IDEALITY OF THE AIRLIFT LOADING SYSTEM

The first idea that comes to mind when surveying the child relations of increasing the ideality of the system is that the system has effectively evolved at this point for a mono-system to a bi-system. Step 4.4.2, "the "mono-bi-poly" terminal DE child relation," which states, "in the process of evolution, technological systems tend to improve through integration into a super-system of higher rank. This may be accomplished by transformation into a bi-system (the combination of two identical or different systems) and/or into a poly-system (the combination of more than two systems)" (Innovation Workbench 2000?).

Step 4.4.1 THE "IMPROVE IDEALITY" TERMINAL DE CHILD RELATION

Step 4.4.2 THE "MONO-BI-POLY" TERMINAL DE CHILD RELATION

Our system has evolved from a mono-system to a bi-system. The next evolutionary progression for the design is to a poly-system. A poly-system loading system is one that has many shelves that can be used to hold pallets.

I suggest placing brackets that can hold pallets at each of the following heights of the pallet loading system:

1) Ground level
2) 12 inches
3) 24 inches
4) 36 inches
5) 48 inches
6) 60 inches
7) 72 inches
8) 84 inches
9) 96 inches
10) 108 inches

At each of these locations, a pallet could either be located or not located. For instance, if the boxes loaded were 30 inches high, place a pallet on the ground level, at 36 inches and at 72 inches. Now there are 3 pallets yielding three times the capacity of the original system and 1.5 times the capacity of the two-level system.

For the ten scenarios, I have analyzed the capacity of the original system and compared it to the capacity of the two-level system and to the poly-level system. The analysis is found in appendix C.

5.2 Conclusions from the Airlift Loading System Case Study

The Airlift Loading System Case Study is an example of the need for disciplined problem formulation and analysis. The original problem formulators clearly grasped that the need for greater volumetric capacity could be met by adding a shelf to the system. Their understanding of the problem led them to a very narrow solution and they committed to that solution very early in the development stage. Had they considered the line of technological evolution they were using was a shift from a mono-system to a bi-system, then they would have been able to forecast that the next step is toward a poly-system.

As long as we depend on developers, designers and inventors to design the next product using a "flash of insight," we will see slow changes such as this. With a disciplined approach that considers the whole system first, creates a logic relationship, then formulates the solution type, a great deal of time and money can be saved. The old adage that "those who fail to study history are doomed to repeat it" is certainly in play for the Airlift Loading System.

CHAPTER 6. ADDITIONAL ILLUSTRATIONS OF METHOD

6.1 TRUCK BED COVERS

Pick-up trucks have coverings that can be purchased after-market. These coverings stretch across the truck bed. There are a number of problems encountered in handling these covers, including:

- Installing the cover requires adding a permanent fastener or hold-down to the truck, which is unattractive and becomes a site for corrosion
- The covers have great localized stress and can tear if they are used to carry large loads
- The covers are difficult to align and attach if there is a large load

A case study of a new Truck bed cover design is found in chapter 6. The truck bed cover design developed arrives at the same approach as a recent new design found in the US Patent database and currently sold in the United States.

Step 1. GATHER INFORMATION ABOUT THE TRUCK BED COVER PROBLEM

Step 1.1 DESCRIBE THE TRUCK BED COVER PROBLEM IN NON-TECHNICAL TERMS

Problem Statement (technical terms):

Pickup bed covers are difficult to fasten if the load is over the top of the truck bed. Furthermore, they are fastened with snaps or hardware that are permanently attached to the truck, causing potential rust spots and generally defacing the pickup truck.

Problem Statement in non-technical terms:

Design a pickup truck bed cover that can accommodate tall loads and does not include any permanent attachments to the truck.

Optional: Possible solutions suggested by reviewing the Problem Statement:

None noted

Step 1.2 DEFINE AND DESCRIBE THE TRUCK BED COVER SYSTEM

Step 1.2.1 NAME THE TRUCK BED COVER SYSTEM

Common or Technical name of System being improved:

Common name- Truck bed covers. Technical name- "tonneau pickup bed covers"

Step 1.2.2 DEFINE THE SYSTEM STRUCTURE

Elements that comprise the system:

1. Truck
2. Truck bed
3. Truck bed cover
4. Tailgate
5. Undercarriage

6. Fastening mechanism truck bed and cover

Supersystem in which the system resides:

Pickup truck

Other Systems in the Supersystem:

- Engine
- Transmission
- Chassis
- Passenger compartment
- Wheels

Step 1.2.3 DEFINE THE SPHERE OF INFLUENCE AND SPAN OF CONTROL ON A TRUCK BED COVER SYSTEM

Element	Control Level
Overall System:	C2- Simple Indirect Control
Element1: Truck	C5- Uncontrollable
Element2: Truck bed	C5- Uncontrollable
Element3: Truck bed cover	C2- Simple Indirect Control
Element4: Tailgate	C5- Uncontrollable
Element5: Undercarriage	C5- Uncontrollable
Element6: Fastening mechanism truck bed and cover	C1- Direct Control
Supersystem: Pickup truck	C5- Uncontrollable
System2: Engine	C5- Uncontrollable
System3: Transmission	C5- Uncontrollable
System4: Passenger compartment	C5- Uncontrollable
System5: Steering mechanism	C5- Uncontrollable

Table 18. Truck Bed Problem Systemic Element Control Levels

Step 1.2.4 DEFINE THE WAY THE TRUCK BED COVER SYSTEM FUNCTIONS

Providing System/Element	Action/Function	Receiving System/Element
Truck bed cover	Encloses	Truck bed
Truck bed cover	Attaches to	Truck
Truck bed cover	Overhangs	Tailgate
Truck bed cover	Cannot obstruct	Undercarriage
Truck bed cover	Cannot obstruct	Wheels
Truck bed cover	Cannot obstruct	Passenger compartment
Fastening mechanism	Attaches to	Truck bed cover
Fastening mechanism	Attaches to	Truck

Table 19. Truck Bed Cover Functions

Step 1.2.5 DEFINE THE TRUCK BED COVER SYSTEM BOUNDARIES AND ENVIRONMENT

This problem will work at the following systemic level:

Truck bed cover

The supersystem in which the defined system operates:

Truck

Other Systems within the supersystem:

Engine

Transmission

Chassis

Wheels

Steering Mechanism

Related Systems:

None

Subsystems of the defined system:

None

Step 1.3 REFINE THE DEFINITION OF THE TRUCK BED COVER PROBLEM

Step 1.3.1 IDENTIFY THE PROBLEM TO BE RESOLVED

1-failure or drawback must be eliminated/corrected

☒ A harmful action or effect is present in the system

Refined Problem Description:

The following drawbacks of the truck bed cover system must be eliminated- it must be able to loads over the top of the truck bed without stretching and without installing any permanent fasteners to the truck.

Step 1.3.2 ESTABLISH THE MECHANISM CAUSING THE PROBLEM.

1. Cover can be stretched to the point of tearing or rupture.
2. Fasteners can cause rusting in the truck bed.
3. Cover can interfere with the operation of the pickup truck.
4. Cover can be difficult or impossible to align with the fasteners due to the size of the load.
5. Cover can come loose when in operation and blow away.

Table 20. Truck Bed Cover Failure Mechanisms

Step 1.3.3 DESCRIBE THE UNDESIRED CONSEQUENCES OF AN UNRESOLVED PROBLEM.

1. Cover is destroyed by excessive stretching.
2. Truck bed becomes rusted at the place where fasteners are attached.
3. Truck bed obstructs vision or operation of truck and causes a traffic accident.
4. Truck bed cannot be used with large load and load cannot be safely transported as a result.
5. Truck bed cover is lost along with the load.

Table 21. Truck Bed Cover Undesired Consequences of an Unresolved Problem.

Step 1.3.4 BRIEFLY DESCRIBE THE HISTORY OF THE PROBLEM

1. Hansen's Expandable tarpaulin assembly- addresses irregularly shaped loads, but permanently attached fasteners to truck bed[227] (patent 5,050,924- 9/24/91)
2. Cao's Protector for a roof and windows of a motor vehicle - attaches a covering over the windows of a vehicle when it is not in use, does not use fasteners- instead it runs a cable under the trunk and hood of the car[228]. (Patent 4,948,191 - 8/14/90)
3. Row's Grain truck cover- a detachable cover that uses permanent fasteners to attach to the truck bed[229]. (Patent 3,481,371- 12/2/69)

Table 22. Truck Bed Cover Patent History

Describe when the problem was first observed.

When covering a pickup truck bed, it was observed that the present truck bed covers all use a detachable cover that is secured with permanent attached fasteners. These fasteners permanently deface the truck and also provide a place where rusting/corrosion can be introduced. Also, these systems are hard to attach for larger loads, causing alignment problems, stretching and stress points at the place where the fastener is located.

Known Solutions with undesirable consequences:

1. Any cover that permanently attaches to the truck
2. Covers with fastener holes that become stress points
3. Covers that must be aligned (holes to fasteners) while hyper extended

Table 23. Truck Bed Cover Known Solutions with Undesirable Consequences

Step 1.3.5 IDENTIFY OTHER SYSTEMS IN WHICH A SIMILAR PROBLEM EXISTS

None identified

Step 1.3.6 IDENTIFY ANY OTHER PROBLEM THAT SHOULD ALSO BE SOLVED IN THE COURSE OF SOLVING THE PRIMARY PROBLEM.

Secondary Problem(s):

None identified

Step 1.4 DEFINE AVAILABLE TRUCK BED COVER RESOURCES

Substance resources

Type of substance resource	Description of substance resource
1. Substance properties	Cover is elastic- it can deform but will return to its original shape
2. Substance properties	Truck is corrosive

Table 24. Truck Bed Cover Substance Resources

Field resources

Source of Field Resource	Type of field resource	Description of field resource
Fields (energy) in a system	Mechanical	Truck bed is rigid

Table 25. Truck Bed Cover Field Resources

Space resources

None Specified

Time resources

None Specified

Informational resources

None Specified

Functional resources

None Specified

Step 1.5 CONSIDER ALLOWABLE CHANGES TO THE TRUCK BED COVER SYSTEM

Acceptable Changes to the System:

Changes are confined to modifications of the existing system. Current consumers will not accept anything too risky or different from current truck bed covers.

Constraints to the system:

Name of Constraint	How is it constrained?	Reasons for constraint	Remove?	Secondary problems?
1. Fasteners	Attached to truck body	Provides a reference point on the truck to the detachable truck bed cover	☒ Yes	☒ Yes*
2. Truck bed cover	Must be expandable	Must be able to accommodate loads of varying sizes	☐ Yes	☐ Yes*
3. Truck bed cover	Must not deform under load	Must be able to retain its strength in resistance to the load	☐ Yes	☐ Yes*
*If secondary problems are caused by removing a constraint, describe below: The truck bed cover must remain with the truck while the truck is in motion, even at 80 mph with a large load.				

Table 26. Truck Bed Cover Constraints

Step 1.6 **FURTHER REFINE TRUCK BED COVER SOLUTION SPACE**

Desired **technical characteristics** compared to the existing characteristics:

Existing Technical Characteristics	Desired Technical Characteristics
Fasteners are attached to truck body	Fasteners are only attached to the truck bed cover
There is a great strain at the point where the fasteners are attached	There must be a distributed load across the truck bed cover.
There must be a distributed load across the truck bed cover.	Truck bed covers are stable but they must be able to grow with the load without expanding

Table 27. Truck Bed Cover Desired Technical Characteristics

Desired **economic characteristics** compared to the existing characteristics:

Not Applicable

Desired **timetables** for the realization of each stage of work

Not Specified

Expected degree of novelty of the solutions:

Slight modification of existing product acceptable

Additional criteria:

Product appearance

Must be attractive and must not deface the appearance of the truck when not in use.

Convenience and low cost of maintenance and service

There should be no cost of maintenance or service.

Other

Truck bed cover must be storable.

Step 2. **CONSTRUCT A TRUCK BED COVER LOGIC DIAGRAM**

Step 2.1 **IDENTIFY CHIEF TRUCK BED COVER UNDESIRABLE EFFECTS**

Refined Problem Description (from Step 1.3.1)

Type 1- The following drawbacks of the truck bed cover system must be eliminated- it must be able to loads over the top of the truck bed without stretching and without installing any permanent fasteners to the truck.

For Type 1 or 2 Problems, list the top five undesirable effects:

1. Truck is permanently defaced
2. There are concentrated stresses at fasteners points
3. Truck bed cover cannot accommodate tall loads
4. Cover is stretched
5. Truck is corroded

Step 2.2 DRAW THE TRUCK BED COVER LOGIC DIAGRAM

Step 2.2.1 CONNECTING ENTITIES

Step 2.2.1.1 CODE THE ENTITIES

Entity	Quantitative (Q) or Qualitative (L)
101 Truck is permanently defaced	L
102 The cover is easily aligned to the truck bed	L
103 There are concentrated stresses at fasteners points	L
104 Load is secured	L
201 Truck is corroded	L
202 Cover is stretched	L
203 Truck bed cover can accommodate tall loads	L
301 sufficient time has elapsed for corrosion to set in	L
302 there are corrosive environmental conditions	L
303 Holes are drilled in the truck bed	L
304 The cover must be lined up with the fastener	L
305 The truck is carrying a large load	L
306 The cover is made of stretchable material	L
307 The hold-downs are stationary	L
308 There is a hole in the truck bed cover at the point where the fastener is attached	L
401 Snaps are used to secure the truck bed cover	L
402 Tiedowns are used to secure the truck bed cover	L

Table 28. Truck Bed Cover Logic Assignments

Step 2.2.1.2 IDENTIFY CONNECTIONS BETWEEN ENTITIES

Cause(s)	Relationship between causes	Effect(s)	Mathematical/Boolean Expression
201, 303	OR	*101*	*201 − 303 ⇒ 101*
301, 302, 303	MAG-AND	*201*	*301 * 302 * 303 ⇒ 201*
304, 305	AND	*102*	*304 * 305 ⇒~ 102*
305, 306	AND	*202*	*305 * 306 ⇒ 202*
306, 307	OR	*203*	*306 + 307 ⇒~ 203*
202, 308	OR	*103*	*202 + 308 ⇒ 103*
303, 308	AND	*104*	*303 * 308 ⇒ 104*
401, 402	OR	*303, 304, 307, 308*	*401 + 402 ⇒ 303 * 304 * 307 * 308*

Table 29. Truck Bed Cover Logical Relationships

Step 2.2.1.3 **CODE ENTITIES AS DESIRABLE, UNDESIRABLE OR NEUTRAL**

Entity	Desirability
101 Truck is permanently defaced	U- Undesirable
102 The cover is easily aligned to the truck bed	D- Desirable
103 There are concentrated stresses at fasteners points	U- Undesirable
104 Load is secured	D- Desirable
201 Truck is corroded	U- Undesirable
202 Cover is stretched	N- Neutral
203 Truck bed cover can accommodate tall loads	D- Desirable
301 sufficient time has elapsed for corrosion to set in	N- Neutral
302 there are corrosive environmental conditions	U- Undesirable
303 Holes are drilled in the truck bed	U- Undesirable
304 The cover must be lined up with the fastener	N- Neutral
305 The truck is carrying a large load	N- Neutral
306 The cover is made of stretchable material	N- Neutral
307 The hold-downs are stationary	N- Neutral
308 There is a hole in the truck bed cover at the point where the fastener is attached	N- Neutral
401 Snaps are used to secure the truck bed cover	N- Neutral
402 Tiedowns are used to secure the truck bed cover	N- Neutral

Table 30. Truck Bed Cover Desirability of Entities

Step 2.2.1.4 **CODE CONTROL OF ENTITIES**

Entity	Control
101 Truck is permanently defaced	C2- Simple Indirect Control
102 The cover is easily aligned to the truck bed	C2- Simple Indirect Control
103 There are concentrated stresses at fasteners points	C2- Simple Indirect Control
104 Load is secured	C2- Simple Indirect Control
201 Truck is corroded	C3- Controlled by Outside Source
202 Cover is stretched	C2- Simple Indirect Control
203 Truck bed cover can accommodate tall loads	C2- Simple Indirect Control
301 sufficient time has elapsed for corrosion to set in	C5- Uncontrollable
302 there are corrosive environmental conditions	C4- Controlled by Nature or Problem Definition
303 Holes are drilled in the truck bed	C1- Direct Control
304 The cover must be lined up with the fastener	C2- Simple Indirect Control
305 The truck is carrying a large load	C4- Controlled by Nature or Problem Definition

Entity	Control
306 The cover is made of stretchable material	C1- Direct Control
307 The hold-downs are stationary	C1- Direct Control
308 There is a hole in the truck bed cover at the point where the fastener is attached	C1- Direct Control
401 Snaps are used to secure the truck bed cover	C1- Direct Control
402 Tiedowns are used to secure the truck bed cover	C1- Direct Control

Table 31. Truck Bed Cover Control of Entities

Step 2.2.2 ASSIGN NUMBERS TO EACH ENTITY.

Entity
101 Truck is permanently defaced
102 The cover is easily aligned to the truck bed
103 There are concentrated stresses at fasteners points
104 Load is secured
201 Truck is corroded
202 Cover is stretched
203 Truck bed cover can accommodate tall loads
301 sufficient time has elapsed for corrosion to set in
302 there are corrosive environmental conditions
303 Holes are drilled in the truck bed
304 The cover must be lined up with the fastener
305 The truck is carrying a large load
306 The cover is made of stretchable material
307 The hold-downs are stationary
308 There is a hole in the truck bed cover at the point where the fastener is attached
401 Snaps are used to secure the truck bed cover
402 Tiedowns are used to secure the truck bed cover

Table 32. Truck Bed Covers Entity Numbers

Step 2.2.3 SUMMARY OF THE ENTITY CODE SCHEME

Step 2.2.3.1 **LIST ALL ENTITIES**

Entity	Unique Nomenclature
101 Truck is permanently defaced	U-101-L-C2
102 The cover is easily aligned to the truck bed	D-102-L-C2
103 There are concentrated stresses at fasteners points	U-103-L-C2
104 Load is secured	D-104-L-C2
201 Truck is corroded	U-201-L-C3
202 Cover is stretched	N-202-L-C2
203 Truck bed cover can accommodate tall loads	D-203-L-C2
301 sufficient time has elapsed for corrosion to set in	N-301-L-C5
302 there are corrosive environmental conditions	U-302-L-C4
303 Holes are drilled in the truck bed	U-303-L-C1
304 The cover must be lined up with the fastener	N-304-L-C2
305 The truck is carrying a large load	N-305-L-C4
306 The cover is made of stretchable material	N-306-L-C1
307 The hold-downs are stationary	N-307-L-C1
308 There is a hole in the truck bed cover at the point where the fastener is attached	N-308-L-C1
401 Snaps are used to secure the truck bed cover	N-401-L-C1
402 Tiedowns are used to secure the truck bed cover	N-402-L-C1

Table 33. Truck Bed Cover Entities with Code Assignments

Step 2.2.4 **TEST THE LOGIC DIAGRAM USING THE RULES OF LOGIC.**

1. ☒ Clarity (seeking to understand)
   - Would I add any verbal explanation if reading the tree to someone else?
   - Is the meaning/context of words unambiguous?
   - Is the connection cause and effect convincing "at face value"?
   - Are intermediate steps missing?
2. ☒ Entity Existence (Complete, properly structured, valid statements of cause and effect)
   - Is it a complete sentence?
   - Does it make sense?
   - Is it free from "if-then" statements?
   - Does it convey only one idea (i.e. not compound entity)?
   - Does it exist in my reality?
3. ☒ Causality existence (Logical connection between cause and effect)
   - Does an "if then" connection really exist, as written?
   - Does the cause, in fact, result in the effect?
   - Does it make sense when read aloud exactly as written?
   - Is the cause intangible? (If so, look for additional predicted effect)

4. ☒Cause insufficiency (A nontrivial dependent element missing)
    - Can the cause, as written, result in the effect on its own?
    - Are there any significant cause factors missing?
    - Is/are the written cause(s) sufficient to justify all parts of the effect(s)?
    - Is an ellipse (an AND Gate) required?
5. ☒Additional cause (A separate, independent cause producing the same effect)
    - Is there anything else that might cause the effect on its own? *(Missing OR Gate)*
    - If the stated cause is eliminated, will the effect be almost completely eliminated?
6. ☒Cause-effect reversal (Arrow pointing in the wrong direction)
    - Is the stated effect really the cause and vice versa?
    - Is the stated cause the reason why or just how we know the effect exists?
7. ☒Predicted effect existence (Additional corroborating effect resulting from cause)
    - Is the cause intangible?
    - Do other unavoidable outcomes exist besides the stated effect?
8. ☒Tautology (Circular logic)
    - Is the cause intangible?
    - Is the effect offered as a rationale for the existence of the cause?
    - Do other unavoidable outcomes exist besides the stated effect?
    - In addition to these logical rules, a few more are required for this approach.
9. ☒Check that all variables are of the right type, Boolean or Quantitative.
10. ☒Check that Quantitative variables are converted to Boolean variables before entering a AND, OR, XOR or NOT gates.
11. ☐Check that Boolean variables are converted to Quantitative variables before entering MAG AND gates.

Inputs to [201] should be quantitative, but they are hard to quantify. How much age, corrosive environment and what size hole are all necessary to determine whether or not corrosion is developed. This can be modeled and it would be modeled except since the presence of holes, [303], is sufficient to cause the terminal effect [101], truck is permanently defaced. Thus corrosion is not necessary and the MAG AND Gate doesn't need to be further refined.

12. ☒Check that there is a "machinery" input entity for each entity that requires a piece of equipment to operate.

Step 2.2.5 COMPLETE THE LOGIC DIAGRAM

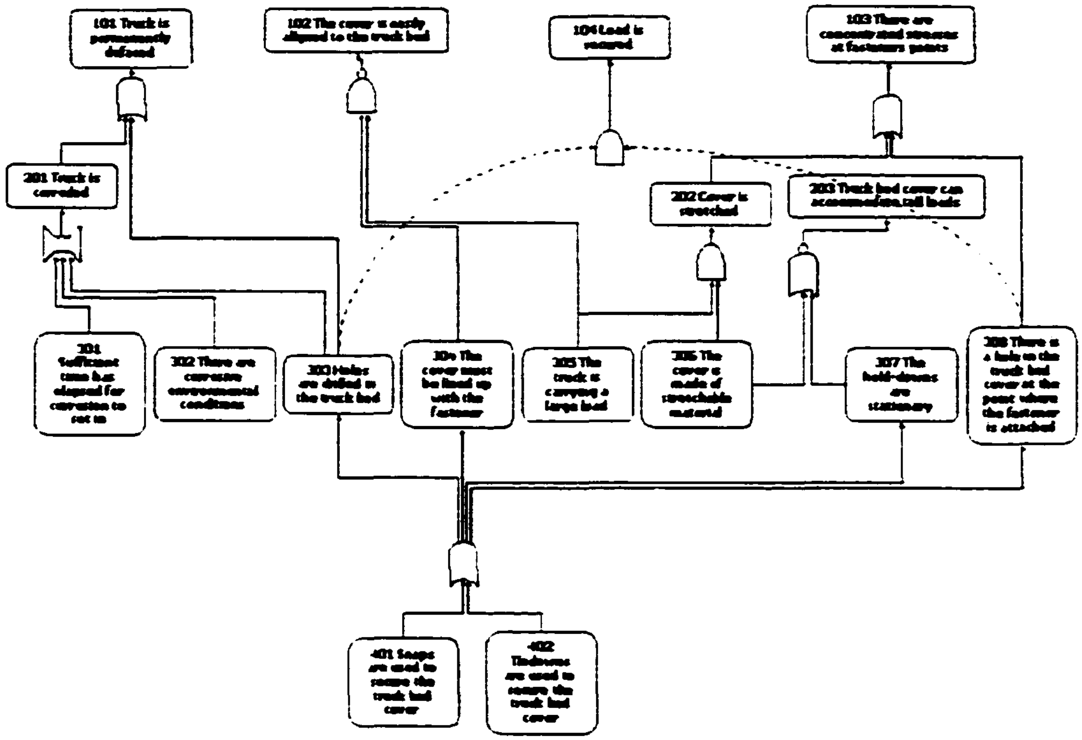


Figure 27. Truck Bed Cover Logic Diagram

Step 3. ANALYZE LOGIC DIAGRAM TO FIND THE CONSTRAINTS OF THE SYSTEM

Step 3.1 FIND THE SWITCHES FOR THE SYSTEM

Terminal Effects Name	Identification	Directly Controllable?	Switch (es)	Level of Control for each switch
101 Truck is permanently defaced	U-101-L-C2	☐ Yes ☒ No	N-401-L-C1 N-402-L-C1	☒ C1 ☐ C2 ☐ C3 ☒ C1 ☐ C2 ☐ C3
[401] and [402] must both be false for [101] to be false				
102 The cover is easily aligned to the truck bed	D-102-L-C2	☐ Yes ☒ No	N-401-L-C1 N-402-L-C1	☒ C1 ☐ C2 ☐ C3 ☒ C1 ☐ C2 ☐ C3
[401] and [402] must both be false for [102] to be true				
103 There are concentrated stresses at fasteners points	U-103-L-C2	☐ Yes ☒ No	N-401-L-C1 N-402-L-C1	☒ C1 ☐ C2 ☐ C3 ☒ C1 ☐ C2 ☐ C3
[401] and [402] must both be false for [103] to be false				
203 Truck bed cover can accommodate tall loads	D-203-L-C2	☐ Yes ☒ No	N-401-L-C1 N-402-L-C1 N-306-L-C1	☒ C1 ☐ C2 ☐ C3 ☒ C1 ☐ C2 ☐ C3 ☒ C1 ☐ C2 ☐ C3

If [306], [401] and [402] are false, then [203] is true				
104 Load is secured	D-104-L-C2	☐ Yes ☒ No	N-401-L-C1 N-402-L-C1	☒ C1 ☐ C2 ☐ C3 ☒ C1 ☐ C2 ☐ C3
[401] and [402] must both be false for [104] to be false				

Table 34. Truck Bed Covers Switch Analysis

The plan at this point is to control entities [401], [402] and [306]. They are:

306 The cover is made of stretchable material	N-306-L-C1
401 Snaps are used to secure the truck bed cover	N-401-L-C1
402 Tiedowns are used to secure the truck bed cover	N-402-L-C1

Table 35. Truck Bed Cover Solution Plan

Controlling these entities means that the cover is not made of stretchable material, that snaps are not used to hold the cover down and that Tiedowns are not used to hold the cover down. The reasoning is that tiedowns and snaps must be attached to the truck, making a permanent hole and also making a stationary target to line up holes in the cover with the fastening mechanism. Stretchable material increases stress on the holes.

The new problem becomes-

If we can't permanently attach the truck bed cover fasteners to the truck, how can we secure the truck bed cover to the truck?

If we don't make the cover out of stretchable material, how can we accommodate large loads?

Before proceeding to find a solution, it is necessary to make sure the logic doesn't create any other problems.

Step 3.2 FOR EACH DE, SEEK TO ENSURE THE LOGICAL VALUE OF THE ENTITY IS = 1.

Entities Controlled	Identification	Switch	Type of control
102 The cover is easily aligned to the truck bed	D-102-L-C2	N-401-L-C1 N-402-L-C1	☒ C1 ☐ C2 ☐ C3 ☒ C1 ☐ C2 ☐ C3
[401] and [402] must both be false for [102] to be true			
104 Load is secured	D-104-L-C2	N-401-L-C1 N-402-L-C1 N-306-L-C1	☒ C1 ☐ C2 ☐ C3 ☒ C1 ☐ C2 ☐ C3 ☒ C1 ☐ C2 ☐ C3
If [401] and [402] are false, then [104] is true			
203 Truck bed cover can accommodate tall loads	D-203-L-C2	N-401-L-C1 N-402-L-C1 N-306-L-C1	☒ C1 ☐ C2 ☐ C3 ☒ C1 ☐ C2 ☐ C3 ☒ C1 ☐ C2 ☐ C3
If [306], [401] and [402] are false, then [203] is true			

Table 36. Truck Bed Cover Desirable Entities

Step 3.3 **FOR EACH UDE, SEEK TO CREATE THE VALUE OF THE NODE = 0**

Entities Controlled	Identification	Switch	Type of control
101 Truck is permanently defaced	U-101-L-C2	N-401-L-C1 N-402-L-C1	☒ C1 ☐ C2 ☐ C3 ☒ C1 ☐ C2 ☐ C3
[401] and [402] must both be false for [101] to be false			
103 There are concentrated stresses at fasteners points	U-103-L-C2	N-401-L-C1 N-402-L-C1	☒ C1 ☐ C2 ☐ C3 ☒ C1 ☐ C2 ☐ C3
[401] and [402] must both be false for [103] to be false			
201 Truck is corroded	U-201-L-C3	U-303-L-C1	☒ C1 ☐ C2 ☐ C3
If no holes are drilled in truck, [303] =0, then [201] is always false			
302 there are corrosive environmental conditions	U-302-L-C4		
[302] cannot be controlled- it is a part of the operating environment of the truck. It is neutralized by no holes being drilled in the truck.			
303 Holes are drilled in the truck bed	U-303-L-C1	N-401-L-C1 N-402-L-C1	☒ C1 ☐ C2 ☐ C3 ☒ C1 ☐ C2 ☐ C3
If [401] and [402] are false, then no holes need to be drilled in the truck.			

Table 37. Truck Bed Covers Undesirable Entities

Step 3.4 **IDENTIFY ANY TRADE-OFFS IN THE DESIGN**

Trade-offs in the as-is design:

These are all physical contradictions-

We want to attach the load to the truck but we don't want to add hardware to the truck

The fasteners should exist in order to secure the load, but they should not exist in order to preserve the value of the truck.

The material of the cover should be stretchable in order to accommodate large loads, but it must not be stretchable in order to reduce localized stress.

There should be holes in the cover to secure the cover to the truck, but there should not be holes in the cover because they localize stress.

Type of Contradiction	Reason
UDE Causes DE	Hardware attached to truck enables us to handle the load
DE Causes UDE	Stretchable material causes localized stress
UDE Counteracts UDE	None noted
DE Counteracts DE	None noted

Figure 28. Truck Bed Cover Contradictions

Step 3.5 **REVIEW TOTAL SYSTEM**

	Root Cause (Check if selected)	UDEs Produced	Produces 70% or more of UDEs?	Related to other Root Cause? (List)
1.	☒ 306 The cover is made of stretchable material N-306-L-C1 ☒ Sphere of control (C1, C2) ☐ Span of Influence (C3) ☐ Neither (C4, C5)	U-103-L-C2	☐ Yes ☐ No ☒ Yes with others marked	☐ Yes ☒ No
2.	☒ 401 Snaps are used to secure the truck bed cover N-401-L-C1 ☒ Sphere of control (C1, C2) ☐ Span of Influence (C3) ☐ Neither (C4, C5)	U-101-L-C2 U-103-L-C2 U-201-L-C3 U-303-L-C1	☐ Yes ☐ No ☒ Yes with others marked	☒ Yes ☐ No N-402-L-C1
3.	☒ 402 Tiedowns are used to secure the truck bed cover N-402-L-C1 ☒ Sphere of control (C1, C2) ☐ Span of Influence (C3) ☐ Neither (C4, C5)	U-101-L-C2 U-103-L-C2 U-201-L-C3 U-303-L-C1	☐ Yes ☐ No ☒ Yes with others marked	☒ Yes ☐ No N-401-L-C1

Table 38. Truck Bed Cover Root Causes

Step 4. GENERATE SOLUTIONS AT THE CRITICAL ENTITIES AND TRADE-OFFS

Summary of Chief Constraints / Problems to be addressed first

Name of Root Cause	Undesirable?	Desirable?	Contradiction?
306 The cover is made of stretchable material N-306-L-C1	☐ If yes, go to Step 4.1	☐ If yes, go to Step 4.2	☒ If yes, go to Step 4.3
Notes: The material of the cover should be stretchable in order to accommodate large loads, but it must not be stretchable in order to reduce localized stress.			
401 Snaps are used to secure the truck bed cover N-401-L-C1	☐ If yes, go to Step 4.1	☐ If yes, go to Step 4.2	☒ If yes, go to Step 4.3
402 Tiedowns are used to secure the truck bed cover N-402-L-C1	☐ If yes, go to Step 4.1	☐ If yes, go to Step 4.2	☒ If yes, go to Step 4.3

Name of Root Cause	Undesirable?	Desirable?	Contradiction?
Notes: 1. We want to attach the load to the truck but we don't want to add hardware to the truck 2. The fasteners should exist in order to secure the load, but they should not exist in order to preserve the value of the truck. 3. There should be holes in the cover to secure the cover to the truck, but there should not be holes in the cover because they localize stress			

Table 39. Truck Bed Cover Root Cause Analysis

Name of Terminal Effect	Desirable?	Notes
101 Truck is permanently defaced	☐ If yes, go to Step 4.4	From analysis in step 3, proceed to Step 4.3.
102 The cover is easily aligned to the truck bed	☒ If yes, go to Step 4.4	Since it is a desirable terminal effect, proceed to Step 4.4 after Step 4.3.
103 There are concentrated stresses at fasteners points	☐ If yes, go to Step 4.4	From analysis in step 3, proceed to Step 4.3.
203 Truck bed cover can accommodate tall loads	☒ If yes, go to Step 4.4	Since it is a desirable terminal effect, proceed to Step 4.4 after Step 4.3.

Table 40. Truck Bed Cover Terminal Effect Analysis

Step 4.1 IF A PARTICULAR CRITICAL ENTITY MUST BE "TURNED OFF," THEN FOLLOW I-TRIZ SOLUTION RECOMMENDATIONS FOR UDE.

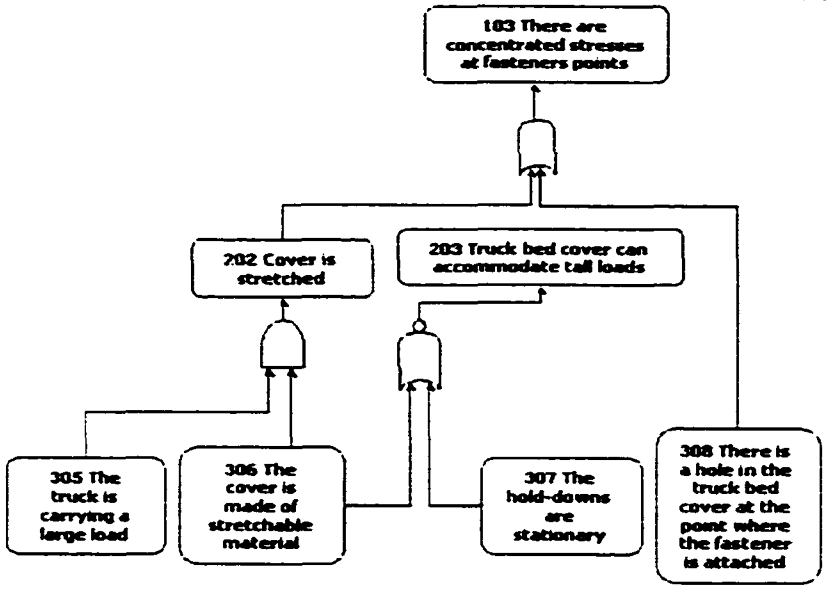
Step 4.1 is not applicable, as no critical entity must be "turned off."

Step 4.2 IF A PARTICULAR CRITICAL ENTITY MUST BE "TURNED ON," THEN FOLLOW I-TRIZ SOLUTION RECOMMENDATIONS FOR DE.

Step 4.1 is not applicable, as no critical entity must be "turned on."

Step 4.3 IF THERE IS A CONTRADICTION, THEN FOLLOW THE I-TRIZ SOLUTION RECOMMENDATIONS FOR CONTRADICTIONS.

1. Type of contradiction:
☐ UDE Causes DE ☐ DE Causes UDE ☒ UDE Counteracts UDE ☐ DE Counteracts DE
The material of the cover should be stretchable in order to accommodate large loads, but it must not be stretchable in order to reduce localized stress. Physical contradiction- the property contradicts itself.
Mathematically:
[305]*[306]⇨[202], [202]+[306]⇨[103], if [306]=0, then [202]=0. If [202]=0 (and [308]=0), then [103]=0.
[103] is an undesirable end effect.
[306]+[307] ⇨ ~[203], if [306] = 0, then [203] =0. [203] is a desirable end effect.



Therefore, [306] must be = 0 in order for [103] to be =0 and [306] must be ≠ 0 for [203] =1.

CHILD RELATION

Step 4.3.2 The "40 Innovation Principles" Contradiction Child Relation

GRANDCHILD RELATION

Using the contradiction table, choose, "area of non-moving object" for the characteristic to be improved, then choose "Tension, pressure" for the characteristic that is degraded as a result. Four suggestions are obtained from the contradiction matrix:

- *Prior action*
- *Dynamicity*
- *Phase transition*
- *Thermal expansion*

Reading the suggestions of these 4, "Dynamicity" seems the most promising-

- "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"

Operator

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

Comments

If the cover were not attached to the truck, but to itself alone, then the straps, which stretch beneath the truck, could expand with the load while the cover remained of a non-stretchable fabric.

Second Grandchild relationship

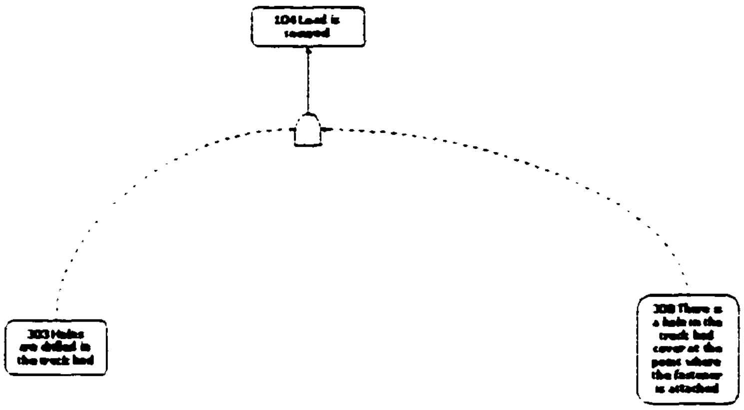
In order to retain tension in the cover, the concept of asymmetry was also used, allowing for tension on the load without making the material stretchable. The principle of "asymmetry" is to "Replace a symmetrical form with an asymmetrical form." The edge of the cover is improved by making it concave with the concavity pointing to the center of the truck, thus creating tension when the cord passes through the seam.

2. Type of contradiction:

☐ UDE Causes DE ☐ DE Causes UDE ☒ UDE Counteracts UDE ☐ DE Counteracts DE

There should be holes in the cover to secure the cover to the truck, but there should not be holes in the cover because they localize stress

Cause: [303], [308]



Effect: *104*

[303]•[308] ⇨ [104]

Child Relation

Step 4.3.2 The "40 Innovation Principles" Contradiction Child Relation

Grandchild Relation

Using the contradiction table, choose, "stability of object" for the characteristic to be improved and then choose "length of moving object" for the characteristic that is degraded as a result. Four suggestions are obtained from the contradiction matrix:

1. *Inversion*
2. *Dynamicity*
3. *Segmentation*
4. *Replacement of a mechanical system*

Reading these four suggestions, "**Replacement of a mechanical system**" seemed to be the most promising:

"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"

Operator

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

Comments

The straps and the holding mechanism are no longer immovable, but movable in relation to the truck. The straps will attach to the cover at a predetermined number of places and will reach under the truck.

3. Type of contradiction: ☐ UDE Causes DE ☒ DE Causes UDE ☐ UDE Counteracts UDE ☐ DE Counteracts DE

We want to attach the load to the truck but we don't want to add hardware to the truck

DE: attach load to truck

UDE: add hardware to truck

This has already been addressed by securing the cover with straps

4. Type of contradiction: ☐ UDE Causes DE ☒ DE Causes UDE ☐ UDE Counteracts UDE ☐ DE Counteracts DE

The fasteners should exist in order to secure the load, but they should not exist in order to preserve the value of the truck.

DE: Fasteners secure load to truck

UDE: Truck is defaced

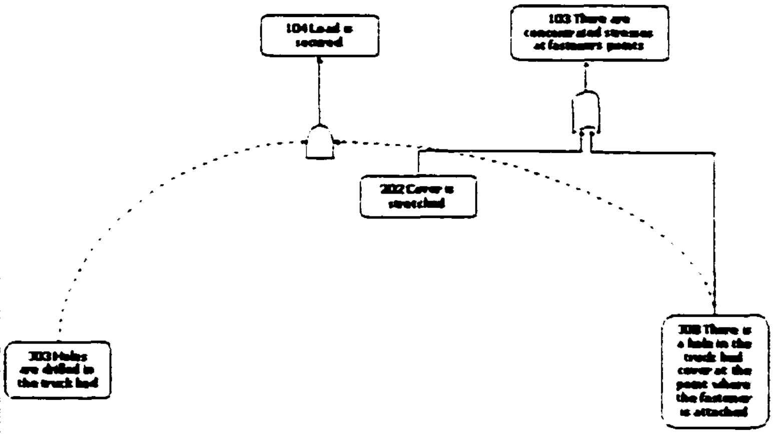
This has already been addressed by securing the cover with straps

5. Type of contradiction:

☐ UDE Causes DE ☐ DE Causes UDE ☐ UDE Counteracts UDE ☐ DE Counteracts DE

Physical contradiction.

Holes in the cover are a cause of the desirable effect '104' and the undesirable effect '103'.



Note that '308'=0 is necessary but not sufficient for '103'=0 while '308'=1 is necessary but not sufficient for '104'=1.

CHILD RELATION

Step 4.3.2 The "40 Innovation Principles" Contradiction Child Relation

GRANDCHILD RELATION

Nesting- Pass an object through a cavity of another object.

The edge of the cover is improved by adding a seam and a cord runs through the seam. The straps connect to the cord thus distributing force throughout the cover.

Figure 29. Truck Bed Cover Solutions to Contradictions

Step 4.4 IF THE DESIGN ONLY HAS DESIRABLE ENTITIES, THEN CONSIDER THE I-TRIZ SOLUTION RECOMMENDATIONS FOR INCREASING THE LEVEL OF IDEALITY OF THE SYSTEM

Refer to Methodology or Innovation Workbench 2000[7] for the Names and descriptions of the child relations, grandchild relations and operators. Next, list your approach using the chosen operator(s) in the comments.

1. Name of Desirable Terminal Effect *102 The cover is easily aligned to the truck bed* **D-102-L-C2** Child Relation *"Make system more universal" terminal child relation.* Grandchild Relation *Introduce elements with dynamic features "Provide the system or process with the ability to perform programmed changes in the shape and/or properties of its elements."* Operator *Grandchild is also the operator* Comments By using the straps under the truck, there is no alignment of a stationary truck to a cover, only of a cover to dynamic straps. Alignment is thereby improved.
2. Name of Desirable Terminal Effect *203 Truck bed cover can accommodate tall loads* **D-203-L-C2** Child Relation *Increase controllability of the existing system that provides the Useful effect.* Grandchild Relation *Self control: "Consider having the system or process adjust itself to changing operating conditions"* Operator *Grandchild is also the operator* Comments *By using the straps under the truck, the whole cover lifts to accommodate the load*

Figure 30. Truck Bed Cover Increasing Ideality Considerations

Summary of total solution:

This solution is a patented redesign of truck bed covers (reproduced here from the patent database, Patent 5,431,474, by R. Burkey[230] and marketed by *Bed Skins* at http://www.bedskins.com/.)[231]

Figure 31. Truck Bed Cover Patent

US005431474A

United States Patent [19]

Burkey

[11] **Patent Number:** **5,431,474**

[45] **Date of Patent:** **Jul. 11, 1995**

[54] **FLEXIBLE VEHICLE CARGO COVER**

[76] Inventor: **Robin L. Burkey**, 5904 Moki Alcova Rt., Casper, Wyo. 82604

[21] Appl. No.: **286,506**

[22] Filed: **Aug. 5, 1994**

[51] **Int. Cl.**[6] **B60P 7/02**

[52] **U.S. Cl.** **296/100**

[58] **Field of Search** .... 296/100, 136; 52/3; 150/166, 167; 160/370.2 R

[56] **References Cited**

U.S. PATENT DOCUMENTS

2,465,021	3/1949	Wheeler	296/100 X
3,481,371	12/1969	Row	296/100 X
4,948,191	8/1990	Cao	296/136 X
5,050,924	9/1991	Hansen	296/100

Primary Examiner—Joseph D. Pape
Attorney, Agent, or Firm—Risto A. Rinne, Jr.

[57] **ABSTRACT**

A flexible cover that is applied over the bed of a pickup truck is described as including a plurality of flexible arches that are disposed along at least two sides of a substantially rectangular center section. The arches are disposed in a concave orientation with an apex of each arch disposed generally furthest away from the center of the cover. A seam, according to one embodiment, traverses along the perimeter of each arch and at least one cable, cord, or strap is disposed therein. At each apex the seam is omitted to permit access to the cable, cord, or strap. The cable, cord, or strap is capable of longitudinal motion within the longitudinal length of each seam. The ends of the cable, cord, or strap preferably contain a ring that is used to attach a first end of a fastener thereto. A fastener fist end is also attached to the cable, cord, or strap at each apex. A second end of each of the fasteners is attached where desired to the underside of the bed. When fastened to the bed, each cable, cord, or strap moves longitudinally within each seam of each arch to evenly distribute the tightening forces and to accommodate oversize cargo items which extend above the plane as defined by the top of the bed of the pickup. According to an alternative embodiment, the seam is either omitted or the cable, cord, or strap is simply not inserted therein. Each cable, cord, or strap is instead attached directly to the perimeter of each of the flexible arches and similarly serves to distribute the tightening forces over the greater perimeter length of the cover as is provided by the arches.

20 Claims, 2 Drawing Sheets

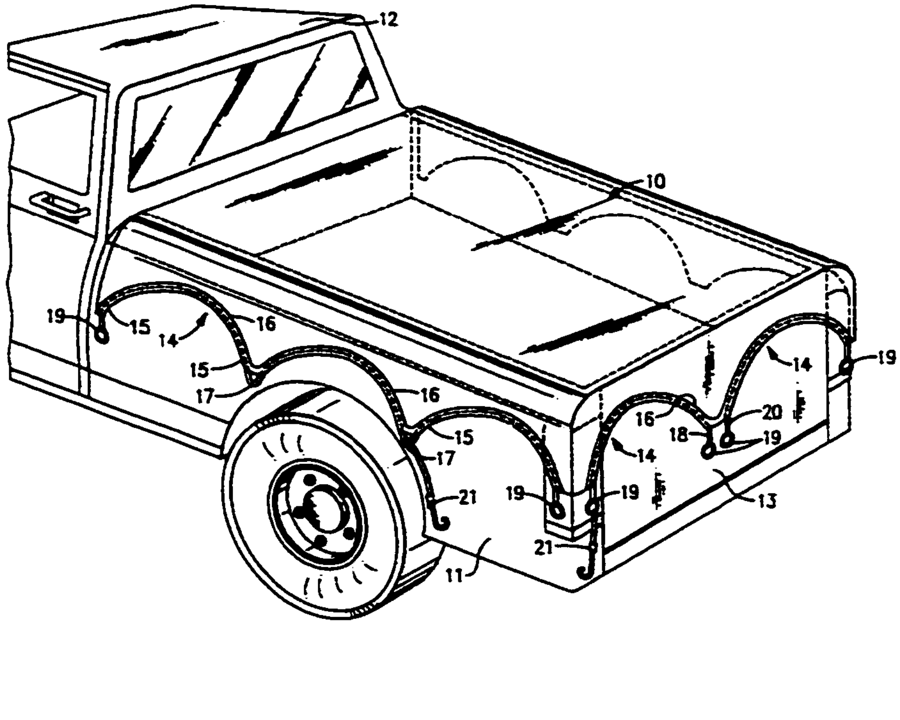


Figure 31. Continued

U.S. Patent July 11, 1995 Sheet 1 of 2 5,431,474

FIG.1

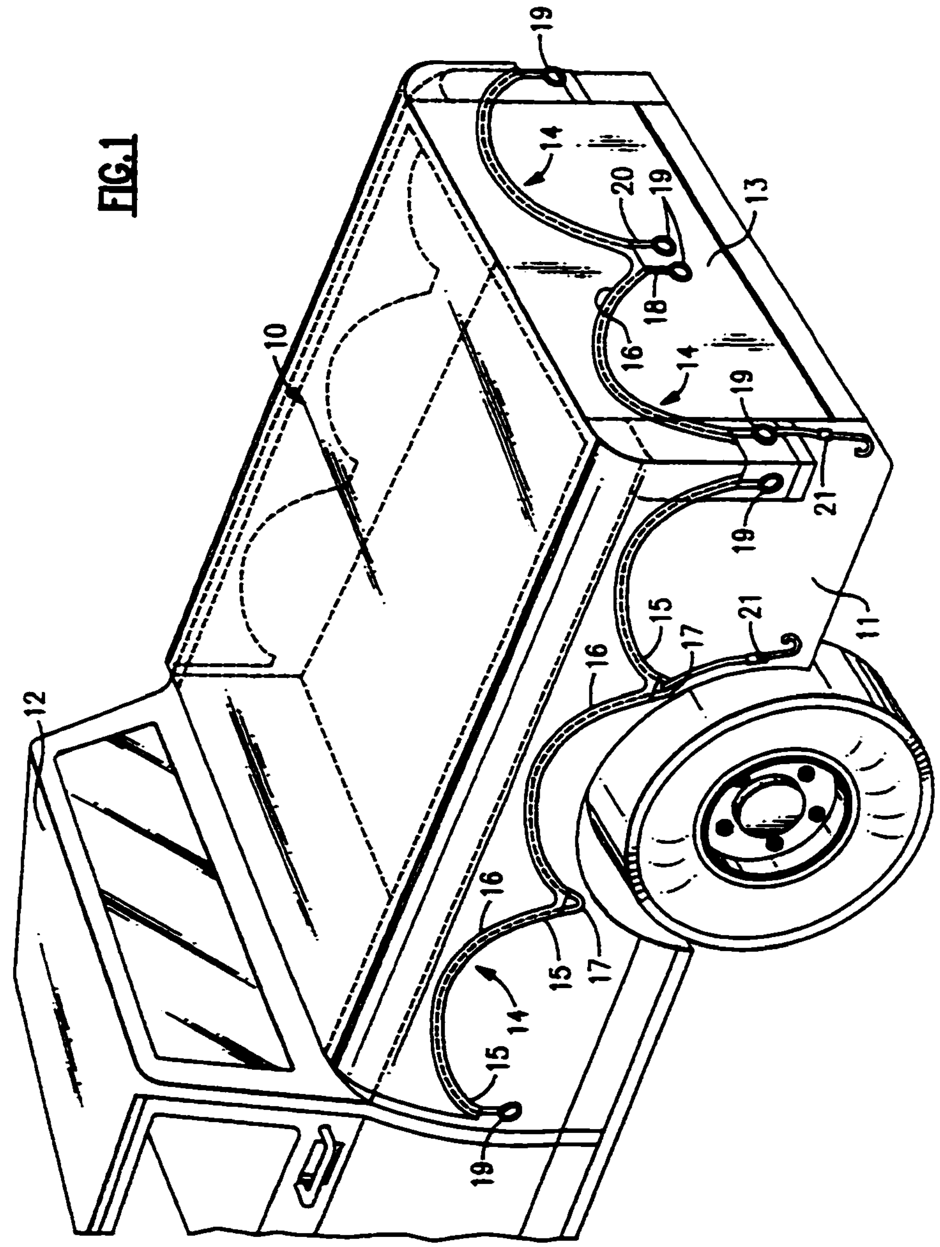


Figure 31. Continued

U.S. Patent July 11, 1995 Sheet 2 of 2 **5,431,474**

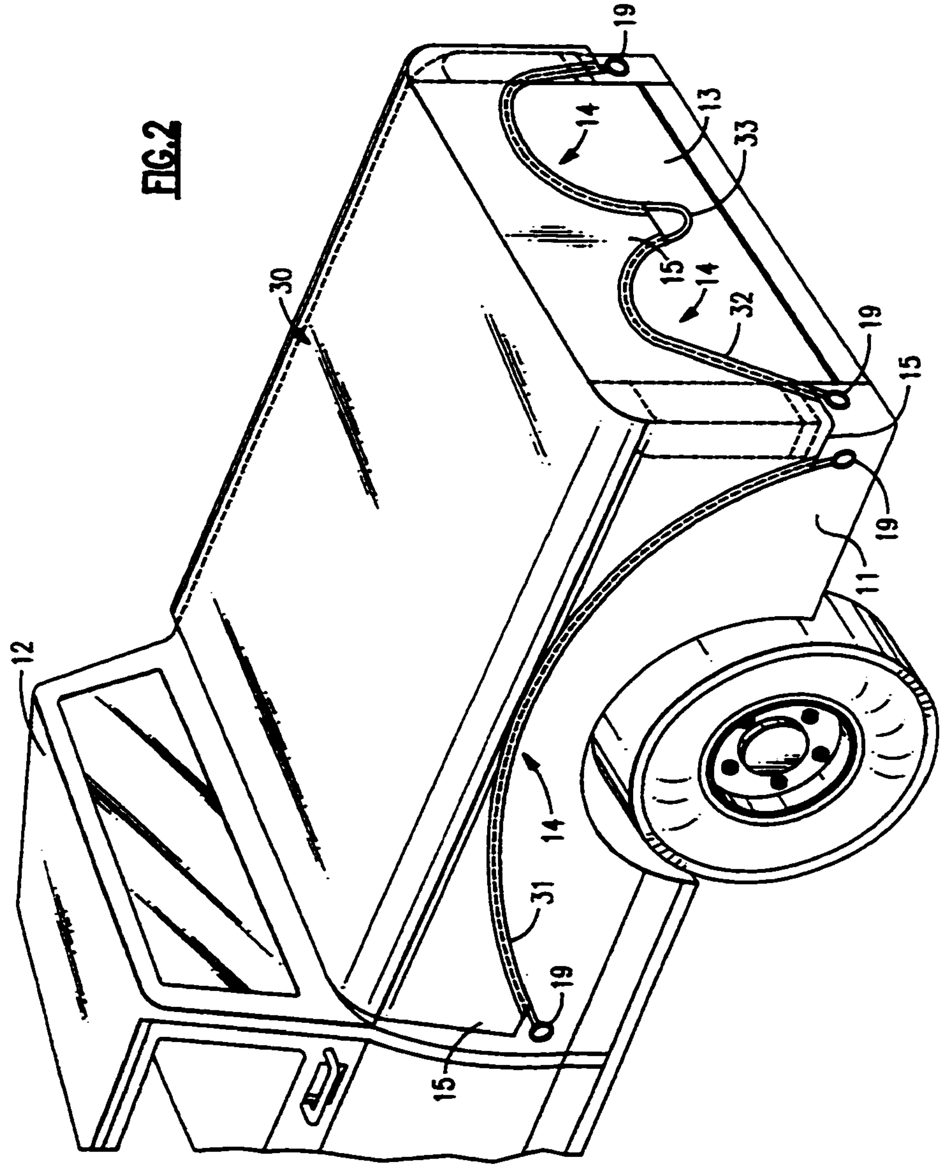


FIG.2

Figure 31. Continued

FLEXIBLE VEHICLE CARGO COVER

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention, in general, relates to vehicle cargo covers and, more particularly, to flexible vehicle cargo covers placed over the bed of a pickup truck.

Flexible types of covers for pickup trucks are known and are presently referred to, generally, as tonneau types of pickup bed covers. However fastening such types of covers to the bed of the vehicle has heretofore proven difficult to achieve, especially when a portion of the load that is placed inside the pickup be extends higher than the top of the bed of the pickup truck.

Existing tonneau covers do not accommodate very large loads because such kinds of covers fasten to snaps or hooks placed along the perimeter of the bed of the pickup truck. An very large load stretches such kinds of covers to the point where they simply cannot reach the fasteners that are fixedly attached to the exterior of the bed of the vehicle.

Also many pickup truck owners do not desire to deface the appearance of their pickup truck by attaching snap fasteners or hooks to the exterior of their pickup truck bed.

Furthermore, when tonneau covers are normally tightened "hot spots" arise whereby the material which comprises the cover is placed under disproportionate strain. Hot spots are caused by the excessive force necessary to stretch the cover over the bed of the pickup in order to reach the attached fasteners. The greatest strain to the cover is experienced in proximity to each fastener that is used. It is in this area where existing types of tonneau covers are most likely to fail.

This problem is further aggravated when the cover must be stretched over a portion of a slightly oversized cargo item. In this instance the cover can be stretched enough to reach the attached fasteners but in order to do so a significant strain is applied to the cover which tends to considerably shorten its useful life.

Also because of the need to align existing tonneau covers so that their position corresponds exactly with fixedly attached fasteners, present covers tend to be difficult and time consuming to attach and to remove.

Accordingly there exists today a need for a flexible vehicle cargo cover that can easily be placed over the bed of a pickup truck that does not require the use of snaps, hooks, or other fasteners that are permanently attached to the exterior of the bed of the vehicle and which can accommodate cargo items that extend above the top of the bed of the pickup truck and which equalize the tightening forces that are applied about the perimeter of the cover.

2. Description of Prior Art

Cargo covers are, in general, known. For example, the following patents describe various types of these devices:

U.S. Pat. No. 4,823,707 to Salsbury et al, Apr. 25, 1989;
U.S. Pat. No. 4,848,824 to Smith et al, Jul. 18, 1989;
U.S. Pat. No. 4,877,283 to Little et al, Oct. 31, 1989;
U.S. Pat. No. 4,900,204 to Summers, Feb. 13, 1990;
U.S. Pat. No. 4,979,776 to Schwickert, Dec. 25, 1990;
U.S. Pat. No. 5,040,934 to Ross, Aug. 20, 1991;
U.S. Pat. No. 5,050,924 to Hansen, Sep. 24, 1991; and
U.S. Pat. No. 5,165,750 to Pirhonen, Nov. 24, 1992.

While the structural arrangements of the above described devices, at first appearance, have similarities with the present invention, they differ in material respects. These differences, which will be described in more detail hereinafter, are essential for the effective use of the invention and which admit of the advantages that are not available with the prior devices.

OBJECTS AND SUMMARY OF THE INVENTION

It is an important object of the present invention to provide a flexible vehicle cargo cover that is easy to install.

It is also an object of the invention to provide a flexible vehicle cargo cover that is easy to remove.

Another object of the invention is to provide a flexible vehicle cargo cover that is able to accommodate cargo items which extend above the top of the bed of a pickup truck.

Still another object of the invention is to provide a flexible vehicle cargo cover that does not include any hardware items that are fixedly attached to the vehicle.

Yet another object of the invention is to provide a flexible vehicle cargo cover that distributes the tightening forces evenly about the perimeter of the cover.

Still yet another important object of the invention is to provide a flexible vehicle cargo cover that includes a reinforced arcuately formed perimeter.

Briefly, a flexible vehicle cargo cover that is constructed in accordance with the principles of the present invention has either a single cord, cable, or strap (or a plurality thereof) which are either housed within a seam that is attached to the perimeter of the cover or are otherwise attached to the cover at the perimeter which includes a plurality of flexible arches that are attached in a concave manner to at least two sides of the cover. The cover and the arches are formed of any preferred flexible type of material including fabric, vinyl, netting, or similar types of materials. The cord, cable, or strap, or the plurality thereof must be flexible to adapt to the shape of the arches and may be formed of either an elastomeric or a non-stretching type of material. When disposed within the seam each cord, cable, or strap is free to permit longitudinal motion thereof within the longitudinal length of each seam to occur. The arches are either attached separately to the cover or are formed integral with it. When a single cord, cable, or strap is used its length is preferably longer than the sum of the lengths of the perimeters of the arches. Disposed at the apex of each of the plurality of arches is provided a gap in the seam which allows access to a segment of the single cord, cable, or strap at each apex or access to each end of each of the plurality thereof. When a plurality of cords, cables, or straps are used, each of the plurality is longer than the perimeter length of each arch so that each end extends beyond each apex. Rings are preferably attached to each end thereof. A fastener is used to fasten the rings that are disposed at each end of each of the cords, cables, or straps to the underside of a bed of a pickup truck and to apply as much tightening force as is desired. Similarly a fastener is used to fasten the cord, cable, or strap at each exposed segment to the underside of the bed as desired. While a fastener is not required to fasten every exposed segment or every ring to the bed a preferred fit of the cover about the bed is obtained when each ring or segment is secured to the bed. The cords apply a tightening force that is distributed evenly among each of the arches along the perime-

Figure 31. Continued

ter of the cover. Accordingly by distributing the tightening forces about the perimeter of the cover, the useful life of the cover is extended during normal use. When large cargo items are placed in the bed which extend above the top of the bed, the cover can be properly secured to the vehicle because the arches serve to prevent excessive stress from occurring at certain locations of the cover by distributing the force evenly about the entire perimeter of the cover. The fasteners are adjusted to compensate for any change in position of the rings or of the exposed segments of cord. Accordingly careful positioning of the cover about the vehicle is not necessary.

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 is a view in perspective of a flexible vehicle cargo cover attached to a bed of a pickup truck.

FIG. 2 is a view in perspective of an alternative embodiment of the flexible vehicle cargo cover wherein at least one strap is attached to the perimeter of the cover.

DETAILED DESCRIPTION OF THE INVENTION

Referring to FIG. 1 is shown, a flexible vehicle cargo cover, identified in general by the reference numeral 10. The cover 10 is situated atop a bed 11 of a pickup truck 12. A portion of the cover 10 overlaps the exterior of a tailgate 13 of the truck 12 and each of the two exterior sides (also referred herein as the sidewalls) of the bed 11.

The amount of overlap over the tailgate 13 and over the exterior sides of the bed 11 of pickup are varied to suit preferences. For example, a larger overlap is appropriate if, from time to time, oversized loads are anticipated. (The manner by which the cover 10 can accommodate oversize loads is described in greater detail hereinbelow.) Conversely, a smaller amount of overlap, for certain people, provides a preferred aesthetic appearance when smaller cargo items or no cargo items are transported.

The cover 10, as shown, is made of a flexible material such as fabric, vinyl, or any similar type of material. The cover includes a central area which covers the bed 11 of the pickup 12 and must therefore be generally rectangular in shape so as to overlap the bed 11 sidewalls. Of course the size of the cover 10 is varied to accommodate small, medium, and large pickup 12 truck beds 11, as well as to vary the amount of preferred overlap over the bed 11 sidewalls as is described hereinabove.

The cover 10 includes a plurality of adjacent perimeter arches, identified in general by the reference numeral 14. The perimeter arches 14 are each formed of an arcuate portion with each apex 15 of each arch 14 extending in a direction that is furthest away from the rectangular central portion of the cover 10. Therefore the arches 14 are concave (as opposed to convex) with respect to the cover 10.

The arches 14 may be attached to the rectangular central portion of the cover 10 by sewing or by other methods known to the art including thermal welding as well as by the use of an adhesive, or alternatively the arches 14 may be formed integrally as part of the overall cover 10 as shown in the preferred embodiment as is herein illustrated and described.

The perimeter arches 14 are also formed of a flexible material that is either identical to or similar to that which is used to form the central portion of the cover 10.

The perimeter arches 14 include a seam 16, according to a first preferred embodiment that is described herein, that runs along the perimeter of three sides of the cover 10. At each apex 15 the seam 16 is omitted for a predetermined length to allow access to a cable 17 that is disposed inside the seam 16.

The seam 16 as referred to herein applies interchangeably to consideration of the seam 16 along the full perimeter length of the three sides as it does to consideration of each seam 16 which is disposed along the perimeter length of the arcuate portion of each arch 14. Accordingly the text and illustrations clarify whether the use of the term seam 16 refers in particular to each arch 14 or to the sum of the perimeter lengths of all of the arches 14 when necessary, and when it is not so specified, the discussion applies equally well to either.

The cable 17 as shown is formed of a continuous length of material that transverses in a contiguous fashion the length of the seam 16 along one side of the bed 11. Of course the cable 17 could easily be extended so as to be contiguous for the entire length of the seam 16 extending fully around each of the two sides of the bed 11 and also around the tailgate 13 as well. By illustrating that the cable 17 may be contiguous for a plurality of arches 14, the drawing figure thereby also teaches that it can be made contiguous for any number of arches 14, including all of the arches 14 of any particular cover 10.

The cable 17 as shown is formed of any suitable material including natural and synthetic fabric, wire, webbing, or strapping, or of an elastomeric material and while it is housed within the seam 16, it is capable of moving longitudinally within the longitudinal length of the seam 16. The cable 17 is used to secure the cover 10 to the truck 12, and its use for that purpose is described in greater detail hereinbelow.

A segmented cord 18 is shown in the vicinity of the tailgate 13 as an alternative to the continuous length cable 17 and is also capable of longitudinal motion within the seam 16. The segmented cord 18 is formed of a fabric and is disposed within the seam 16 of only one of the arches 14 and is constructed so as to be slightly longer than the length of the seam 16. Of course the segmented cord 18, if desired, could be extended in length so as to pass through the seam 16 of a plurality of arches 14.

The segmented cord 18 includes two ends each of which extend beyond the seam 16 at each apex 15. Each of the two ends preferably includes a ring 19 that is attached to the end thereof. Each ring 19 is used to secure the cover to the truck 12 as is described in greater detail hereinafter. A ring 19 is also preferably attached at each end of the cable 17 that was described hereinabove, and is similarly used. If the ring 19 is omitted the end of the cable 17 is formed into a loop (not shown) or other hardware is provided at each cable 17 end to aid in fastening the cover 10 to the bed 11.

The front of the cover 10 (i.e. That portion of the cover 10 that is disposed opposite to the tailgate 13) does not normally include any perimeter arches 14 as it would not be practical to affix the cover 10 as is described in greater detail hereinbelow to the outside of the bed 11 area that is located intermediate the bed 11 and the cab of the truck 12.

An elastomeric cord 20 is shown in the vicinity of the tailgate 13 adjacent to and as an alternative to the segmented cord 18. The elastomeric cord 20 is formed of

Figure 31. Continued

an elastomeric material that is also housed within the seam 16. While the elastomeric cord 20 is only shown in the seam 16 of one arch 14 it can of course be extended in length to pass through the seam 16 of a plurality of arches 14.

The elastomeric cord 20 stretches when a tightening force is applied to it and this is beneficial for use with certain types of fasteners having a limited capability to reach the underside of the bed as is described in greater detail hereinbelow in order to attach the cover 10 to the bed 11.

A fastener 21 is shown attached to the cable 17 at one apex 15 at the sidewall of the bed 11 and to the ring 19 of the segmented cord 18 at the rear of the bed 11. The fastener 21 includes a first end which is attached to either the cable 17 or the ring 19 and a second end which is attached where desired to the underside of the bed 11. Any of a variety of fasteners 21 may be used and are available commercially. The fastener may be of a non-stretching type as shown or an elastomeric type of fasteners (not shown) may be employed. As many fasteners 21 are used as is necessary to adequately secure the cover 10 to the bed 11. It is preferable to use one fastener 21 at each apex 15 and at each ring 19 to achieve an optimum fit of the cover 10 about the bed 11.

When the fasteners 21 are tightened, the cable 17 or the segmented cord 18 or the elastomeric cord 20 (or plurality thereof) are urged closer toward the underside of the bed 11. As they move closer to the bed 11 underside, they apply a force which tends to stretch the cover 10. This force is distributed evenly through the seam 16 as each cable 17, cord 18, or elastomeric cord 20 moves longitudinally a small amount within the seam 16 of each arch 14. As a natural result of the shape of each arch 14, which is disposed in a concave-in manner toward the center of the cover 10, the tightening force is thus distributed evenly along the entire perimeter length of each seam 16 by each cable 17, cord 18, or elastomeric cord 20.

Accordingly, the cover 10 does not experience localized areas of great stress along any portion of its perimeter as would occur in a modified seam area (not shown) of a modified type of cover (not shown) which did not include the arches 14 or with other types of modified covers (not shown) which rely upon snap or hook fasteners (not shown) that are attached at predetermined locations to the bed 11 of the truck 12.

The arches 14 evenly distribute the forces that are applied to the cover 10 when the cover is fastened to the bed 11. When a large cargo item (not shown) is placed in the bed 11 that protrudes above the top of the bed 11, the modified type of cover as described hereinabove will experience great stress if it is pulled with sufficient force to engage the snap or hook fasteners that are attached to the bed 11. If the large cargo item extends far enough above the bed 11 it will not even be possible to attach the modified type of cover to the snap or hook fasteners without tearing or otherwise damaging the modified type of cover.

The cover 10, as herein described, is easily attached even when large cargo items are placed in the bed 11. Each fastener 21 is merely extended to accommodate the oversize cargo item and to adapt to the location of rings 19 and exposed segments of the cables 17. Another benefit that is provided by the cover 10 is that there are no snap fasteners, hooks, or other hardware that are permanently or otherwise attached to the exterior of the bed 11. When the cover 10 is removed, the bed 11 is in factory new condition. Many truck 12 owners are reluctant to attach hardware items to the bed 11 for aesthetic reasons.

When short fasteners (not shown) are used or when special types of fasteners (not shown) are used, the length of which cannot be varied, the elastomeric cord 20 provides the necessary adjustment to accommodate such types of short or special fasteners by stretching as required. Accordingly for certain types of applications an elastomeric cord 20 is preferred for use within the seam 16 of each arch 14.

Referring now to FIG. 2, a second preferred embodiment is herein described wherein a modified cover, identified in general by the reference numeral 30, is shown. Similar reference numerals are used to describe similar components appearing in FIG. 1. The modified cover 30 includes a strap 31 that is attached to the modified cover 30 along one side thereof. The strap 31 is formed of natural or synthetic webbing material such as nylon and is attached to the modified cover 30 by sewing, gluing, thermal welding, or by any other suitable process.

Only one of the perimeter arches 14 is shown as being formed along one side of the bed 11 of the truck 12. However as is shown in FIG. 1, a plurality of arches 14 may be used along any side of the modified cover 30. The strap 31 is attached to the arch 14 along the arcuate portion of the arch 14. Rings 19 are attached to each end thereof which extend beyond each of the apexes 15. The rings 19 are useful to secure the modified cover 30 to the bed 11 by use of the fasteners 21 (not shown in FIG. 2).

A plurality of two arches 14 are shown overlapping the tailgate 13 and a continuous strap 32 is attached thereto to the two arches 14. Intermediate the two arches 14 over the tailgate 13, the continuous strap 32 extends beyond the apex 15 where it is not attached to the modified cover 30. At this location the continuous strap 32 forms a loop 33 that is useful to attach one of the fasteners (not shown) thereto.

Of course, the continuous strap 32 may be extended in length to include all of the arches 14 or any preferred number of arches 14. Similarly as many of the straps 31 may be used as there are arches 14, if desired.

The continuous strap 32 (or the straps 31) that are attached to the arches 14 distribute the tightening forces along the perimeter length of each arch 14. The tightening forces are applied to the modified cover 30 by the fasteners (not shown) when the modified cover 30 is secured to the bed 11 and accordingly, serve to accomplish the objectives of the invention as described hereinbefore.

It is obvious that for any size of bed 11 the arches 14 of the cover 10 or of the modified cover 30 increase the perimeter length thereof as opposed to the known prior type of a rectangular cover (not shown). Accordingly, any force that is applied to secure the cover 10 or the modified cover 30 to the bed 11 is distributed over a greater perimeter length than would be the situation with the shorter perimeter length of the rectangular cover.

The same force, when applied to a greater perimeter length, lessens the amount of force that is applied to any unit of perimeter length thereby reducing the stress upon the perimeter of either the cover 10 or of the modified cover 30. Reduced stress to either the cover 10 or the modified cover 30 serve to increase the useful life thereof.

Figure 31. Continued

The invention has been shown, described and illustrated in substantial detail with reference to the presently preferred embodiment. It will be understood by those skilled in this art that other and further changes and modifications may be made without departing from the spirit and scope of the invention which is defined by the claims appended hereto.

What is claimed is:

1. A vehicle cargo cover for covering a generally rectangular shaped top of a bed of a pickup truck, comprising:

a) a flexible material having a shape corresponding substantially with the shape of said bed;

b) a plurality of arches disposed about the perimeter of at least two sides of said material, each of said arches including a concave portion that is disposed toward the center of said material and having two apexes, each of said apexes being disposed furthest away from said center of said material;

c) a plurality of seams attached to the perimeter of each of said arches, said seams being non-continuous between said apex of one of said arches and said apex of said adjacent arch; and

d) at least one cord disposed within each of said seams, said cord capable of longitudinal motion thereof within the longitudinal length of each of said seams;

whereby when a force is applied to said at least one cord to secure said cover to said bed, said at least one cord moves within each of said seams to distribute said force evenly about the perimeter of said material.

2. The vehicle cargo cover of claim 1 wherein each of said at least one cord includes a first and a second end and a ring is attached to each of said first and said second ends.

3. The vehicle cargo cover of claim 1 wherein said at least one cord includes a plurality of cords.

4. The vehicle cargo cover of claim 1 wherein each of said at least one cord is disposed within only one of said seams.

5. The vehicle cargo cover of claim 1 wherein each of said at least one cord is disposed within a plurality of said seams.

6. The vehicle cargo cover of claim 1 wherein said at least one cord is formed of a fabric.

7. The vehicle cargo cover of claim 1 wherein said at least one cord is formed of a cable.

8. The vehicle cargo cover of claim 1 wherein said at least one cord is formed of an elastomeric material.

9. The vehicle cargo cover of claim 1 including at least one fastener for securing said at least one cord to said bed.

10. A vehicle cargo cover for covering a generally rectangular shaped top of a bed of a pickup truck, comprising:

a) a flexible fabric material having a shape corresponding substantially with the shape of said bed;

b) a plurality of arches disposed adjacent to each other about the perimeter of at least two sides of said material, each of said arches including a concave portion that is disposed toward the center of said material and having two apexes, each of said apexes being disposed furthest away from said center of said material;

c) a plurality of seams attached to the perimeter of each of said arches, said seams being non-continuous between said apex of one of said arches and said apex of said adjacent arch; and

d) a cord disposed within each of said seams, said cord capable of longitudinal motion thereof within the longitudinal length of each of said seams;

whereby when a force is applied to said cord to secure said cover to said bed, said cord moves within each of said seams to distribute said force evenly about the perimeter of said material.

11. The vehicle cargo cover of claim 10 wherein said cord includes a first and a second end and a ring is attached to said first and said second ends.

12. The vehicle cargo cover of claim 10 wherein said cord is disposed within a plurality of said seams.

13. The vehicle cargo cover of claim 10 wherein said cord is formed of a fabric.

14. The vehicle cargo cover of claim 10 wherein said cord is formed of a cable.

15. The vehicle cargo cover of claim 10 wherein said cord is formed of an elastomeric material.

16. The vehicle cargo cover of claim 10 including at least one fastener for securing said cord to said bed.

17. A vehicle cargo cover for covering a generally rectangular shaped top of a bed of a pickup truck, comprising:

a) a flexible material having a shape corresponding substantially with the shape of said bed;

b) a plurality of arches disposed about the perimeter of at least two sides of said material, each of said arches including a concave portion that is disposed toward the center of said material and having two apexes, each of said apexes being disposed furthest away from said center of said material;

c) at least one flexible strap attached to the perimeter of each of said arches;

whereby when a force is applied to said at least one flexible strap to secure said cover to said bed, said at least one flexible strap distributes said force evenly about the perimeter of each of said arches.

18. The vehicle cargo cover of claim 17 wherein each of said at least one flexible strap includes a first and a second end and a ring is attached to each of said first and said second ends.

19. The vehicle cargo cover of claim 17 wherein said at least one flexible strap includes a plurality of flexible straps.

20. The vehicle cargo cover of claim 17 wherein said at least one flexible strap is formed of a fabric.

* * * * *

6.2 SHUTTLE BIKE PROBLEM

Bicyclers would like to ride through the woods and over small streams and lakes with their bicycles, but they are constrained to only travel over dry land because bicycles are constrained to only travel over land. Shuttle boats that use bicycle parts are bulky and generally require one-time conversion. This study creates a new bi-system that incorporates a bicycle and a shuttle boat into a single design that can be easily converted from one mode to the other and back while hiking.

Step 1. GATHER INFORMATION ABOUT THE PROBLEM

Step 1.1 DESCRIBE THE PROBLEM IN NON-TECHNICAL TERMS

Problem Statement (technical terms are okay):

Sometimes when biking and hiking one encounters terrain that cannot be crossed by bicycle and the bicycle itself becomes a liability. Especially when confronted with a body of water, a biker has to either abandon his bike or go back the way he came. We need a bike that can travel on rugged terrain and also cross bodies of water such as ponds or lakes.

Problem Statement in non-technical terms:

Design a bicycle that can travel over rugged terrain and water.

Optional: Possible solutions suggested by reviewing the Problem Statement:

1.	Carry a light canoe when biking through terrain with small bodies of water.
2.	Wear hip boots when cycling to be able to wade through shallow water.
3.	Carry an inflatable raft in a backpack when cycling.
4.	Create a hybrid bicycle-watercraft.

Table 41. Shuttlebike Possible Solutions Suggested by Problem Statement

Step 1.2 DEFINE AND DESCRIBE THE SYSTEM

Step 1.2.1 NAME THE SYSTEM

Common or Technical name of System being improved:

Bicycle

Step 1.2.2 DEFINE THE SYSTEM STRUCTURE

Elements that comprise the system:

1. Bicycle frame
2. Wheels
3. Transmission (2 sprockets and chain)
4. Engine (Bicyclist)
5. Steering mechanism
6. Seat
7. Luggage/equipment stowage

Other Elements (see addendum):

Supersystem in which the system resides:

Outdoors

Other Systems in the Supersystem:

1) Automobiles
2) Hikers
3) Animals
4) Trees and other vegetation
5) Terrain, including streets, bodies of water, rocky terrain, woods

Step 1.2.3 DEFINE THE SPHERE OF INFLUENCE AND SPAN OF CONTROL ON A SYSTEM

Element	Control Level
Overall System: **Bicycle**	C2- Simple Indirect Control
Element1: **Bicycle frame.**	C2- Simple Indirect Control
Element2: **Wheels.**	C2- Simple Indirect Control
Element3: **Transmission (2 sprockets and chain).**	C2- Simple Indirect Control
Element4: **Engine (Bicyclist).**	C4- Controlled by Nature or Problem Definition
Element5: **Steering mechanism.**	C2- Simple Indirect Control
Element6: **Seat.**	C2- Simple Indirect Control
Element7: **Luggage/equipment stowage.**	C2- Simple Indirect Control
Supersystem: **Outdoors**	C5- Uncontrollable
System2: **Automobiles**	C4- Controlled by Nature or Problem Definition
System3: **Hikers**	C4- Controlled by Nature or Problem Definition
System4: **Animals**	C4- Controlled by Nature or Problem Definition
System5: **Terrain**, including streets, bodies of water, rocky terrain, woods	C4- Controlled by Nature or Problem Definition

Table 42. Shuttlebike System Elements

Step 1.2.4 DEFINE THE WAY THE SYSTEM FUNCTIONS

Providing System/Element	Action/Function		Receiving System/Element
Engine (Bicyclist)	1)	Provides energy to	Transmission
Transmission	2)	Transmits energy to	Wheels
Bicycle frame	3)	Holds together	Bicycle
Steering mechanism	4)	Steers	Bicycle
Seat	5)	Supports	Bicyclist
Equipment stowage	6)	Stows	Luggage/ Auxiliary systems
Wheels	7)	Touch	Outdoors
Wheels	8)	Move	Bicycle

Table 43. Shuttlebike Functional Relationships

Step 1.2.5 DEFINE THE SYSTEM BOUNDARIES AND ENVIRONMENT

This problem will work at the following systemic level:

One level above the system (bi-system with water transportation device).

The supersystem in which the defined system operates:

Outdoors

Other Systems within the supersystem:

1) Automobiles
2) Hikers
3) Animals
4) Trees and other vegetation
5) Terrain, including streets, bodies of water, rocky terrain, woods
6) Food and water

Related Systems:

Automobiles remove energy from system, using the following type field (if applicable): mechanical. (Automobiles cause bicycles to do extra work, e.g. to avoid them in traffic, and therefore they remove energy from the system.)

Hikers remove energy from system, using the following type field: mechanical.

Animals remove energy from system, using the following type field: mechanical.

Vegetation removes energy from system, using the following type field: mechanical.

Terrain removes energy from system, using the following type field: mechanical.

Food and Water supplies energy to the system, using the following type field: chemical.

Subsystems of the defined system:

Bicycle frame

Waterproof portion of hull (where vehicle contacts the water)

Wheels

Floatation portion of the shuttle-bike

Transmission (2 sprockets and chain)

Propulsion subsystem for floatation

Engine (Operator)

Steering mechanism

Seat

Luggage/equipment stowage

Optional: Possible solutions suggested by reviewing the System Description:

1. Bi-system is a natural direction for systemic evolution (Mono-Bi-Poly).
2. Minimal disassembly is desirable.
3. It would be desirable if the pedals, sprocket and chain could propel the boat as well as the bike; the seat would therefore have a dual function.

4. The floatation subsystem cannot interfere with the operation while in bicycle mode; this may suggest an inflatable device for floatation.

Step 1.3 REFINE THE DEFINITION OF THE PROBLEM

Step 1.3.1 IDENTIFY THE PROBLEM TO BE RESOLVED

A product/process or its part/operation must be improved:

A useful parameter or characteristic is insufficient

A required useful action is absent

Refined Problem Description:

Combine the functionality of a floatation device with that of a bicycle.

Step 1.3.2 ESTABLISH THE MECHANISM CAUSING THE PROBLEM.

All known ways in which a failure can occur at the systemic level:

1. Bicycle sinks in a pond
2. Bicycle is damaged by moisture or salt water
3. Bicycle must travel around the water
4. Floatation apparatus interferes with the operation of the bicycle
5. Floatation device increases weight of the system to an unacceptable level
6. Conversion between land use and over water use of the vehicle is time consuming or inconvenient
7. In addition to carrying essentially two transportation devices, operator must also carry tools and assembly instructions
8. Bicycle must be stowed when traveling over water and floatation device must be stowed when traveling over land

Step 1.3.3 DESCRIBE THE UNDESIRED CONSEQUENCES OF AN UNRESOLVED PROBLEM.

1. Bicyclist cannot travel over bodies of water.
2. Terrains that include water and land must be avoided.

Step 1.3.4 BRIEFLY DESCRIBE THE HISTORY OF THE PROBLEM

Patents:

1. United States Patent 5,547,406[232] - Device uses a bicycle frame to make a shuttle bike. Operator must remove the bicycle wheels to assemble the floatation device. It is not transportable although it is convertible. Removal of bicycle wheels is not a simple task.
2. United States Patent D375,930[233] - device is essentially a canoe that is propelled with a bicycle chain. It cannot be changed between a bicycle and an aquacycle configuration
3. United States Patent 6,077,134[234] "Combination bicycle and boat"- Despite the promising title, this device is not suited for traveling across land, only water.
4. United States Patent 5,362,264[235] "Water-bicycle"- not equipped to travel over land. Called a water-bicycle because it is propelled by foot pedals.

5. United States Patent 4,926,777[236] (Davis, Jr.) May 22, 1990, "Aquatic wheelchair"- from Abstract, "An aquatic wheelchair having a main flotation body of thermoplastic material of closed cell construction including a seat portion and an integral backrest portion. Flotation paddle wheels are connected to the seat portion and a flotation stabilizer wheel assembly is detachably connected to the backrest portion. The flotation paddle wheels are constructed and arranged to facilitate the grasping thereof by the user for manually propelling the wheelchair not only on soft terrain but also in water."

Describe when the problem was first observed.

When observing in cross-country mountain bicycle racing it was noted that mountain bikes are equipped to travel over rugged terrain including woods, rocky hills and roads but not over water.

If there is a known solution to the problem that has undesired consequences, document the solution and the consequence. It is possible TRIZ Design techniques can be applied to remove the technical contradiction later on.

Known Solutions with undesirable consequences:

1. Motorized amphibious vehicles (motors not desirable for exercise)
2. Anything requiring excessive stowage

Step 1.3.5 IDENTIFY OTHER SYSTEMS IN WHICH A SIMILAR PROBLEM EXISTS

1. Amphibious assault vehicles
2. Wheel chair floatation device

Step 1.3.6 IDENTIFY ANY OTHER PROBLEM THAT SHOULD ALSO BE SOLVED IN THE COURSE OF SOLVING THE PRIMARY PROBLEM.

Secondary Problem(s):

None identified

Optional: Possible solutions suggested by reviewing the Refined Definition of the Problem:

None identified

Step 1.4 DEFINE THE SOLUTION SPACE

Ideal Final Result (optimal solution):

"Create an inflatable "bicycle boat"—or a "shuttle"—that would be easy to carry and allow a bicyclist the opportunity to ride across the water as well as on land."[237]

Optional: Possible solutions suggested by reviewing the Ideal Final Result:

None.

Step 1.5 DEFINE AVAILABLE RESOURCES

Substance resources

Type of substance resource	Description of substance resource
Substance flows	Water
Substance properties	Water- liquid medium, corrodes metal, contains algae and debris

Table 44. Shuttlebike Substance Resources

Field resources

Source of Field Resource	Type of field resource	Description of field resource
1. Fields (energy) in a system	Mechanical	Energy from pedals can be used in propulsion of floatation device
2. Fields of dissipation - energy waste	Mechanical	Energy from pedaling could be stored in a battery in addition to being used to propel machine.

Table 45. Shuttlebike Field Resources

Space resources

Type of space resource	Description of space resource
Travel through	Shuttlebike must travel through liquid and travel over land
Nesting (matreshka)	Components of Shuttlebike may be nested, for instance, floatation device may be deflated and stored in backpack

Table 46. Shuttlebike Space Resources

Time resources

None noted

Informational resources

None noted

Functional resources

None noted

Step 1.6 CONSIDER ALLOWABLE CHANGES TO THE SYSTEM

Acceptable Changes to the System:

1. Floatation device may attach to bicycle so long as no permanent changes are made
2. Floatation device may be added to any detachable part of the system, such as the rider's clothing or the luggage department when not in use

Constraints to the system:

Name of Constraint	How is it constrained?	Reasons for constraint	Remove?	Secondary problems?
Wheels	May not be removed	Time constraint	☐Yes	☐Yes*
Frame	May not be significantly altered	Reduced value of bicycle	☒Yes	☐Yes*
Bicycle	Must not be altered	Floatation device must not devalue bicycle	☐Yes	☐Yes*
Storage	Must be minimal	Too much weight will slow bicyclist down	☐Yes	☐Yes*
Separation of functions	Must be maintained	Floatation capacity must not impair land travel and bicycle function must not preclude floatation	☐Yes	☐Yes*

Table 47. Shuttlebike System Constraints

Optional: Possible solutions suggested by Considering Allowable Changes to the System:

Bicycle must be independent from floatation device

Floatation device must be compressed to be carried while bicycle is in operation

Step 1.7 FURTHER REFINE SOLUTION SPACE

Desired **technical characteristics** compared to the existing characteristics:	
Existing Technical Characteristics	Desired Technical Characteristics
Bicycle will not float	Bicycle-system is amphibious
Bicycle is powered by foot pedals	Floatation device is also powered by bicycle's foot pedals
Bicycle is steered by turning handlebars	Floatation device is also steered by turning handlebars

Table 48. Shuttlebike Desired Technical Characteristics

Desired **economic characteristics** compared to the existing characteristics:

Specify an acceptable cost of each prospective change, an acceptable amount of investment for implementing each change, etc.

Existing Economic Characteristics					
Investment	Maintenance	FV	Interest Rate	Life Time	PV (Calculate)
$500- 2,000	$100/year +1% investment	10% investment	12%	10 years	($1,077.17)- ($2,613.63)
Cost of a mountain bike- this cost is an investment the bicyclist must make in order to ride.					
Desired Economic Characteristics					
Investment	Maintenance	FV	Interest Rate	Life Time	PV (Calculate)
$1,000	$100/year	$100	12%	10 years	($1,532.82)
Additional cost we believe a bicyclist will be willing to pay for the additional capability to travel through water. This will be considered viable if we can make a 20% profit in the first two years with sales of 1,000 units per year.					

Desired timetables for the realization of each stage of work

Concept Development	Begin: 4/2002, End: 5/2002
Evaluation of Solutions	Begin: 5/2002, End: 6/2002
Prototype Development	Begin: 6/2002, End: 9/2002
Testing and Evaluation	Begin: 9/2002, End: 10/2002
Implementation	Begin: 10/2002, End: 5/2003- Production of first 1,000 units.

Table 49. Shuttlebike Economic Characteristics

Expected degree of novelty of the solutions:

Combination of 2 or more systems acceptable

Additional criteria:

Product appearance

Bicycle is unchanged in appearance except when in floatation mode.

Convenience and low cost of maintenance and service

Minimal tools for conversion, minimal weight addition to system, minimal effort to convert

Optional: Possible solutions suggested by Further Refining the Solution Space:

None noted

Step 2. CONSTRUCT A LOGIC DIAGRAM

Step 2.1 IDENTIFY CHIEF UNDESIRABLE EFFECTS

Refined Problem Description (from Step 1.3.1)

Combine the functionality of a floatation device with that of a bicycle.

Terminal desirable effect:

Bicycle can travel across water

Step 2.2 DRAW THE LOGIC DIAGRAM

Step 2.2.1 CONNECTING ENTITIES

Step 2.2.1.1 CODE THE ENTITIES

Entity	Quantitative or Qualitative
101. Bi-system of bicycle and amphibious vehicle exists	L- Logical/Qualitative
201. System can travel across land (land mode)	L- Logical/Qualitative
202. System can travel across water (amphibious mode)	L- Logical/Qualitative
301. System uses a standard commercially available bicycle or mountain bike for land mode	L- Logical/Qualitative
302. System can be converted between land and water mode	L- Logical/Qualitative
401. System has power to move	L- Logical/Qualitative
402. System can be steered	L- Logical/Qualitative
403. System can be stopped	L- Logical/Qualitative
404. System is buoyant	L- Logical/Qualitative
501. Power is provided by transmitting power from legs through pedals through bicycle chain to wheels	L- Logical/Qualitative
502. Turning a propeller in the water provides power.	L- Logical/Qualitative
503. Steering is provided by turning the front wheel via the handlebars	L- Logical/Qualitative
504. Steering is provided by turning a rudder	L- Logical/Qualitative
505. Vehicle is stopped by applying hand brakes	L- Logical/Qualitative
506. Vehicle is stopped by reversing the propeller	L- Logical/Qualitative
507. Buoyancy is provided by attaching floats	L- Logical/Qualitative
601. Rotary motion is perpendicular to direction of travel	L- Logical/Qualitative
602. Rotary motion is parallel to direction of travel	L- Logical/Qualitative
603. Wheels are at the lowest point	L- Logical/Qualitative
604. Rudder is below water level	L- Logical/Qualitative
605. Propeller is below water level	L- Logical/Qualitative

Table 50. Shuttlebike Entity Coding

Step 2.2.1.2 IDENTIFY CONNECTIONS BETWEEN ENTITIES

Cause(s)	Relationship between causes	Effect(s)	Mathematical/Boolean Expression
201,202	AND	*101*	*201*202⇒101*
301,302	AND	*202*	*301*302⇒202*
401,402,403	AND	*301*	*401*402*403⇒301*
401,402,403,404	AND	*302*	*401*402*403*404⇒302*
501,502	AND	*401*	*501*502⇒401*
503,504	AND	*402*	*503*504⇒402*
505,506	AND	*403*	*505*506⇒403*
601,602,603,605	AND, NOT	*501,502*	*(602*603)*~(601*605)⇒501* *~(602*603)*(601*605)⇒502*
603,603	AND, NOT	*503,504*	*603*~604⇒503* *~603*604⇒504*

Table 51. Shuttlebike Logical Relationships

Step 2.2.1.3 CODE ENTITIES AS DESIRABLE, UNDESIRABLE OR NEUTRAL

Entity	Desirability
101. Bi-system of bicycle and amphibious vehicle exists	D- Desirable
201. System can travel across land (land mode)	D- Desirable
202. System can travel across water (amphibious mode)	D- Desirable
301. System uses a standard commercially available bicycle or mountain bike for land mode	D- Desirable
302. System can be converted between land and water mode	D- Desirable
401. System has power to move	D- Desirable
402. System can be steered	D- Desirable
403. System can be stopped	D- Desirable
404. System is buoyant	D- Desirable
501. Power is provided by transmitting power from legs through pedals through bicycle chain to wheels	D- Desirable
502. Turning a propeller in the water provides power.	D- Desirable
503. Steering is provided by turning the front wheel via the handlebars	D- Desirable
504. Steering is provided by turning a rudder	D- Desirable
505. Vehicle is stopped by applying hand brakes	D- Desirable
506. Vehicle is stopped by reversing the propeller	D- Desirable
507. Buoyancy is provided by attaching floats	D- Desirable
601. Rotary motion is perpendicular to direction of travel	D- Desirable

Entity	Desirability
602. Rotary motion is parallel to direction of travel	D- Desirable
603. Wheels are at the lowest point	D- Desirable
604. Rudder is below water level	D- Desirable
605. Propeller is below water level	D- Desirable

Table 52. Shuttlebike Desirability

Step 2.2.1.4 CODE CONTROL OF ENTITIES

Entity	Control
101. Bi-system of bicycle and amphibious vehicle exists	C2- Simple Indirect Control
201. System can travel across land (land mode)	C2- Simple Indirect Control
202. System can travel across water (amphibious mode)	C2- Simple Indirect Control
301. System uses a standard commercially available bicycle or mountain bike for land mode	C1- Direct Control
302. System can be converted between land and water mode	C2- Simple Indirect Control
401. System has power to move	C2- Simple Indirect Control
402. System can be steered	C2- Simple Indirect Control
403. System can be stopped	C2- Simple Indirect Control
404. System is buoyant	C2- Simple Indirect Control
501. Power is provided by transmitting power from legs through pedals through bicycle chain to wheels	C1- Direct Control
502. Turning a propeller in the water provides power.	C2- Simple Indirect Control
503. Steering is provided by turning the front wheel via the handlebars	C1- Direct Control
504. Steering is provided by turning a rudder	C2- Simple Indirect Control
505. Vehicle is stopped by applying hand brakes	C1- Direct Control
506. Vehicle is stopped by reversing the propeller	C1- Direct Control
507. Buoyancy is provided by attaching floats	C1- Direct Control
601. Rotary motion is perpendicular to direction of travel	C2- Simple Indirect Control
602. Rotary motion is parallel to direction of travel	C2- Simple Indirect Control
603. Wheels are at the lowest point	C1- Direct Control
604. Rudder is below water level	C2- Simple Indirect Control
605. Propeller is below water level	C2- Simple Indirect Control

Table 53. Shuttlebike Control Levels

Step 2.2.2 ASSIGN NUMBERS TO EACH ENTITY.

Entity	Number
Bi-system of bicycle and amphibious vehicle exists	101.
System can travel across land (land mode)	201.
System can travel across water (amphibious mode)	202.
System uses a standard commercially available bicycle or mountain bike for land mode	301.
System can be converted between land and water mode	302.
System has power to move	401.
System can be steered	402.
System can be stopped	403.
System is buoyant	404.
Power is provided by transmitting power from legs through pedals through bicycle chain to wheels	501.
Turning a propeller in the water provides power.	502.
Steering is provided by turning the front wheel via the handlebars	503.
Steering is provided by turning a rudder	504.
Vehicle is stopped by applying hand brakes	505.
Vehicle is stopped by reversing the propeller	506.
Buoyancy is provided by attaching floats	507.
Rotary motion is perpendicular to direction of travel	601.
Rotary motion is parallel to direction of travel	602.
Wheels are at the lowest point	603.
Rudder is below water level	604.
Propeller is below water level	605.

Table 54. Shuttlebike Entity Number Assignments

Step 2.2.3 SUMMARY OF THE ENTITY CODE SCHEME

Entity	Unique Nomenclature
Bi-system of bicycle and amphibious vehicle exists	D-101-L-C2
System can travel across land (land mode)	D-201-L-C2
System can travel across water (amphibious mode)	D-202-L-C2
System uses a standard commercially available bicycle or mountain bike for land mode	D-301-L-C1
System can be converted between land and water mode	D-302-L-C2
System has power to move	D-401-L-C2
System can be steered	D-402-L-C2
System can be stopped	D-403-L-C2
System is buoyant	D-404-L-C2
Power is provided by transmitting power from legs through pedals through bicycle chain to wheels	D-501-L-C1
Turning a propeller in the water provides power.	D-502-L-C2
Steering is provided by turning the front wheel via the handlebars	D-503-L-C1
Steering is provided by turning a rudder	D-504-L-C2
Vehicle is stopped by applying hand brakes	D-505-L-C1
Vehicle is stopped by reversing the propeller	D-506-L-C1
Buoyancy is provided by attaching floats	D-507-L-C1
Rotary motion is perpendicular to direction of travel	D-601-L-C2
Rotary motion is parallel to direction of travel	D-602-L-C2
Wheels are at the lowest point	D-603-L-C1
Rudder is below water level	D-604-L-C2
Propeller is below water level	D-605-L-C2

Table 55. Shuttlebike Complete Entity Names

Step 2.2.4 TEST THE LOGIC DIAGRAM USING THE RULES OF LOGIC.

1. ☒ Clarity (seeking to understand)

- Would I add any verbal explanation if reading the tree to someone else?
- Is the meaning/context of words unambiguous?
- Is the connection cause and effect convincing "at face value"?
- Are intermediate steps missing?

2. ☒ Entity Existence (Complete, properly structured, valid statements of cause and effect)

- Is it a complete sentence?
- Does it make sense?
- Is it free from "if-then" statements?
- Does it convey only one idea (i.e. not compound entity)?

- Does it exist in my reality?

3. ☒ Causality existence (Logical connection between cause and effect)

- Does an "if then" connection really exist, as written?
- Does the cause, in fact, result in the effect?
- Does it make sense when read aloud exactly as written?
- Is the cause intangible? (If so, look for additional predicted effect)

4. ☒ Cause insufficiency (A nontrivial dependent element missing)

- Can the cause, as written, result in the effect on its own?
- Are there any significant cause factors missing?
- Is/are the written cause(s) sufficient to justify all parts of the effect(s)?
- Is an ellipse (*an AND Gate*) required?

5. ☒ Additional cause (A separate, independent cause producing the same effect)

- Is there anything else that might cause the effect on its own? *(Missing OR Gate)*
- If the stated cause is eliminated, will the effect be almost completely eliminated?

6. ☒ Cause-effect reversal (Arrow pointing in the wrong direction)

- Is the stated effect really the cause and vice versa?
- Is the stated cause the reason why or just how we know the effect exists?

7. ☒ Predicted effect existence (Additional corroborating effect resulting from cause)

- Is the cause intangible?
- Do other unavoidable outcomes exist besides the stated effect?

8. ☒ Tautology (Circular logic)

- Is the cause intangible?
- Is the effect offered as a rationale for the existence of the cause?
- Do other unavoidable outcomes exist besides the stated effect?
- In addition to these logical rules, a few more are required for this approach.

9. ☒ Check that all variables are of the right type, Boolean or Quantitative.
10. ☒ Check that Quantitative variables are converted to Boolean variables before entering a AND, OR, XOR or NOT gates.
11. ☒ Check that Boolean variables are converted to Quantitative variables before entering MAG AND gates.
12. ☒ Check that there is a "machinery" input entity for each entity that requires a piece of equipment to operate.

Step 2.2.5 COMPLETE THE LOGIC DIAGRAM

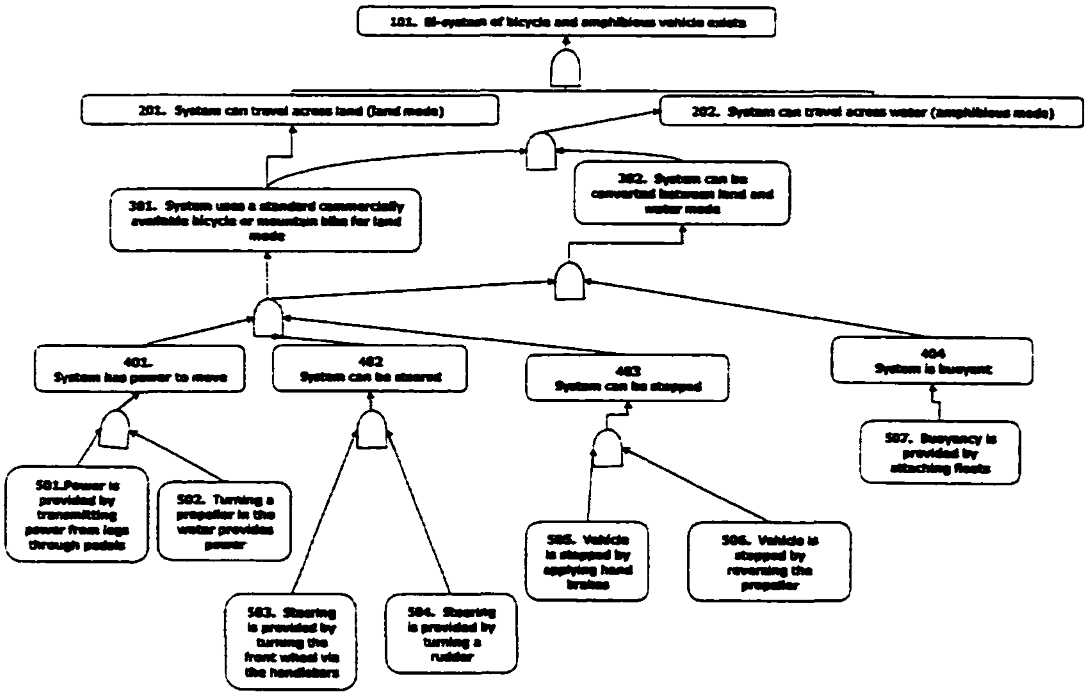


Figure 32. Overall Logic Diagram for Shuttle bike System

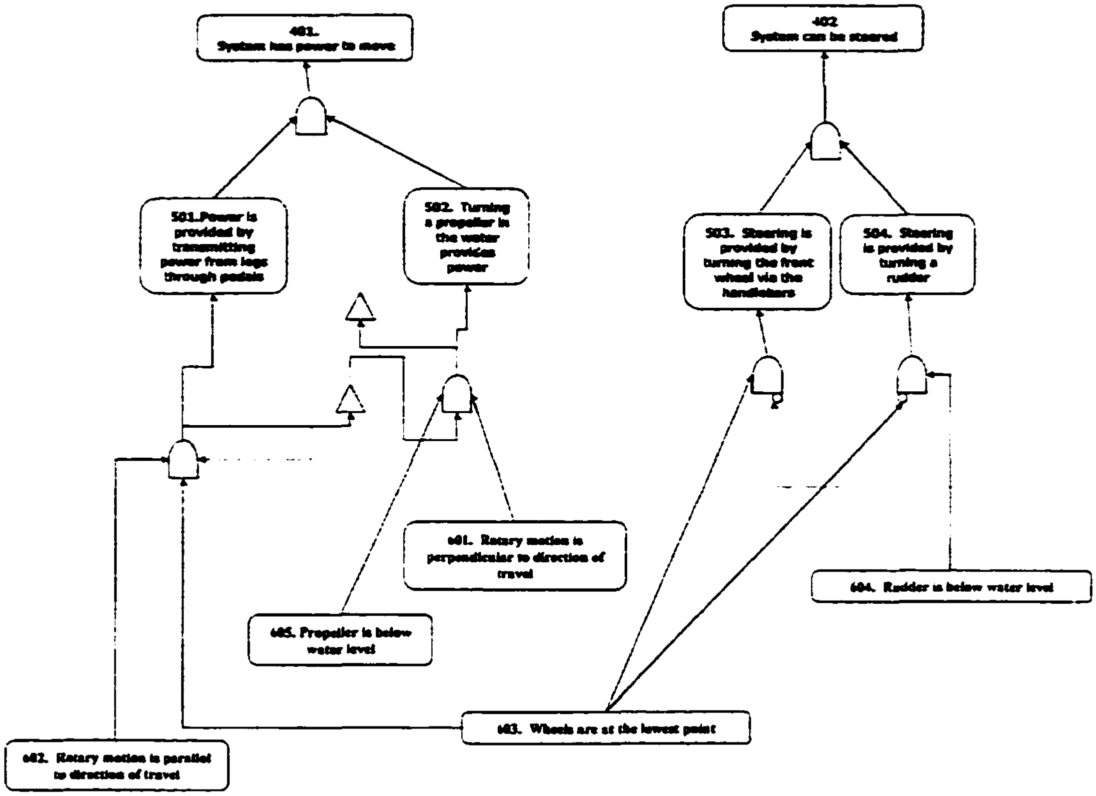


Figure 33. Detailed Logic Diagram for Shuttle Bike

Step 3. **ANALYZE LOGIC DIAGRAM TO FIND THE CONSTRAINTS OF THE SYSTEM**

Step 3.1 **FIND THE SWITCHES FOR THE SYSTEM**

Terminal Effects Name	Identification	Directly Controllable?	Switch(es)	Level of Control for each switch
101. Bi-system of bicycle and amphibious vehicle exists	D-101-L-C2	☐ Yes ☒ No	D-201-L-C2 D-202-L-C2	☒ C1 ☐ C2 ☐ C3 ☐ C1 ☒ C2 ☐ C3
For 101 to be true, the physical contradiction of 201 and 202 must be resolved. They must be separated in time, meaning at one time the system must be in mode 201 (land) and at another time, it must be in mode 202 (amphibious).				
201. System can travel across land (land mode)	D-201-L-C1	☒ Yes ☐ No	D-501-L-C1 D-503-L-C1 D-505-L-C1	☒ C1 ☐ C2 ☐ C3 ☒ C1 ☐ C2 ☐ C3 ☒ C1 ☐ C2 ☐ C3
Land mode is controlled by having a standard commercially available bike. The three necessary functions of land mode are power (501), steering (503) and braking (505). All of these are standard on commercially available bikes, therefore they are listed as completely controllable (C1)				
202. System can travel across water (amphibious mode)	D-202-L-C2	☐ Yes ☒ No	D-502-L-C2 D-504-L-C2 D-506-L-C1 D-507-L-C1	☐ C1 ☒ C2 ☐ C3 ☐ C1 ☒ C2 ☐ C3 ☒ C1 ☐ C2 ☐ C3 ☒ C1 ☐ C2 ☐ C3
Amphibious mode is controlled by providing power (502), steering (504), braking (506) and floatation (507). These modes are new features that must be removed when not in amphibious mode due to the conflicts shown below. 506 and 507 can be directly implemented.				
502.Turning a propeller in the water provides power.	D-502-L-C2	☐ Yes ☒ No	D-601-L-C2 D-602-L-C2 D-603-L-C1 D-605-L-C2	☐ C1 ☒ C2 ☐ C3 ☐ C1 ☒ C2 ☐ C3 ☒ C1 ☐ C2 ☐ C3 ☐ C1 ☒ C2 ☐ C3
601 and 605 must be true while 602 and 603 must be false. Also, 601 is in contradiction with 602 and 603 is in contradiction with 605.				
504. Steering is provided by turning a rudder	D-504-L-C2	☐ Yes ☒ No	D-603-L-C1 D-604-L-C2	☒ C1 ☐ C2 ☐ C3 ☐ C1 ☒ C2 ☐ C3
603 must be false while 604 must be true, in direct contradiction to the necessary conditions for steering in land mode.				

Table 56. Shuttlebike System Switches

The new problem becomes to create a conversion kit that can transform a bike into an amphibious vehicle, by addressing power, steering, braking and buoyancy. This should be accomplished by applying the following changes to the system:

Rotary motion supplied by pedaling must be parallel to the direction of travel while in land mode but must be perpendicular to the direction of travel while in amphibious mode.

Propeller must be above the surface of the water while in land mode but below the surface of the water while in amphibious mode.

Rudder must be above the surface of the water while in land mode but below the surface of the water while in amphibious mode.

Additional constraints remain at this point to make the system convertible and transportable.

Before proceeding to find a solution, it is necessary to make sure the logic doesn't create any other problems.

Step 3.2 **FOR EACH DE, SEEK TO ENSURE THE LOGICAL VALUE OF THE ENTITY IS = 1.**

Terminal Effects Name	Identification	Switch(es)	Level of Control
101. Bi-system of bicycle and amphibious vehicle exists	D-101-L-C2	D-201-L-C2	☒ C1 ☐ C2 ☐ C3
		D-202-L-C2	☐ C1 ☒ C2 ☐ C3
101 is controlled by having a mechanism to convert from land mode (201) to amphibious mode (202)			
201. System can travel across land (land mode)	D-201-L-C1	D-501-L-C1	☒ C1 ☐ C2 ☐ C3
		D-503-L-C1	☒ C1 ☐ C2 ☐ C3
		D-505-L-C1	☒ C1 ☐ C2 ☐ C3
While in land mode, system is a commercially available bicycle.			
202. System can travel across water (amphibious mode)	D-202-L-C2	D-502-L-C2	☐ C1 ☒ C2 ☐ C3
		D-504-L-C2	☐ C1 ☒ C2 ☐ C3
		D-506-L-C1	☒ C1 ☐ C2 ☐ C3
		D-507-L-C1	☒ C1 ☐ C2 ☐ C3
System is placed in amphibious mode by applying conversion kit. This conversion kit sets 502, 504, 506 and 507 to "True," forcing 202 to a value of "true."			
502.Turning a propeller in the water provides power.	D-502-L-C2	D-601-L-C2	☐ C1 ☒ C2 ☐ C3
		D-602-L-C2	☐ C1 ☒ C2 ☐ C3
		D-603-L-C1	☒ C1 ☐ C2 ☐ C3
		D-605-L-C2	☐ C1 ☒ C2 ☐ C3
While in amphibious mode, 602 and 603 are set to "false" while 601 and 605 are set to true, ∴ 502 is true. *~(602*603)*(601*605)⇨502*			
504. Steering is provided by turning a rudder	D-504-L-C2	D-603-L-C1	☒ C1 ☐ C2 ☐ C3
		D-604-L-C2	☐ C1 ☒ C2 ☐ C3
In amphibious mode, 603 is false and 604 is true, ∴504 is true. *(~603*604⇨504)*			

Table 57. Shuttlebike Desirable Element Analysis

Step 3.3 **FOR EACH UDE, SEEK TO CREATE THE VALUE OF THE NODE = 0**

There are no UDEs

Step 3.4 **IDENTIFY ANY TRADE-OFFS IN THE DESIGN**

Trade-offs in the as-is design:

These are all physical contradictions-

Rotary motion supplied by pedaling must be parallel to the direction of travel while in land mode but must be perpendicular to the direction of travel while in amphibious mode.

Propeller must be above the surface of the water while in land mode but below the surface of the water while in amphibious mode.

Rudder must be above the surface of the water while in land mode but below the surface of the water while in amphibious mode.

Step 3.5 **REVIEW TOTAL SYSTEM**

Identify Root Causes and Core Problems

D-505-L-C1

D-506-L-C1

D-507-L-C1

D-601-L-C2

D-602-L-C2

D-603-L-C1

D-604-L-C2

D-605-L-C2

Step 4. **GENERATE SOLUTIONS AT THE CRITICAL ENTITIES AND TRADE-OFFS**

Summary of Chief Constraints/Problems to be addressed first

Name of Root Cause	Undesirable?	Desirable?	Contradiction?
Vehicle is stopped by applying hand brakes D-505-L-C1	☐ If yes, go to Step 4.1	☒ If yes, go to Step 4.2	☐ If yes, go to Step 4.3
Notes: For land mode, this is inherent in bicycle design without amphibious attachment.			
Vehicle is stopped by reversing the propeller D-506-L-C1	☐ If yes, go to Step 4.1	☒ If yes, go to Step 4.2	☐ If yes, go to Step 4.3
Notes: For amphibious mode, this is a specification for the propeller/pedal/control system			
Buoyancy is provided by attaching floats D-507-L-C1	☐ If yes, go to Step 4.1	☒ If yes, go to Step 4.2	☒ If yes, go to Step 4.3
Notes: For amphibious mode only. This actually provides an inherent contradiction already addressed by other design constraints. Namely, the floatation devices cannot be attached while in land mode but must be attached while in amphibious mode.			
Rotary motion is perpendicular to direction	☐ If yes, go to Step 4.1	☒ If yes, go to	☒ If yes, go to

Name of Root Cause	Undesirable?	Desirable?	Contradiction?
of travel D-601-L-C2		Step 4.2	Step 4.3
Notes: For amphibious mode, the propeller must be perpendicular to the water to transmit forward thrust. This is a contradiction of 602.			
Rotary motion is parallel to direction of travel D-602-L-C2	☐ If yes, go to Step 4.1	☒ If yes, go to Step 4.2	☒ If yes, go to Step 4.3
Notes: For land mode, this is inherent in bicycle design without amphibious attachment. Rotation moves wheels that contact the ground producing forward motion. This is a contradiction of 601.			
Wheels are at the lowest point D-603-L-C1	☐ If yes, go to Step 4.1	☒ If yes, go to Step 4.2	☒ If yes, go to Step 4.3
Notes: For land mode, this is inherent in bicycle design without amphibious attachment. This is a contradiction of 604 and 605.			
Rudder is below water level D-604-L-C2	☐ If yes, go to Step 4.1	☒ If yes, go to Step 4.2	☒ If yes, go to Step 4.3
Notes: For amphibious mode, the rudder must be in the water to steer. This is a contradiction of 603.			
Propeller is below water level D-605-L-C2	☐ If yes, go to Step 4.1	☒ If yes, go to Step 4.2	☒ If yes, go to Step 4.3
Notes: For amphibious mode, the propeller must be below the water line to move and to stop motion. This is a contradiction of 603.			

Table 58. Shuttlebike Root Causes

Name of Terminal Effect	Desirable?	Notes
Bi-system of bicycle and amphibious vehicle exists D-101-L-C2	☒ If yes, go to Step 4.4	This design increases ideality by converting a mono-system (bicycle) to a bi-system.

Table 59. Shuttlebike Terminal Effect

Step 4.1 **IF A PARTICULAR CRITICAL ENTITY MUST BE "TURNED OFF," THEN FOLLOW I-TRIZ SOLUTION RECOMMENDATIONS FOR UDE.**

There are no UDEs to be addressed.

Step 4.2 **IF A PARTICULAR CRITICAL ENTITY MUST BE "TURNED ON," THEN FOLLOW I-TRIZ SOLUTION RECOMMENDATIONS FOR DE.**

1. Name of DE Vehicle is stopped by applying hand brakes D-505-L-C1 This functionality is inherent in the bicycle design and is satisfied by using a commercially available bicycle.
2. Name of DE Vehicle is stopped by reversing the propeller D-506-L-C1 This functionality is necessary to stop in amphibious mode. Since bicycle pedals can turn backwards, this is the same problem as is addressed in designing a way to provide rotary motion to the propeller.
3. Name of DE Buoyancy is provided by attaching floats D-507-L-C1 This is existing technology.
4. Name of DE Rotary motion is perpendicular to direction of travel D-601-L-C2 From the Shuttlebike website: "The propulsion system begins with a pivoting roller/gear mechanism that attaches to the frame and adjusts to contact the rear wheel when the bike is used on the water. From there the power is transferred by means of a flexible drive shaft to the gear/propeller/rudder assembly attached to the front wheel."
5. Name of DE Rotary motion is parallel to direction of travel D-602-L-C2 Standard bicycle gear provided as a part of commercial bicycle.
6. Name of DE Wheels are at the lowest point D-603-L-C1 Standard bicycle gear provided as a part of commercial bicycle.
7. Name of DE Rudder is below water level D-604-L-C2 Rudder is attached to the front wheel and extends below the waterline.
8. Name of DE Propeller is below water level D-605-L-C2 Propeller is attached to the front wheel and extends below the waterline.

Table 60. Shuttlebike Desirable Effect Controls

Step 4.3 **IF THERE IS A CONTRADICTION, THEN FOLLOW THE I-TRIZ SOLUTION RECOMMENDATIONS FOR CONTRADICTIONS.**

1. Type of contradiction: ☒ DE Counteracts DE Cause: Buoyancy is provided by attaching floats (D-507-L-C1) Effect: Floatation device cannot be attached while in land mode
2. Type of contradiction: ☒ DE Counteracts DE Cause: Rotary motion is perpendicular to direction of travel (D-601-L-C2) Effect: Rotary motion is parallel to direction of travel (D-602-L-C2)
3. Type of contradiction: ☒ DE Counteracts DE Cause: Wheels are at the lowest point (D-603-L-C1) Effect: Rudder is below water level (D-604-L-C2) and Propeller is below water level (D-605-L-C2)

Table 61. Shuttlebike Contradictions

All of these contradictions are physical contradictions that can be solved with the TRIZ concept of "separation in space."

Child relation: The desirable effect necessary for amphibious mode should be in place in order to operate amphibiously and should not exist in order to avoid hindering operating in land mode.

Grandchild relation: Apply separation principles to satisfy contradictory requirements.

Operator: Separate opposite requirements in time, "If a system or process must satisfy contradictory requirements, perform contradictory functions or operate under contradictory conditions, try to (actually or theoretically) schedule the process so that conflicting requirements, functions or operations take effect at different times."

Step 4.4 **IF THE DESIGN ONLY HAS DESIRABLE ENTITIES, THEN CONSIDER THE I-TRIZ SOLUTION RECOMMENDATIONS FOR INCREASING THE LEVEL OF IDEALITY OF THE SYSTEM**

Name of Desirable Terminal Effect

Bi-system of bicycle and amphibious vehicle exists (D-101-L-C2)

The entity statement implies that this transformation has already taken place, namely changing a mono-system (bicycle) to a bi-system. This is an established line of evolution from TRIZ.

Child Relation

Consider transitioning to the next generation of the system that will provide transportation in a more effective way and will be free of existing problem of inability to cross water.

Grandchild Relation

Consider the possibility to transform the existing system that provides transportation into bi- or poly-system.

Operator

Complementary bi-system (bi-system with shifted characteristics)

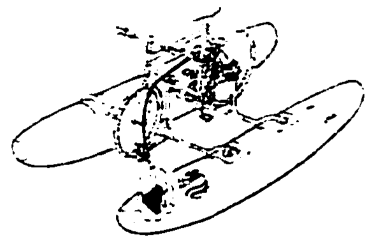
Comments

From *IWB2000*[7]: "If you have two systems with different (including opposing) desired properties, they can be integrated into one system. When the desired properties are combined in this way, a system with new properties often results."

Figure 34. Shuttlebike Ideality Part of Solution

Summary of total solution:

This problem was identified and solved by Shuttlebike USA[237] (see http://www.shuttlebikeusa.com/index.html). The following is a drawing and a description of their product that meets all of the desired characteristics of a bicycle and an amphibious vehicle by transforming between the two by means of a kit and some permanent clamps on the bicycle. It also solves the problem of transportability and minimizes the amount of tools involved to construct the assembly:



SHUTTLE-BIKE® ASSEMBLY AND OPERATION

Here's how you can turn your bicycle into a waterbike: first unzip your shuttle-bike kit ® backpack. Take out the floats, frame, pump and propulsion assembly.

1.The SHUTTLE-BIKE KIT ® adapts to your bike with a set of "fixed" clamps universally adaptable to many different bikes on the market with round frame tubes. Permanently fastened on the frame, they do not hinder the use of the mountain-bike on the road. These universal clamps come with a series of plastic bushings that, in addition to prevent scuffing the frame paint, adapt to frames of most common diameters.

BEFORE ORDERING, CHECK THE DIAMETER OF YOUR FRAME TUBES so you get the correct size clamps. We recommend that "Shuttle-Bikers" install the permanent clamps at home, or have it done by an experienced bike mechanic, before riding on the water.

2. The permanent clamp accessories are designed to lock onto the SHUTTLE-BIKE® frame without using any tools—the whole kit snaps together, tightens and inflates by hand and pedal-power in about 10 minutes.

3. The floats can be blown up by means of a small pump especially designed and patented for the SHUTTLE-BIKE®. This pump will allow you to inflate the floats by pedaling on the spot, since the frame suspends the rear wheel a few centimeters above the ground, so it works much like an exercise bike.

4. Once the frame is attached to the bike, the floats are attached to the frame and then the propulsion system is attached to the bike.

5. The propulsion system begins with a pivoting roller/gear mechanism that attaches to the frame and adjusts to contact the rear wheel when the bike is used on the water. From there the power is transferred by means of a flexible drive shaft to the gear/propeller/rudder assembly attached to the front wheel. The pump is removed from the gear/propeller/rudder assembly, the prop is snapped on and you are ready to ride the waves! The propeller/rudder allows you to steer with the handlebars—you can do a 360° turn in place by turning the handlebar 90° in either direction! Since the drive roller contacts the rear wheel, all the gears of your bike can be used to achieve the best cruising or speed combinations. You get all the fun of bicycling and boating at the same time!

6. Just step between one of the floats and carry your Shuttle-Bike® to the water, push it in, step on a float (you won't tip over), mount and RIDE! It's as fun as it looks.

Figure 35. Shuttlebike Description from Shuttlebike USA

CHAPTER 7. CONCLUSIONS AND FURTHER RESEARCH

7.1 CONCLUSIONS

Design efforts should solve systemic problems. In order to solve a systemic problem, you need to understand the true nature of the problem, the nature of the system and the way the system is connected to elements within and without.

This study provides a method to focus the problem and then diagram its relation to its components (called entities) as well as other surrounding systems. After focusing the problem, it uses the knowledge of the designer to create a logical view of the entire system, as it currently exists. This picture, or logical diagram, becomes something that can be analyzed objectively. The analysis of the diagram leads the designer to the areas that can be redesigned or improved by innovation. Once the areas are identified, the conceptual form of the design is developed using the tools provided in TRIZ.

Four case studies have been provided to demonstrate the method proposed in this dissertation. These case studies clearly show that

- Careful problem formulation may lead the designer to solve a different problem than originally anticipates (airbag problem was originally thought to be a problem with small statured drivers, but in reality it is a problem of not enough distance between the driver and the airbag at the time of deployment)
- Understanding oF Directed Evolution and the concepts of TRIZ lead to better designs earlier (Airlift Loading System was solved at the bi-system level but should have been elevated to the polysystem level, as described in TRIZ literature)
- Systemically identifying the logical make-up of a problem leads to better, more complete solutions (Shuttlebike demonstrates this)
- Methods used in this study can reproduce other recent design innovations (Truck bed covers, Shuttle bikes)

Finally, armed with knowledge of the best places to redesign the system, the designer can use the full arsenal of TRIZ tools to develop innovative solutions using proven methods from historical data.

The result is a focused design that is conceptually guaranteed to address the identified problem.

7.2 CONTRIBUTIONS

This dissertation provides six contributions to the body of research:

1. This research presents a new method to identify and solve design problems in the conceptual stage.
2. This research integrates and expands the disciplines of TRIZ, TOC and logic.
3. This research creates a new logic diagram that can be used in the solution of a design concept.
4. This researches improves upon a problem solving worksheet that is useful in guiding the designer through the design process (see Appendix B).
5. This research establishes codes for design entities that are useful in analyzing designs, including 3 degrees of Desirability and 5 levels of Control.

6. This research provides a bridge between qualitative and quantitative design elements such that one diagram and method can be used in the presence of both factors.

7.3 FURTHER RESEARCH

There are many phases of design and development from problem identification to manufacture. There are many different tools developed separately to aid the designer to make better designs. These tools have become very difficult to apply because there are so many of them and a developer must rely on whatever methods that he has been trained to use. This study demonstrates that two of these methods can be integrated together nicely and combined with a third tool, logic. This study could also be used recursively to assess the entire design and development process and create a new self-contained process that encompasses the best of these current practices in one place.

As stated earlier, the design phase can be divided into three sub-phases:

- Configuration Design
- Parameter Design
- Tolerance Design

The activities regarding quality during the design phase are sometimes called "off-line quality control." The activities that take place during manufacture are sometimes called "on-line quality control."

Likewise, on-line quality control can be subdivided into the following sub-phases:

- Diagnosis and Adjustment
- Prediction and Correction
- Measurement and Disposition

In the design phase, there is considerable feed-forward consideration of on-line quality control. For instance, it is necessary to consider the acceptable disposition of defective units and the expected defects and defective rates of the process. Additionally, it is necessary to understand and consider the constraints of manufacture. Likewise, on-line quality control is a necessary feedback to the design phase.

Although this is not an exhaustive list, the following general classification of techniques are considered:

Method/Originator	Country	Central Concept	Tools employed
AD/ Suh	USA	Simplify design	Characteristic vectors, design matrices
CAIV	USA	Cost is a design variable	TOC (Total Operating Cost)
DFMA/ Boothroyd	USA	Manufacturing Considerations in Design Phase	DFMA
ISO-9000	Europe	Processes must be standard, auditable and repeatable	Independent assessment
Zero quality control: JIT	Japan	Minimize inventory	JIT, Kanban
Poka Yoke	Japan	Make design mistake proof	Poka-Yoke
QFD/ Akao	Japan	Organize Information to meet Customer needs	House of Quality
Robust Engineering/ Taguchi, Box	USA, Japan	Make design insensitive to variation	CCD, RSM, DOE, QLF
TOC (Theory of Constraints)/ Goldratt	Israel	Key to solving a problem is identifying and overcoming constraints	CRT, CRD, FRT, PRT, TT
TQM- Qualitative methods/ Deming	Japan, USA	Visualize problem	Brainstorming, NGT, Force Field Analysis, Flowcharting, Cause and Effect (Fishbone) Diagram, Check Sheet, Affinity Diagram, Interrelationship Diagraph
TQM- Quantitative methods/ Shewhart	USA, UK	Reduce variation	SPC, Pareto Charts, Scatter Diagram, Control Charts, Histogram, Run Chart, Box Plot, Cp/Cpk, Regression
TRIZ/ Altshuller	USSR	Learn and repeat the innovative process	IFR, TC/PC, Contradiction matrix, 40 inventive principles, 76 standard solutions, AFD, Ideation, Patterns of evolution, Psychological Inertia, Su-Field Analysis, ARIZ

Table 62. Current Methods for Design Improvement

A practitioner who is trained in one method or set of methods will tend to use it for every problem. To quote a TOC website, "if your only tool is a hammer, then every problem looks like a nail." Furthermore, each method has its own school of followers who are anxious to train and consult companies in their methods. These practitioners may be well intentioned, but they leave a definite impression that only their methods can solve your design problems and you not only need their methods, but also you need their services to use the methods.

7.4 AN IDEAL FINAL RESULT FOR THE OVERALL DESIGN METHODS PROBLEM

An optimal solution to the design problem is one that encompasses all of the objectives of the methods mentioned without using all of their methods. For the design methods problem, I have identified the following IFR:

1. The unit is fit for its intended use
2. Every unit produced will conform to specification with minimal deviation from target values
3. Product operates in a wide range of operating environments (design is robust)
4. Inventory while manufacturing is low
5. Design is free of technical compromises
6. Design is easy to manufacture
7. Cost to manufacture is minimized
8. Throughput is maximized
9. Process is auditable and repeatable
10. Failure modes of design are anticipated and design is made mistake-proof
11. Crucial cost decisions are made early in the process

The solution must encompass the entire design process, from conceptualization to implementation to fielding of the finished product. Therefore, it must include features to identify the scope of the existing problem as well as have feed-forward and feedback controls. It must be both qualitative and quantitative and it must be iterative and as automated as possible.

7.5 THE PROBLEM OF FINDING THE RIGHT PROBLEM

The question to ask the design instructor is, "If your method is so good, why aren't you out designing new and improved products?" The answer is usually either that the instructor is altruistically trying to better mankind by teaching or the instructor lacks a good application or problem to apply his tools. Innovation methods only claim to require a cursory amount of subject matter expertise and there is really no reason to constrain inventors from inventing a variety of new products.

An avenue of further research would be to find a way to generate new problem statements and to locate new problems in need of solving. Again, the methods of this study could be used recursively to identify a good method to find the right problem to start with.

7.6 CONCLUSION

The method described in this doctoral dissertation is a tremendous place to start to develop problems statements and to solve design problems with innovative solutions. The proposed method in this dissertation provides an excellent tool to define a design problem, focus it down to the necessary elements to be improved for the next level of solution, develop a strategy to obtain the desired results with a minimum of design compromise and to find an innovative solution to the design problem. It has tremendous potential and advances the art of invention by converting it to a systemic process that can be applied by any designer, engineer or inventor.

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APPENDIX A. LIST OF ACRONYMS

AD	Axiomatic Design
AFD	Anticipatory Failure Determination
AHP	Analytical Hierarchy Process
ANSI	American National Standards Institute
ARIZ	Algorithm of Inventive Problem Solving
ASQ	American Society for Quality
CA	Customer Attribute
CAI	Computer Aided Innovation
CAIV	Cost as an Independent Variable
CCD	Central Composite Design
CF	Cash Flow
COQ	Cost of Quality
C_p	Process Capability
CPIPT	Cost-Performance Integrated Process Team
CRD	Conflict Resolution Diagram (also called Evaporating Cloud)
CRIMS	Cost-Risk Identification and Management System
CRT	Current Reality Tree
CYA	Cover Your Assets
D	Desirability
DE	Desirable Entity
DFA	Design for Assembly
DFM	Design for Manufacture
DFMA	Design for Manufacture and Assembly
DOE	Design of Experiments
DP	Design Parameters
DTC	Dimension, Time, Cost Operator (in TRIZ context)
DTC	Design to Cost (in CAIV context)
DV	Design Variable
ELF	Empirical Loss Function
EMF	Electro-Magnetic Force
EvC	Evaporating Cloud (also called Conflict Resolution Diagram)
FFCSS	Forward Facing Child Safety Seat
FMEA	Failure mode and effect analysis
FMECA	Failure Mode, Effect and Criticality Analysis
FR	Functional Requirement
FRT	Future Reality Tree

GM	General Motors Corporation
HE	Harmful Effect (TRIZ)
HOQ	House of Quality
I	Inventory/Investment
IC	Information Content
IFR	Ideal Final Result
IIHS	Insurance Institute for Highway Safety
INLF	Inverted Normal Loss Function
IPLF	Inverted Probability Loss Function
IPT	Integrated Process Team
ISO	International Organization for Standardization
JIT	Just in Time
LCC	Life Cycle Cost
LF	Loss Function
LSL	Lower Specification Limit
LTB	Larger the Best
NGT	Nominal Group Technique
NHTSA	National Highway Traffic Safety Administration
NIH	Not Invented Here
NLP	Neuro-Linguistic Programming
NP	Net Profit
NTB	Nominal the Best
OE	Operating Expense
PC	Physical Contradiction
PDP	Problem Definition Parameter
PRT	Prerequisite Tree
PV	Process Variable
QC	Quality Control
QFD	Quality Function Deployment
QLF	Quality Loss Function
QLF	Quality Loss Function
RFCSS	Rear Facing Child Safety Seat
ROI	Return On Investment
RSM	Response Surface Methodology
S-Curve	"S" Shaped Curve to describe technical evolution in TRIZ
S-Field	Substance-Field Analysis
SNR	Signal to Noise Ratio
SPC	Statistical Process Control

STB	Smaller the Best
Su-Field	Substance-Field Analysis
T	Throughput
TC	Technical Contradiction
TIPS	Theory of Inventive Problem Solving
TOC	Theory of Constraints
TOC	Total Operating Cost (in CAIV context)
TQM	Total Quality Management
TRIZ	Theory of Inventive Problem Solving (in Russian, the first letters spell TRIZ)
TT	Transition Tree
UDE	Undesirable Effect
UE	Useful Effect (TRIZ)
USL	Upper Specification Limit
VA/VE	Value Analysis/Value Engineering
VR	Virtual Reality
ZPC	Zero Process Control

APPENDIX B. PROBLEM SOLVING WORKSHEET

Problem: take an existing design, identify its weaknesses and modify it in some way to improve it.

Step 1. GATHER INFORMATION ABOUT THE PROBLEM

Step 1.1 DESCRIBE THE PROBLEM IN NON-TECHNICAL TERMS

Problem Statement (technical terms are okay):

Has this been reviewed to ensure a layman can understand it? ☐

If a layman cannot understand the problem statement, rewrite it. One method is to describe the problem to a layman and then have the layman paraphrase the problem.

Problem Statement in non-technical terms (if applicable):

Optional: Possible solutions suggested by reviewing the Problem Statement:

1.
2.
3.
4.
5.
Others (see addendum)

Step 1.2 DEFINE AND DESCRIBE THE SYSTEM

Step 1.2.1 NAME THE SYSTEM

Common or Technical name of System being improved:

Step 1.2.2 DEFINE THE SYSTEM STRUCTURE

Elements that comprise the system:

1.
2.
3.
4.
5.
6.
7.
8.

Other Elements (see addendum):

Supersystem in which the system resides:

Other Systems in the Supersystem:

1.
2.
3.
4.
5.

Other Systems (if over 5) (see addendum):

Step 1.2.3 DEFINE THE SPHERE OF INFLUENCE AND SPAN OF CONTROL ON A SYSTEM

For overall system and for each element, define basic control level.

- "-C1" means that the system can be directly manipulated or controlled. If a system were at the C1 level, there would be no problem to solve because we could directly control it.
- "-C2" indicates simple *indirect* control- for systems that, through manipulation of inputs or the logic of the system, can be changed. These changes are simple because we do not need to get authority from an outside agency to change the inputs.
- "-C3" indicates a system that is controlled by an outside source or agency. Since someone controls these, they are by definition under our *sphere of influence*.
- "-C4" indicates a system that is controlled by nature or is "given" for the problem. These are outside of our sphere of influence, unless we are allowed to redefine the problem.
- "-C5" indicates a system that is completely outside our sphere of influence. If a whole system is at the C5 level, the problem is completely insoluble. Elements of the systems may be considered at the C5 level.

Overall System: C2- Simple Indirect Control
Element1: Control Level- C2- Simple Indirect Control
Element2: Control Level- C2- Simple Indirect Control
Element3: Control Level- C2- Simple Indirect Control
Element4: Control Level- C2- Simple Indirect Control
Element5: Control Level- C2- Simple Indirect Control
Element6: Control Level- C2- Simple Indirect Control
Element7: Control Level- C2- Simple Indirect Control
Element8: Control Level- C2- Simple Indirect Control
Other Elements: (see addendum)
Supersystem: Control Level- C2- Simple Indirect Control
System2: Control Level- C2- Simple Indirect Control
System3: Control Level- C2- Simple Indirect Control
System4: Control Level- C2- Simple Indirect Control
System5: Control Level- C2- Simple Indirect Control
Other Systems (see addendum)

Step 1.2.4 DEFINE THE WAY THE SYSTEM FUNCTIONS

For instance, *Element1 provides energy to Element 2:*

Providing System/Element	Action/Function	Receiving System/Element
	1. 2. 3. 4. 5. 6. 7. 8.	
	Other (See Addendum)	

Step 1.2.5 DEFINE THE SYSTEM BOUNDARIES AND ENVIRONMENT

This problem will work at the following systemic level:

The supersystem in which the defined system operates:

Other Systems within the supersystem:
1.
2.
3.
4.
5.
6. (see addendum)

Related Systems:
1. System2 Supplies Energy to the system, using the following type field (if applicable): mechanical.
2. System2 Supplies Energy to the system, using the following type field (if applicable): mechanical.
3. System2 Supplies Energy to the system, using the following type field (if applicable): mechanical.
4. System2 Supplies Energy to the system, using the following type field (if applicable): mechanical.
5. System2 Supplies Energy to the system, using the following type field (if applicable): mechanical.
6. System2 Supplies Energy to the system, using the following type field (if applicable): mechanical.
7. System2 Supplies Energy to the system, using the following type field (if applicable): mechanical.
8. System2 Supplies Energy to the system, using the following type field (if applicable): mechanical.

Other related systems:
(see addendum)
Subsystems of the defined system:
1.
2.
3.
4.
5.
6. (see addendum)

Optional: Possible solutions suggested by reviewing the System Description:

1.
2.
3.
4.
5.
Others (see addendum)

Step 1.3 REFINE THE DEFINITION OF THE PROBLEM

Step 1.3.1 IDENTIFY THE PROBLEM TO BE RESOLVED

Choose from one of the four generic categories of problems:
1-failure or drawback must be eliminated/corrected
Choose sub-category Check as many as apply and fill in description below:
1. A failure or drawback must be eliminated/corrected:
   - ☐ A harmful action or effect is present in the system
   - ☐ An undesired parameter or characteristic is too high
2. The root causes of a failure or drawback must be discovered (Failure Analysis):
   - ☐ The mechanism causing the failure or drawback is not clear
   - ☐ One or more obstacles connected with the failure/drawback have no apparent explanation
3. A product/process or its part/operation must be improved:
   - ☐ A useful parameter or characteristic is insufficient
   - ☐ A required useful action is absent
   - ☐ A required useful action is implemented ineffectively or incompletely
4. Information about an object's condition must be detected:
   - ☐ Required information about an object's condition is absent
   - ☐ Required information about an object's condition is insufficient

Refined Problem Description:

Step 1.3.2 ESTABLISH THE MECHANISM CAUSING THE PROBLEM.

Identify all known ways in which a failure can occur at the systemic level:

1.
2.
3.
4.
5.
Others (see addendum)

Step 1.3.3 **DESCRIBE THE UNDESIRED CONSEQUENCES OF AN UNRESOLVED PROBLEM.**

1.
2.
3.
4.
5.
Others (see addendum)

Step 1.3.4 **BRIEFLY DESCRIBE THE HISTORY OF THE PROBLEM**

If this problem has previously been addressed, discuss the features and success of earlier design solutions.

1.
2.
3.
4.
5.
Others (see addendum)

Check the patent database to see if there are any patents that deal with the particular problem at hand. **List Patents:**

1.
2.
3.
4.
5.
Others (see addendum)

Describe when the problem was first observed. Often, problems are a byproduct of earlier solutions to different problems. Note the previous problem and why the solution caused this problem. An acceptable solution should not reintroduce earlier problems.

If there is a known solution to the problem that has undesired consequences, document the solution and the consequence. It is possible TRIZ Design techniques can be applied to remove the technical contradiction later on.

Known Solutions with undesirable consequences:

1.
2.
3.
4.
5.
Others (see addendum)

Step 1.3.5 **IDENTIFY OTHER SYSTEMS IN WHICH A SIMILAR PROBLEM EXISTS**

1.
2.
3.
4.
5.
Others (see addendum)

Step 1.3.6 **IDENTIFY ANY OTHER PROBLEM THAT SHOULD ALSO BE SOLVED IN THE COURSE OF SOLVING THE PRIMARY PROBLEM.**

Secondary Problem(s):

1.
2.
3.
4.
5.
Others (see addendum)

Optional: Possible solutions suggested by reviewing the Refined Definition of the Problem:

1.
2.
3.
4.
5.
Others (see addendum)

Step 1.4 DEFINE THE SOLUTION SPACE

In TRIZ theory, the ideal solution is called the ideal final result . Answer the question, "If there were an ideal design, what would its features be?" State the problem in terms of a system that is "ideal" in that it has no undesirable entities and optimized desirable entities. It does not matter that this design is not practical or possible to design.

Ideal Final Result (optimal solution):

Optional: Possible solutions suggested by reviewing the Ideal Final Result:

1.
2.
3.
4.
5.
Others (see addendum)

Step 1.5 DEFINE AVAILABLE RESOURCES

Substance resources

"Substance resources include any kind of material from which the system and its surroundings are composed." (IWB2000[7])

Type of substance resource	Description of substance resource
1. Waste	
2. Waste	
3. Waste	
4. Waste	
5. Waste	
Others (see addendum)	

Field resources

"Field resources include any kind of field existing in the system or its surroundings that can potentially be used." IWB2000[7]

Source of Field Resource	Type of field resource	Description of field resource
1. Fields (energy) in a system	mechanical	
2. Fields (energy) in a system	mechanical	
3. Fields (energy) in a system	mechanical	
4. Fields (energy) in a system	mechanical	
5. Fields (energy) in a system	mechanical	
Others (see addendum)		

Space resources

"Space resources include free, unoccupied space existing in a system or its surroundings. This space can be used to place new objects, either to save space or there are space limitations." (IWB2000[7])

Type of space resource	Description of space resource
1. Occupy vacant space	
2. Occupy vacant space	
3. Occupy vacant space	
4. Occupy vacant space	
5. Occupy vacant space	
Others (see addendum)	

Time resources

"Time resources include time intervals before the start, after the finish and between the cycles of a technological process, which are partially or completely unused." (IWB2000[7])

Type of space resource	Description of space resource
1. Preliminary action	
2. Preliminary action	
3. Preliminary action	
4. Preliminary action	
5. Preliminary action	
Others (see addendum)	

Informational resources

"Informational resources include additional information about the system, which can be obtained with help of dissipation fields, or matter or fields passing through the system." (IWB2000[7])

Type of informational resource	Description of informational resource
1. Fields of dissipation	
2. Fields of dissipation	
3. Fields of dissipation	
4. Fields of dissipation	
5. Fields of dissipation	
Others (see addendum)	

Functional resources

"Functional resources include the capability of a system or its surroundings to perform additional functions. A super-effect is an additional (usually unexpected) benefit arising as a result of innovation." *(IWB2000[7])*

Type of functional resource	Description of functional resource
1. Resources - functions	
2. Resources - functions	
3. Resources - functions	
4. Resources - functions	
5. Resources - functions	
Others (see addendum)	

Optional: Possible solutions suggested by reviewing the Available Resources:

1.
2.
3.
4.
5.
Others (see addendum)

Step 1.6 CONSIDER ALLOWABLE CHANGES TO THE SYSTEM

In order to further define the possible form of the final solution, consider what changes are acceptable to the system. For instance, is a complete change to the system acceptable or are the changes confined to only slight modifications of the existing system?

If there are areas within the system that cannot be changed, define how they are constrained. For instance, perhaps a certain variable cannot decrease below a certain value or must remain constant.

If there are constraints to the system, define the reasons for the imposed restrictions. It may be possible to remove the restriction instead of living with it. Consider whether removing the restrictions causes new (secondary) problems and evaluate if it might be better to resolve these problems rather than the "original" problem

Acceptable Changes to the System:

1.
2.
3.
4.
5.
Others (see addendum)

Constraints to the system:

Name of Constraint	How is it constrained?	Reasons for constraint	Remove?	Secondary problems?
1.			☐Yes	☐Yes*
2.			☐Yes	☐Yes*
3.			☐Yes	☐Yes*
4.			☐Yes	☐Yes*
5.			☐Yes	☐Yes*
Others				
*If secondary problems are caused by removing a constraint, describe below:				

Optional: Possible solutions suggested by Considering Allowable Changes to the System:

1.
2.
3.
4.
5.
Others (see addendum)

Step 1.7 FURTHER REFINE SOLUTION SPACE

Desired **technical characteristics** compared to the existing characteristics:

Existing Technical Characteristics | Desired Technical Characteristics

Others (see addendum)

Desired **economic characteristics** compared to the existing characteristics:

Specify an acceptable cost of each prospective change, an acceptable amount of investment for implementing each change, etc.

Existing Economic Characteristics

Investment	Maintenance	FV	Interest Rate	Life Time	PV (Calculate)
$0				20 year	
$0				20 year	
$0				20 year	
$0				20 year	

$0				20 year	
Others (see addendum)					
Desired Economic Characteristics					
Investment	Maintenance	FV	Interest Rate	Life Time	PV (Calculate)
$0				20 year	
$0				20 year	
$0				20 year	
$0				20 year	
$0				20 year	
Others (see addendum)					
Desired timetables for the realization of each stage of work					

Concept Development	Begin: , End:
Evaluation of Solutions	Begin: , End:
Prototype Development	Begin: , End:
Testing and Evaluation	Begin: , End:
Implementation	Begin: , End:

Expected degree of novelty of the solutions:

Slight modification of existing product acceptable

Additional criteria:

Product appearance

Convenience and low cost of maintenance and service

Other

1.
2.
3.
4.
5.
Others (see addendum)

Optional: Possible solutions suggested by Further Refining the Solution Space:

1.
2.
3.
4.
5.
Others (see addendum)

Step 2. **CONSTRUCT A LOGIC DIAGRAM**

This section will guide you through construction of a logic diagram. Even simple logic diagrams can become long and cumbersome. For this reason, it is impossible to make enough fill-in blocks on this worksheet to accommodate the many possible entities that may be introduced. Use the instructions as a guide and build the logic diagram using post-it notes or graphical software.

Step 2.1 **IDENTIFY CHIEF UNDESIRABLE EFFECTS**

See Refined Problem Description. If the problem is type 1 or 2, then the undesirable terminal effects should be defined. If the problem is type 3, identify the terminal desirable effect that must be improved. If the terminal effect is a measurement (type 4), determine the entity to be measured.

Types of problems:

1. A failure or drawback must be eliminated/corrected:
2. The root causes of a failure or drawback must be discovered (Failure Analysis):
3. A product/process or its part/operation must be improved:
4. Information about an object's condition must be detected:

Copy Refined Problem Description here (from Step 1.3.1)

For Type 1 or 2 Problems, list the top five undesirable effects:
1.
2.
3.
4.
5.

For Type 3 Problems, list the terminal desirable effect:

For Type 4 Problems, list the entity to be measured:

Step 2.2 DRAW THE LOGIC DIAGRAM

Step 2.2.1 CONNECTING ENTITIES

Step 2.2.1.1 CODE THE ENTITIES

List each known entity. In practice, this is a recursive process. At first, you may only list the terminal effects, next you construct their causal entities, then you determine the causes of the causal entities and so on. Since causation is addressed in the next step (2.2.1.2), you will have to work back and forth between these two steps. If you run out of room, continue on the addendum sheet.

Code each entity as Quantitative or Qualitative:

Entity	Quantitative or Qualitative
101.	L- Logical/Qualitative
102.	L- Logical/Qualitative
103.	L- Logical/Qualitative
104.	L- Logical/Qualitative
105.	L- Logical/Qualitative
106.	L- Logical/Qualitative
107.	L- Logical/Qualitative
108.	L- Logical/Qualitative
109.	L- Logical/Qualitative
301.	L- Logical/Qualitative
202.	L- Logical/Qualitative
203.	L- Logical/Qualitative
204.	L- Logical/Qualitative
205.	L- Logical/Qualitative
206.	L- Logical/Qualitative
207.	L- Logical/Qualitative
208.	L- Logical/Qualitative
209.	L- Logical/Qualitative
301.	L- Logical/Qualitative
302.	L- Logical/Qualitative
Others (see addendum)	

Step 2.2.1.2 IDENTIFY CONNECTIONS BETWEEN ENTITIES

For each effect, ask, "What causes this to occur?"
After listing the suspected causal entities, ask for each one.
"If the cause occurs, will the effect occur without any other stimulus?"

"Can the effect occur without the stated cause, given that other causes occur?"
"Is there a cumulative or additive effect necessary to cause the desired effect?"
"What is the mathematical relationship between quantitative causes and effects?"
"What is the logical relationship between qualitative causes and effects?"
See also Dittmer's Categories of Legitimate Reservation and additional rules of logic offered.

Cause(s)	Relationship between causes	Effect(s)	Mathematical/Boolean Expression
	AND		ex: $A + B \Rightarrow C, \sim C \Rightarrow D$, *etc.*
	AND		ex: $A + B \Rightarrow C, \sim C \Rightarrow D$, *etc.*
	AND		ex: $A + B \Rightarrow C, \sim C \Rightarrow D$, *etc.*
	AND		ex: $A + B \Rightarrow C, \sim C \Rightarrow D$, *etc.*
	AND		ex: $A + B \Rightarrow C, \sim C \Rightarrow D$, *etc.*
	AND		ex: $A + B \Rightarrow C, \sim C \Rightarrow D$, *etc.*
	AND		ex: $A + B \Rightarrow C, \sim C \Rightarrow D$, *etc.*
	AND		ex: $A + B \Rightarrow C, \sim C \Rightarrow D$, *etc.*
	AND		ex: $A + B \Rightarrow C, \sim C \Rightarrow D$, *etc.*
Others (see addendum)			

Step 2.2.1.3 CODE ENTITIES AS DESIRABLE, UNDESIRABLE OR NEUTRAL

Entity	Desirability
1.	D- Desirable
2.	D- Desirable
3.	D- Desirable
4.	D- Desirable
5.	D- Desirable
6.	D- Desirable
7.	D- Desirable
8.	D- Desirable
9.	D- Desirable
Others (see addendum)	

Step 2.2.1.4 CODE CONTROL OF ENTITIES

Entity	Control
1.	C2- Simple Indirect Control
2.	C2- Simple Indirect Control
3.	C2- Simple Indirect Control
4.	C2- Simple Indirect Control
5.	C2- Simple Indirect Control
6.	C2- Simple Indirect Control
7.	C2- Simple Indirect Control
8.	C2- Simple Indirect Control
9.	C2- Simple Indirect Control
Others (see addendum)	

Step 2.2.2 ASSIGN NUMBERS TO EACH ENTITY.

Entity	Number
1.	101
2.	101
3.	101
4.	101
5.	101
6.	101
7.	101
8.	101

9.	101
Others (see addendum)	

Step 2.2.3 **SUMMARY OF THE ENTITY CODE SCHEME**

D- U- N-	101 102 Etc.	Q L	-C1 -C2 -C3 -C4 -C5

First position (desirability):

"D-" for desirable entities

"U-" for undesirable entities

"N-" for neutral entities.

Second position (Indenture):

First digit represents where it is in the logic of the system (100- terminal effect, 200- immediate causes of terminal effect and so on)

Second two digits are sequentially ordered (01, 02, 03…99)

Third position (variable type)-

Q- quantitative

L- logical or Boolean

Fourth Position (control)

-C1 for entities under *direct* control

-C2 for entities under *indirect* control

-C3 for entities that are controlled by an outside source or agency.

-C4 for entities that are controlled by nature or are "given" for the problem.

-C5 for entities completely outside of sphere of influence.

List all entities

Entity	Unique Nomenclature
1.	D-101-L -C1
2.	D-101-L -C1
3.	D-101-L -C1
4.	D-101-L -C1
5.	D-101-L -C1
6.	D-101-L -C1
7.	D-101-L -C1
8.	D-101-L -C1
9.	D-101-L -C1
Others (see addendum)	

Step 2.2.4 **TEST THE LOGIC DIAGRAM USING THE RULES OF LOGIC.**

1. ☐Clarity (seeking to understand)
   a. Would I add any verbal explanation if reading the tree to someone else?
   b. Is the meaning/context of words unambiguous?
   c. Is the connection cause and effect convincing "at face value"?
   d. Are intermediate steps missing?
2. ☐Entity Existence (Complete, properly structured, valid statements of cause and effect)
   a. Is it a complete sentence?
   b. Does it make sense?
   c. Is it free from "if-then" statements?
   d. Does it convey only one idea (i.e. not compound entity)?
   e. Does it exist in my reality?
3. ☐Causality existence (Logical connection between cause and effect)
   a. Does an "if then" connection really exist, as written?
   b. Does the cause, in fact, result in the effect?

c. Does it make sense when read aloud exactly as written?
d. Is the cause intangible? (if so, look for additional predicted effect)

4. ☐Cause insufficiency (A nontrivial dependent element missing)
   a. Can the cause, as written, result in the effect on its own?
   b. Are there any significant cause factors missing?
   c. Is/are the written cause(s) sufficient to justify all parts of the effect(s)?
   d. Is an ellipse *(an AND Gate)* required?
5. ☐Additional cause (A separate, independent cause producing the same effect)
   a. Is there anything else that might cause the effect on its own? *(Missing OR Gate)*
   b. If the stated cause is eliminated, will the effect be almost completely eliminated?
6. ☐Cause-effect reversal (Arrow pointing in the wrong direction)
   a. Is the stated effect really the cause and vice versa?
   b. Is the stated cause the reason why or just how we know the effect exists?
7. ☐Predicted effect existence (Additional corroborating effect resulting from cause)
   a. Is the cause intangible?
   b. Do other unavoidable outcomes exist besides the stated effect?
8. ☐Tautology (Circular logic)
   a. Is the cause intangible?
   b. Is the effect offered as a rationale for the existence of the cause?
   c. Do other unavoidable outcomes exist besides the stated effect?

In addition to these logical rules, a few more are required for this approach.

9. ☐Check that all variables are of the right type, Boolean or Quantitative.
10. ☐Check that Quantitative variables are converted to Boolean variables before entering a AND, OR, XOR or NOT gates.
11. ☐Check that Boolean variables are converted to Quantitative variables before entering MAG AND gates.
12. ☐Check that there is a "machinery" input entity for each entity that requires a piece of equipment to operate.

Step 2.2.5 **COMPLETE THE LOGIC DIAGRAM**

Draw the Logic Diagram on a separate sheet and paste here.

Step 3. **ANALYZE LOGIC DIAGRAM TO FIND THE CONSTRAINTS OF THE SYSTEM**

Step 3.1 **FIND THE SWITCHES FOR THE SYSTEM**

Terminal Effects Name	Identification	Directly Controllable?	Switch(es)	Level of Control for each switch
1.	D-101-L -C1	☐ Yes ☒ No		☒ C1 ☐ C2 ☐ C3 ☒ C1 ☐ C2 ☐ C3 ☒ C1 ☐ C2 ☐ C3 ☐ C1 ☒ C2 ☐ C3 ☐ C1 ☒ C2 ☐ C3
2.	D-101-L -C1	☐ Yes ☒ No		☒ C1 ☐ C2 ☐ C3 ☒ C1 ☐ C2 ☐ C3 ☒ C1 ☐ C2 ☐ C3 ☐ C1 ☒ C2 ☐ C3 ☐ C1 ☒ C2 ☐ C3
3.	D-101-L -C1	☐ Yes ☒ No		☒ C1 ☐ C2 ☐ C3 ☒ C1 ☐ C2 ☐ C3 ☒ C1 ☐ C2 ☐ C3 ☐ C1 ☒ C2 ☐ C3 ☐ C1 ☒ C2 ☐ C3
4.	D-101-L -C1	☐ Yes ☒ No		☒ C1 ☐ C2 ☐ C3 ☒ C1 ☐ C2 ☐ C3 ☒ C1 ☐ C2 ☐ C3 ☐ C1 ☒ C2 ☐ C3

				☐ C1 ☒ C2 ☐ C3
5.	D-101-L -C1	☐ Yes ☒ No		☒ C1 ☐ C2 ☐ C3 ☒ C1 ☐ C2 ☐ C3 ☒ C1 ☐ C2 ☐ C3 ☐ C1 ☒ C2 ☐ C3 ☐ C1 ☒ C2 ☐ C3
Others (see addendum)				

Step 3.2 **FOR EACH DE, SEEK TO ENSURE THE LOGICAL VALUE OF THE ENTITY IS = 1.**

Switch		Entities Controlled	Type of control
Name	Identification		
1.	D-101-L -C1		☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1 ☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1 ☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1 ☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1 ☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1 ☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1 ☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1 ☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1
2.	D-101-L -C1		☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1 ☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1 ☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1 ☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1 ☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1 ☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1 ☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1 ☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1
3.	D-101-L -C1		☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1 ☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1 ☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1 ☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1 ☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1 ☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1 ☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1 ☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1
4.	D-101-L -C1		☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1 ☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1 ☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1 ☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1 ☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1 ☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1 ☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1 ☐ = 0 ☐ = 1 ☐ ≠ 0 ☐ ≠ 1
Others (see addendum)			

Step 3.3 **FOR EACH UDE, SEEK TO CREATE THE VALUE OF THE NODE = 0**

Switch		Entities Controlled	Type of control
Name	Identification		

1.	U-101-L -C1		☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1 ☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1 ☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1 ☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1 ☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1 ☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1 ☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1 ☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1
2.	U-101-L -C1		☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1 ☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1 ☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1 ☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1 ☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1 ☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1 ☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1 ☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1
3.	U-101-L -C1		☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1 ☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1 ☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1 ☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1 ☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1 ☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1 ☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1 ☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1
4.	U-101-L -C1		☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1 ☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1 ☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1 ☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1 ☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1 ☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1 ☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1 ☐ =0 ☐ =1 ☐ ≠0 ☐ ≠1
Others (see addendum)			

Step 3.4 IDENTIFY ANY TRADE-OFFS IN THE DESIGN

Type of Contradiction	Entity 1	Entity 2	Reason
UDE Causes DE	1. U-101-L -C1	D-101-L -C1	
	2. U-101-L -C1	D-101-L -C1	
	3. U-101-L -C1	D-101-L -C1	
	Others (see addendum)		

DE Causes UDE	1. D-101-L -C1	U-101-L -C1	
	2. D-101-L -C1	U-101-L -C1	
	3. D-101-L -C1	U-101-L -C1	
	Others (see addendum)		

UDE Counteracts UDE	1. U-101-L -C1	U-101-L -C1	
	2. U-101-L -C1	U-101-L -C1	
	3. U-101-L -C1	U-101-L -C1	
	Others (see addendum)		

DE Counteracts DE	1. D-101-L -C1	D-101-L -C1	
	2. D-101-L -C1	D-101-L -C1	
	3. D-101-L -C1	D-101-L -C1	
	Others (see addendum)		

Step 3.5 **REVIEW TOTAL SYSTEM**

Identify Root Causes and Core Problems
Root Causes:

	Root Cause (Check if selected)	UDEs Produced	Produces 70% or more of UDEs?	Related to other Root Cause? (List)
1.	☒ D-101-L -C1 ☐ Sphere of control (C1, C2) ☐ Span of Influence (C3) ☐ Neither (C4, C5)	U-101-L -C1 U-101-L -C1 U-101-L -C1 U-101-L -C1 U-101-L -C1	☐ Yes ☐ No ☐ Yes with others marked	☐ Yes ☐ No U-101-L -C1 U-101-L -C1 U-101-L -C1 U-101-L -C1
2.	☒ D-101-L -C1 ☐ Sphere of control (C1, C2) ☐ Span of Influence (C3) ☐ Neither (C4, C5)	U-101-L -C1 U-101-L -C1 U-101-L -C1 U-101-L -C1 U-101-L -C1	☐ Yes ☐ No ☐ Yes with others marked	☐ Yes ☐ No U-101-L -C1 U-101-L -C1 U-101-L -C1 U-101-L -C1
3.	☒ D-101-L -C1 ☐ Sphere of control (C1, C2) ☐ Span of Influence (C3) ☐ Neither (C4, C5)	U-101-L -C1 U-101-L -C1 U-101-L -C1 U-101-L -C1 U-101-L -C1	☐ Yes ☐ No ☐ Yes with others marked	☐ Yes ☐ No U-101-L -C1 U-101-L -C1 U-101-L -C1 U-101-L -C1
4.	☒ D-101-L -C1 ☐ Sphere of control (C1, C2) ☐ Span of Influence (C3) ☐ Neither (C4, C5)	U-101-L -C1 U-101-L -C1 U-101-L -C1 U-101-L -C1 U-101-L -C1	☐ Yes ☐ No ☐ Yes with others marked	☐ Yes ☐ No U-101-L -C1 U-101-L -C1 U-101-L -C1 U-101-L -C1
5.	☒ D-101-L -C1 ☐ Sphere of control (C1, C2) ☐ Span of Influence (C3) ☐ Neither (C4, C5)	U-101-L -C1 U-101-L -C1 U-101-L -C1 U-101-L -C1 U-101-L -C1	☐ Yes ☐ No ☐ Yes with others marked	☐ Yes ☐ No U-101-L -C1 U-101-L -C1 U-101-L -C1 U-101-L -C1
	Others (see addendum)			

Step 4. **GENERATE SOLUTIONS AT THE CRITICAL ENTITIES AND TRADE-OFFS**

Summary of Chief Constraints/Problems to be addressed first

Name of Root Cause	Undesirable?	Desirable?	Contradiction?
1. D-101-L -C1	☐ If yes, go to Step 4.1	☐ If yes, go to Step 4.2	☐ If yes, go to Step 4.3
Notes:			
2. D-101-L -C1	☐ If yes, go to Step 4.1	☐ If yes, go to Step 4.2	☐ If yes, go to Step 4.3
Notes:			
3. D-101-L -C1	☐ If yes, go to Step 4.1	☐ If yes, go to Step 4.2	☐ If yes, go to Step 4.3
Notes:			
4. D-101-L -C1	☐ If yes, go to Step 4.1	☐ If yes, go to Step 4.2	☐ If yes, go to Step 4.3
Notes:			
5. D-101-L -C1	☐ If yes, go to Step 4.1	☐ If yes, go to Step 4.2	☐ If yes, go to Step 4.3
Notes:			
Others (see addendum)			

Name of Terminal Effect	Desirable?	Notes
1. D-101-L -C1	☐ If yes, go to Step 4.4	
2. D-101-L -C1	☐ If yes, go to Step 4.4	
3. D-101-L -C1	☐ If yes, go to Step 4.4	
4. D-101-L -C1	☐ If yes, go to Step 4.4	
5. D-101-L -C1	☐ If yes, go to Step 4.4	
Others (see addendum)		

Parent relationships

Step 4.1 **IF A PARTICULAR CRITICAL ENTITY MUST BE "TURNED OFF," THEN FOLLOW I-TRIZ SOLUTION RECOMMENDATIONS FOR UDE.**

Refer to Methodology or Innovation Workbench 2000 for the Names and descriptions of the child relations, grandchild relations and operators. Next, list your approach using the chosen operator(s) in the comments.

1. Name of UDE

U-101-L -C1

Child Relation

Grandchild Relation

Operator

Comments

2. Name of UDE

U-101-L -C1

Child Relation

Grandchild Relation

Operator

Comments

3. Name of UDE

U-101-L -C1

Child Relation

Grandchild Relation

Operator

Comments

4. Name of UDE U-101-L -C1 Child Relation Grandchild Relation Operator Comments
5. Name of UDE U-101-L -C1 Child Relation Grandchild Relation Operator Comments
Others (see addendum)

Step 4.2 IF A PARTICULAR CRITICAL ENTITY MUST BE "TURNED ON," THEN FOLLOW I-TRIZ SOLUTION RECOMMENDATIONS FOR DE.

Refer to Methodology or Innovation Workbench 2000 for the Names and descriptions of the child relations, grandchild relations and operators. Next, list your approach using the chosen operator(s) in the comments.

1. Name of DE D-101-L -C1 Child Relation Grandchild Relation Operator Comments
2. Name of DE D-101-L -C1 Child Relation Grandchild Relation Operator Comments

3. Name of DE D-101-L -C1 Child Relation Grandchild Relation Operator Comments
4. Name of DE D-101-L -C1 Child Relation Grandchild Relation Operator Comments
5. Name of DE D-101-L -C1 Child Relation Grandchild Relation Operator Comments
Others (see addendum)

Step 4.3 **IF THERE IS A CONTRADICTION, THEN FOLLOW THE I-TRIZ SOLUTION RECOMMENDATIONS FOR CONTRADICTIONS.**

Refer to Methodology or Innovation Workbench 2000 for the Names and descriptions of the child relations, grandchild relations and operators. Next, list your approach using the chosen operator(s) in the comments.

1. Type of contradiction: ☐ UDE Causes DE ☐ DE Causes UDE ☐ UDE Counteracts UDE ☐ DE Counteracts DE Cause: D-101-L -C1 Effect: D-101-L -C1 Child Relation Grandchild Relation Operator Comments

2. Type of contradiction: ☐ UDE Causes DE ☐ DE Causes UDE ☐ UDE Counteracts UDE ☐ DE Counteracts DE

Cause: D-101-L -C1
Effect: D-101-L -C1
Child Relation

Grandchild Relation

Operator

Comments

3. Type of contradiction: ☐ UDE Causes DE ☐ DE Causes UDE ☐ UDE Counteracts UDE ☐ DE Counteracts DE

Cause: D-101-L -C1
Effect: D-101-L -C1
Child Relation

Grandchild Relation

Operator

Comments

4. Type of contradiction: ☐ UDE Causes DE ☐ DE Causes UDE ☐ UDE Counteracts UDE ☐ DE Counteracts DE

Cause: D-101-L -C1
Effect: D-101-L -C1
Child Relation

Grandchild Relation

Operator

Comments

5. Type of contradiction: ☐ UDE Causes DE ☐ DE Causes UDE ☐ UDE Counteracts UDE ☐ DE Counteracts DE

Cause: D-101-L -C1
Effect: D-101-L -C1
Child Relation

Grandchild Relation

Operator

Comments

Others (see addendum)

Step 4.4 IF THE DESIGN ONLY HAS DESIRABLE ENTITIES, THEN CONSIDER THE I-TRIZ SOLUTION RECOMMENDATIONS FOR INCREASING THE LEVEL OF IDEALITY OF THE SYSTEM

Refer to Methodology or Innovation Workbench 2000 for the Names and descriptions of the child relations, grandchild relations and operators. Next, list your approach using the chosen operator(s) in the comments.

1. Name of Desirable Terminal Effect D-101-L -C1 Child Relation Grandchild Relation Operator Comments
2. Name of Desirable Terminal Effect D-101-L -C1 Child Relation Grandchild Relation Operator Comments
3. Name of Desirable Terminal Effect D-101-L -C1 Child Relation Grandchild Relation Operator Comments
4. Name of Desirable Terminal Effect D-101-L -C1 Child Relation Grandchild Relation Operator Comments
5. Name of Desirable Terminal Effect D-101-L -C1 Child Relation Grandchild Relation Operator Comments
Others (see addendum)

Summary of total solution:

APPENDIX C. AIRLIFT LOADING SYSTEM CASE STUDY COST ANALYSIS

Purpose

The purpose of this cost analysis is to provide an objective analysis of the proposed Multiple Level Airlift Loading Systems in terms of Return on Investment (ROI) and Measures of Merit (MoM). There are two different proposed configurations of the Multiple Level Airlift Loading System, the Bi-Level System and the Poly-Level System. This study therefore will compare three different possible configurations:

- Status quo- airlifting supplies without a loading system
- Multiple Level Airlift Loading System with two pallet positions (Design #1)
- Multiple Level Airlift Loading System with ten pallet positions (Design #2)

Measures of Merit

This study compares the three loading system configurations with regard to the following parameters:

- Cost
- Volume
- Footprint
- Weight

Cost

Goal

The goal of the Cost Merit of Measure is to minimize cost over the life cycle without sacrificing payload.

Cost of Development (COD)

The Cost Of Development (COD) is unknown at his time for Design #1 and Design #2. COD for status quo is zero. For comparison, ROI will be used to calculate the maximum permissible COD in order for Design #1 and Design #2 to be preferable.

Cost of Manufacture (COM)

The Cost Of Manufacture (COM) is unknown at his time for Design #1 and Design #2. COM for status quo is zero. For comparison, ROI will be used to calculate the maximum permissible COM in order for Design #1 and Design #2 to be preferable.

Cost Per Mission (CPM)

Cost Per Mission (CPM) is a function of number of planes, type of planes and length of trips. This study assumes that there are 10 trips per year as defined in the ten mission scenarios. There are four types of planes available, referred to as Planes 1, 2, 3 and 4.

The following costs per flight hour and number of pallets are given:

Aircraft	Number of pallets	Cost per flight hour
Plane 1	5	\$ 3,570
Plane 2	11	\$ 6,000
Plane 3	15	\$ 6,460
Plane 4	30	\$ 14,600

There is only one kind of pallet available. Because of considerable capital investment and compatibility with cargo hold securing units, it must be used. Each pallet is 96 inches wide by 96 inches deep. Each pallet weighs 300 pounds. Each pallet position has a capacity of 12,000 pounds.

The cargo hold area is 120 inches tall.

There are ten airlift missions per year, ranging from 15 to 25 flight hours each. Some missions can use any combination of the four aircraft, while others may only certain types of aircraft, as shown below:

Mission	One way flight time	Aircraft used
Mission 1	15 hrs	Planes 1 and 3
Mission 2	16 hrs	Planes 3 and 4
Mission 3	17 hrs	Plane 4
Mission 4	18 hrs	Plane 4

Mission	One way flight time	Aircraft used
Mission 5	19 hrs	Mixed
Mission 6	20 hrs	Planes 3 and 4
Mission 7	21 hrs	Plane 1
Mission 8	22 hrs	Planes 2 and 3
Mission 9	23 hrs	Planes 3 and 4
Mission 10	24 hrs	Mixed

Cargo is not stackable. Different kinds of cargo may not be mixed on a pallet. Ten cargo configuration scenarios are defined:

Scenario 1	Size 1	Size 2
Number of Pallets	32 pallets	40 pallets
Number of Boxes per Pallet	2	1
Number of Boxes	64 boxes	40 boxes
Size of box-width	48.0 in	96.0 in
Size of box-depth	96.0 in	96.0 in
Size of box-height	24.0 in	24.0 in
Volume per box	64.0 ft3	128.0 ft3
Total Volume	4096.0 ft3	5120.0 ft3
Weight per box	1,088 lb	2,176 lb
Total Weight	69,632 lb	87,040 lb

SCENARIO 2	Size 1	Size 2	Size 3
Number of Pallets	12 pallets	40 pallets	40 pallets
Number of Boxes per Pallet	9	3	1
Number of Boxes	108 boxes	120 boxes	40 boxes
Size of box-width	32.0 in	32.0 in	96.0 in
Size of box-depth	32.0 in	80.0 in	88.0 in
Size of box-height	30.0 in	36.0 in	20.4 in
Volume per box	17.8 ft3	53.3 ft3	99.7 ft3
Total Volume	1920.0 ft3	6400.0 ft3	3989.3 ft3
Weight per box	302 lb	907 lb	1,695 lb
Total Weight	32,640 lb	108,800 lb	67,819 lb

Scenario 3	Size 1
Number of Pallets	140 pallets
Number of Boxes per Pallet	1
Number of Boxes	140 boxes
Size of box-width	50.0 in
Size of box-depth	60.0 in
Size of box-height	40.0 in
Volume per box	69.4 ft3
Total Volume	9722.2 ft3
Weight per box	1,181 lb
Total Weight	165,278 lb

Scenario 4	Size 1	Size 2	Size 3
Number of Pallets	32 pallets	40 pallets	12 pallets
Number of Boxes per Pallet	1	2	3
Number of Boxes	32 boxes	80 boxes	36 boxes
Size of box-width	90.0 in	48.0 in	50.0 in
Size of box-depth	88.0 in	88.0 in	32.0 in
Size of box-height	20.4 in	88.0 in	36.0 in
Volume per box	93.5 ft3	215.1 ft3	33.3 ft3
Total Volume	2992.0 ft3	17208.9 ft3	1200.0 ft3
Weight per box	1,590 lb	3,657 lb	567 lb
Total Weight	50,864 lb	292,551 lb	20,400 lb

Scenario 5	Size 1	Size 2	Size 3
Number of Pallets	32 pallets	120 pallets	55 pallets
Number of Boxes per Pallet	2	3	1
Number of Boxes	64 boxes	360 boxes	55 boxes
Size of box-width	54.0 in	32.0 in	96.0 in
Size of box-depth	40.0 in	40.0 in	88.0 in
Size of box-height	20.4 in	40.0 in	30.0 in
Volume per box	25.5 ft3	29.6 ft3	146.7 ft3
Total Volume	1632.0 ft3	10666.7 ft3	8066.7 ft3
Weight per box	434 lb	504 lb	2,493 lb
Total Weight	27,744 lb	181,333 lb	137,133 lb

Scenario 6	Size 1	Size 2	Size 3
Number of Pallets	35 pallets	35 pallets	40 pallets
Number of Boxes per Pallet	2	2	1
Number of Boxes	70 boxes	70 boxes	40 boxes
Size of box-width	50.0 in	50.0 in	88.0 in
Size of box-depth	40.0 in	30.0 in	88.0 in
Size of box-height	10.0 in	30.0 in	30.0 in
Volume per box	11.6 ft3	26.0 ft3	134.4 ft3
Total Volume	810.2 ft3	1822.9 ft3	5377.8 ft3
Weight per box	197 lb	443 lb	2,286 lb
Total Weight	13,773 lb	30,990 lb	91,422 lb

Scenario 7	Size 1	Size 2
Number of Pallets	15 pallets	70 pallets
Number of Boxes per Pallet	2	1
Number of Boxes	30 boxes	70 boxes
Size of box-width	48.0 in	96.0 in
Size of box-depth	96.0 in	96.0 in
Size of box-height	24.0 in	24.0 in
Volume per box	64.0 ft3	128.0 ft3
Total Volume	1920.0 ft3	8960.0 ft3
Weight per box	1,088 lb	2,176 lb
Total Weight	32,640 lb	152,320 lb

Scenario 8	Size 1	Size 2	Size 3
Number of Pallets	15 pallets	12 pallets	20 pallets
Number of Boxes per Pallet	9	3	1
Number of Boxes	135 boxes	36 boxes	20 boxes
Size of box-width	32.0 in	32.0 in	96.0 in
Size of box-depth	32.0 in	80.0 in	88.0 in
Size of box-height	30.0 in	36.0 in	20.4 in
Volume per box	17.8 ft3	53.3 ft3	99.7 ft3
Total Volume	2400.0 ft3	1920.0 ft3	1994.7 ft3
Weight per box	302 lb	907 lb	1,695 lb
Total Weight	40,800 lb	32,640 lb	33,909 lb

Scenario 9	Size 1
Number of Pallets	95 pallets
Number of Boxes per Pallet	1
Number of Boxes	95 boxes
Size of box-width	50.0 in
Size of box-depth	60.0 in
Size of box-height	40.0 in
Volume per box	69.4 ft3
Total Volume	6597.2 ft3
Weight per box	1,181 lb
Total Weight	112,153 lb

Scenario 10	Size 1	Size 2	Size 3
Number of Pallets	68 pallets	21 pallets	45 pallets
Number of Boxes per Pallet	1	2	3
Number of Boxes	68 boxes	42 boxes	135 boxes
Size of box-width	90.0 in	48.0 in	50.0 in
Size of box-depth	88.0 in	88.0 in	32.0 in
Size of box-height	20.4 in	88.0 in	36.0 in
Volume per box	93.5 ft3	215.1 ft3	33.3 ft3
Total Volume	6358.0 ft3	9034.7 ft3	4500.0 ft3
Weight per box	1,590 lb	3,657 lb	567 lb
Total Weight	108,086 lb	153,589 lb	76,500 lb

Equations to calculate cost per mission for the status quo are discussed in the Airlift Loading System Case Study.

For Designs 1 and 2, the number of pallet positions required is diminished, thereby changing the number of planes necessary for mission success. The new equation for the number of pallet positions required for Design #1 is:

IF $H_{CONTAINER} \geq 50$ inches, $PP_{DESIGN\ \#1} = PP_{STATUS\ QUO}$, $PP_{DESIGN\ \#1}$ = CEILING ($PP_{STATUS\ QUO} \div 2$, 1)

Where:

$H_{CONTAINER}$ is the height of the container

$PP_{DESIGN\ \#1}$ is the number of pallet positions needed for Design #1 and

$PP_{STATUS\ QUO}$ is the number of pallet positions needed for Status Quo.

The new equations for the number of pallet positions required for Design #2 is:

$D_{SHELVES}$ = 12*CEILING (($H_{CONTAINER}$ +1)/12,1)

Where:

$D_{SHELVES}$ is the distance between shelves

$N_{PALLETS}$ = IF ($D_{SHELVES}$ = 12, 10
$D_{SHELVES}$ = 24, 5
$D_{SHELVES}$ = 36, 4
$D_{SHELVES}$ = 48, 3
$D_{SHELVES}$ = 60, 2
$D_{SHELVES}$ > 60, 1)

Where:

$N_{PALLETS}$ is the number of pallets on each loading system

$PP_{DESIGN\ \#2}$ = CEILING ($PP_{STATUS\ QUO} \div N_{PALLETS}$, 1)

Where:

$PP_{DESIGN\ \#2}$ is the number of pallet positions needed for Design #2

Cost per year of Operation (CYO)

Cost per year of Operation (CYO) = ΣCPM for all 10 missions

LCC over a 20 Year Period

LCC = COD + COM + CYO (P/A, 10%, 20 years)

Where CYO (P/A, 10%, 20 years) means: given an annual rate of CYO, disbursed once a year for 20 years at an interest rate of 10%, calculate the Present Value of the money.

From earlier discussion:

- COD and COM = 0 for status quo,
- COM and COM are unknown for Designs 1 and 2

Therefore,

- LCC_{SQ} = CYOSQ (P/A, 10%, 20 years)
- $LCC_{DESIGN\ \#1} = COM_{DESIGN\ \#1} + CYO_{DESIGN\ \#1}$ (P/A, 10%, 20 years)
- $LCC_{DESIGN\ \#2} = COM_{DESIGN\ \#2} + CYO_{DESIGN\ \#2}$ (P/A, 10%, 20 years)

Volume

The objective for volume is to use as much of the available volume onboard the plane as possible. Since each pallet position is 96 inches wide by 96 inches deep by 120 inches tall, the available volumetric capacity per plane is:

Plane 1	3,200 ft^3
Plane 2	7,040 ft^3
Plane 3	9,600 ft^3
Plane 4	19,200 ft^3

Percentage Capacity used by Volume (PCV) = Volume used by cargo ÷ Total Available Volumetric Capacity * 100%

Footprint

The footprint is defined as the area of floor space available for loading. For Design #1, the footprint can be doubled. For Design #2, the footprint may be increased up to 10 fold, depending on the height of the cargo.

Aircraft	Number of Pallet positions	Foot print, Status quo	Foot print, Design #1	Foot print, Design #2
Plane 1	5	3,840 ft^2	Up to 7,680 ft^2	Up to 38,400 ft^2
Plane 2	11	8,448 ft^2	Up to 16,896 ft^2	Up to 84,480 ft^2
Plane 3	15	11,520 ft^2	Up to 23,040 ft^2	Up to 115,200 ft^2
Plane 4	30	23,040 ft^2	Up to 46,080 ft^2	Up to 230,400 ft^2

Weight

With aircraft, the overall objective with regard to weight is that it should be kept to a minimum. For the purposes of this comparison, there is no weight consideration given for the cost of a mission so long as the weight is kept below 12,000 pounds per pallet position.

For the BALS loading systems, the weight capacity of the load is diminished by the weight of the loading system. Given that:

- Each pallet weighs 300 pounds
- Design #1 weighs 500 pounds (1,100 pounds with 2 pallets)
- Design #2 weighs 500 pounds (from 800 pounds with one pallet to 3,500 pounds with 10 pallets)

The following table shows the amount of weight available for cargo with each configuration:

		Weight Available, fully loaded		
Aircraft	Number of pallets	Status quo	Design #1	Design #2
Plane 1	5	58,500 lb	54,500 lb	42,500 lb
Plane 2	11	128,700 lb	119,900 lb	93,500 lb
Plane 3	15	175,500 lb	163,500 lb	127,500 lb
Plane 4	30	351,000 lb	327,000 lb	255,000 lb

Mission Scenarios

Ten mission scenarios were chosen to compare the three configurations. Each scenario is analyzed for the following:

1. Lowest possible cost
2. Volumetric capacity
3. Weight capacity
4. Footprint

The missions and their results are shown below.

Mission 1

Mission 1 description

Scenario 1 is comprised of 104 non-stackable boxes of two different sizes that fit onto 72 pallets and use approximately 19% of the volumetric capacity of the aircraft.

Scenario 1	Size 1	Size 2
Number of Pallets	32 pallets	40 pallets
Number of Boxes per Pallet	2	1
Number of Boxes	64 boxes	40 boxes
Size of box-width	48.0 in	96.0 in
Size of box-depth	96.0 in	96.0 in
Size of box-height	24.0 in	24.0 in
Volume per box	64.0 ft^3	128.0 ft^3
Total Volume	4096.0 ft^3	5120.0 ft^3
Weight per box	1,088 lb	2,176 lb
Total Weight	69,632 lb	87,040 lb

Mission 1 is 15 hours one-way (30 hours round trip) and uses Planes 1 and 3.

Mission 1 analysis

Using the equations above the following results are obtained for Mission 1:

Mission 1	Status quo	Design #1	Design #2
Number of pallet positions required	72 pallets	36 pallets	18 pallets
Number of Plane 1s needed	0 Plane(s)	0 Plane(s)	1 Plane(s)
Number of Plane 2s needed	0 Plane(s)	0 Plane(s)	0 Plane(s)
Number of Plane 3s needed	5 Plane(s)	3 Plane(s)	1 Plane(s)
Number of Plane 4s needed	0 Plane(s)	0 Plane(s)	0 Plane(s)
Number of pallet positions available	75 pallet positions	45 pallet positions	20 pallet positions
Cost per mission (CPM)	$2,190,000	$1,314,000	$545,100
Savings over status quo- 1 trip		$876,000	$1,644,900
Volumetric capacity	48,000 ft3	28,800 ft3	12,800 ft3
Percentage capacity used by volume (PCV)	19%	32%	72%
Weight capacity	900,000 lb	540,000 lb	240,000 lb
Weight of load, pallets and loading systems	178,272 lb	196,272 lb	187,272 lb
Percentage capacity used by weight (PCW)	20%	36%	78%
CYO (P/A, 10%, 20yr)	-$20,509,175	-$12,305,505	-$5,104,818
Savings over status quo		$8,203,670	$15,404,357
Savings of Design #2 over Design #1			$7,200,687
Savings per loading system unit over status quo		$227,880	$855,798
Savings Design #2 over Design #1 per loading system			$400,038
Footprint	4,800 ft2	2,880 ft2	1,280 ft2

Mission 1, lowest possible cost

The best choice for this mission is Design #2.

Design #1 saves $8.2 million present value dollars over the status quo over a 20-year period at 10% interest. In one trip, the 36 units save $876 thousand over status quo, less the cost of manufacture and cost of development. If the cost of development and the cost of manufacture for 36 units is less than $876 thousand, Design #1 is superior to the status quo.

Design #2 saves $15.4 million present value dollars over the status quo over a 20-year period at 10% interest. In one trip, the 18 units save $1644.9 thousand over status quo, less the cost of manufacture and cost of development. If the cost of development and the cost of manufacture for 18 units is less than $1644.9 thousand, Design #2 is superior to the status quo.

Volumetric capacity

Status quo uses 19% of its volumetric capacity.
Design #1 uses 32% of its volumetric capacity.
Design #2 uses 72% of its volumetric capacity.

Weight capacity

Status quo uses 20% of its weight capacity.
Design #1 uses 36% of its weight capacity.
Design #2 uses 78% of its weight capacity.

Footprint

The footprint of Status quo is 4800 ft2.
The footprint of Design #1 is 2880 ft2.
The footprint of Design #2 is 1280 ft2.

Mission 2

Mission 2 description

Scenario 2 is comprised of 268 non-stackable boxes of three different sizes that fit onto 92 pallets and use approximately 18% of the volumetric capacity of the aircraft.

Scenario 2	Size 1	Size 2	Size 3
Number of Pallets	12 pallets	40 pallets	40 pallets
Number of Boxes per Pallet	9	3	1
Number of Boxes	108 boxes	120 boxes	40 boxes
Size of box-width	32.0 in	32.0 in	96.0 in
Size of box-depth	32.0 in	80.0 in	88.0 in
Size of box-height	30.0 in	36.0 in	20.4 in
Volume per box	17.8 ft3	53.3 ft3	99.7 ft3
Total Volume	1920.0 ft3	6400.0 ft3	3989.3 ft3
Weight per box	302 lb	907 lb	1,695 lb
Total Weight	32,640 lb	108,800 lb	67,819 lb

Mission 2 is 16 hours one-way (32 hours round trip) and uses Planes 3 and 4.

Mission 2 analysis

Using the equations above the following results are obtained for Mission 2:

Mission 2	Status quo	Design #1	Design #2
Number of pallet positions required	92 pallets	46 pallets	25 pallets
Number of Plane 1s needed	0 Plane(s)	0 Plane(s)	0 Plane(s)
Number of Plane 2s needed	0 Plane(s)	0 Plane(s)	0 Plane(s)
Number of Plane 3s needed	7 Plane(s)	4 Plane(s)	2 Plane(s)
Number of Plane 4s needed	0 Plane(s)	0 Plane(s)	0 Plane(s)
Number of pallet positions available	105 pallet positions	60 pallet positions	30 pallet positions
Cost per mission (CPM)	$3,270,400	$1,868,800	$934,400
Savings over status quo- 1 trip		$1,401,600	$2,336,000
Volumetric capacity	67,200 ft3	38,400 ft3	19,200 ft3
Percentage capacity used by volume (PCV)	18%	32%	64%
Weight capacity	1,260,000 lb	720,000 lb	360,000 lb
Weight of load, pallets and loading systems	236,859 lb	259,859 lb	249,959 lb

Mission 2	Status quo	Design #1	Design #2
Percentage capacity used by weight (PCW)	19%	36%	69%
CYO (P/A, 10%, 20yr)	-$30,627,035	-$17,501,163	-$8,750,581
Savings over status quo		$13,125,872	$21,876,453
Savings of Design #2 over Design #1			$8,750,581
Savings per loading system unit over status quo		$285,345	$875,058
Savings Design #2 over Design #1 per loading system			$350,023
Footprint	6,720 ft2	3,840 ft2	1,920 ft2

Mission 2, lowest possible cost

The best choice for this mission is Design #2.

Design #1 saves $13.13 million present value dollars over the status quo over a 20-year period at 10% interest. In one trip, the 46 units save $1401.6 thousand over status quo, less the cost of manufacture and cost of development. If the cost of development and the cost of manufacture for 46 units is less than $1401.6 thousand, Design #1 is superior to the status quo.

Design #2 saves $21.88 million present value dollars over the status quo over a 20-year period at 10% interest. In one trip, the 25 units save $2336 thousand over status quo, less the cost of manufacture and cost of development. If the cost of development and the cost of manufacture for 25 units is less than $2336 thousand, Design #2 is superior to the status quo.

Volumetric capacity

Status quo uses 18% of its volumetric capacity.

Design #1 uses 32% of its volumetric capacity.

Design #2 uses 64% of its volumetric capacity.

Weight capacity

Status quo uses 19% of its weight capacity.

Design #1 uses 36% of its weight capacity.

Design #2 uses 69% of its weight capacity.

Footprint

The footprint of Status quo is 6720 ft2.

The footprint of Design #1 is 3840 ft2.

The footprint of Design #2 is 1920 ft2.

Mission 3

Mission 3 description

Scenario 3 is comprised of 140 non-stackable boxes of one size that fits onto 140 pallets and uses approximately 10% of the volumetric capacity of the aircraft.

Scenario 3	Size 1
Number of Pallets	140 pallets
Number of Boxes per Pallet	1
Number of Boxes	140 boxes
Size of box-width	50.0 in
Size of box-depth	60.0 in
Size of box-height	40.0 in
Volume per box	69.4 ft3
Total Volume	9722.2 ft3
Weight per box	1,181 lb
Total Weight	165,278 lb

Mission 3 is 17 hours one-way (34 hours round trip) and uses Plane 4.

Mission 3 analysis

Using the equations above the following results are obtained for Mission 3:

Mission 3	Status quo	Design #1	Design #2
Number of pallet positions required	140 pallets	70 pallets	47 pallets
Number of Plane 1s needed	0 Plane(s)	0 Plane(s)	0 Plane(s)
Number of Plane 2s needed	0 Plane(s)	0 Plane(s)	0 Plane(s)
Number of Plane 3s needed	0 Plane(s)	0 Plane(s)	0 Plane(s)
Number of Plane 4s needed	5 Plane(s)	3 Plane(s)	2 Plane(s)
Number of pallet positions available	150 pallet positions	90 pallet positions	60 pallet positions
Cost per mission (CPM)	$2,482,000	$1,489,200	$992,800
Savings over status quo- 1 trip		$992,800	$1,489,200
Volumetric capacity	96,000 ft3	57,600 ft3	38,400 ft3
Percentage capacity used by volume (PCV)	10%	17%	25%
Weight capacity	1,800,000 lb	1,080,000 lb	720,000 lb
Weight of load, pallets and loading systems	207,278 lb	242,278 lb	231,078 lb
Percentage capacity used by weight (PCW)	12%	22%	32%
CYO (P/A, 10%, 20yr)	-$23,243,732	-$13,946,239	-$9,297,493
Savings over status quo		$9,297,493	$13,946,239
Savings of Design #2 over Design #1			$4,648,746
Savings per loading system unit over status quo		$132,821	$296,728
Savings Design #2 over Design #1 per loading system			$98,909
Footprint	9,600 ft2	5,760 ft2	3,840 ft2

Mission 3, lowest possible cost

The best choice for this mission is Design #2.

Design #1 saves $9.3 million present value dollars over the status quo over a 20-year period at 10% interest. In one trip, the 70 units save $992.8 thousand over status quo, less the cost of manufacture and cost of development. If the cost of development and the cost of manufacture for 70 units is less than $992.8 thousand, Design #1 is superior to the status quo.

Design #2 saves $13.95 million present value dollars over the status quo over a 20-year period at 10% interest. In one trip, the 47 units save $1489.2 thousand over status quo, less the cost of manufacture and cost of development. If the cost of development and the cost of manufacture for 47 units is less than $1489.2 thousand, Design #2 is superior to the status quo.

Volumetric capacity

Status quo uses 10% of its volumetric capacity.
Design #1 uses 17% of its volumetric capacity.
Design #2 uses 25% of its volumetric capacity.

Weight capacity

Status quo uses 12% of its weight capacity.
Design #1 uses 22% of its weight capacity.
Design #2 uses 32% of its weight capacity.

Footprint

The footprint of Status quo is 9600 ft2.
The footprint of Design #1 is 5760 ft2.
The footprint of Design #2 is 3840 ft2.

Mission 4

Mission 4 description

Scenario 4 is comprised of 148 non-stackable boxes of three different sizes that fit onto 72 pallets and use approximately 37% of the volumetric capacity of the aircraft.

Scenario 4	Size 1	Size 2	Size 3
Number of Pallets	32 pallets	40 pallets	12 pallets
Number of Boxes per Pallet	1	2	3
Number of Boxes	32 boxes	80 boxes	36 boxes
Size of box-width	90.0 in	48.0 in	50.0 in
Size of box-depth	88.0 in	88.0 in	32.0 in
Size of box-height	20.4 in	88.0 in	36.0 in
Volume per box	93.5 ft3	215.1 ft3	33.3 ft3
Total Volume	2992.0 ft3	17208.9 ft3	1200.0 ft3
Weight per box	1,590 lb	3,657 lb	567 lb
Total Weight	50,864 lb	292,551 lb	20,400 lb

Mission 4 is 18 hours one-way (36 hours round trip) and uses Plane 4.

Mission 4 analysis

Using the equations above the following results are obtained for Mission 4:

Mission 4	Status quo	Design #1	Design #2
Number of pallet positions required	84 pallets	62 pallets	51 pallets
Number of Plane 1s needed	0 Plane(s)	0 Plane(s)	0 Plane(s)
Number of Plane 2s needed	0 Plane(s)	0 Plane(s)	0 Plane(s)
Number of Plane 3s needed	0 Plane(s)	0 Plane(s)	0 Plane(s)
Number of Plane 4s needed	3 Plane(s)	3 Plane(s)	2 Plane(s)
Number of pallet positions available	90 pallet positions	90 pallet positions	60 pallet positions
Cost per mission (CPM)	$1,576,800	$1,576,800	$1,051,200
Savings over status quo- 1 trip		$0	$525,600
Volumetric capacity	57,600 ft3	57,600 ft3	38,400 ft3
Percentage capacity used by volume (PCV)	37%	37%	56%
Weight capacity	1,080,000 lb	1,080,000 lb	720,000 lb
Weight of load, pallets and loading systems	389,015 lb	432,015 lb	415,415 lb
Percentage capacity used by weight (PCW)	36%	40%	58%
CYO (P/A, 10%, 20yr)	-$14,766,606	-$14,766,606	-$9,844,404
Savings over status quo		$0	$4,922,202
Savings of Design #2 over Design #1			$4,922,202
Savings per loading system unit over status quo		$0	$96,514
Savings Design #2 over Design #1 per loading system			$96,514
Footprint	5,760 ft2	5,760 ft2	3,840 ft2

Mission 4, lowest possible cost

The best choice for this mission is Design #2.

Design #1 does not save any money over status quo.

Design #2 saves $4.92 million present value dollars over the status quo over a 20-year period at 10% interest. In one trip, the 51 units save $525.6 thousand over status quo, less the cost of manufacture and cost of development. If the cost of development and the cost of manufacture for 51 units is less than $525.6 thousand, Design #2 is superior to the status quo.

Volumetric capacity

Status quo uses 37% of its volumetric capacity.

Design #1 uses 37% of its volumetric capacity.
Design #2 uses 56% of its volumetric capacity.

Weight capacity

Status quo uses 36% of its weight capacity.
Design #1 uses 40% of its weight capacity.
Design #2 uses 58% of its weight capacity.

Footprint

The footprint of Status quo is 5760 ft2.
The footprint of Design #1 is 5760 ft2.
The footprint of Design #2 is 3840 ft2.

Mission 5

Mission 5 description

Scenario 5 is comprised of 479 non-stackable boxes of three different sizes that fit onto 207 pallets and use approximately 15% of the volumetric capacity of the aircraft.

Scenario 5	Size 1	Size 2	Size 3
Number of Pallets	32 pallets	120 pallets	55 pallets
Number of Boxes per Pallet	2	3	1
Number of Boxes	64 boxes	360 boxes	55 boxes
Size of box-width	54.0 in	32.0 in	96.0 in
Size of box-depth	40.0 in	40.0 in	88.0 in
Size of box-height	20.4 in	40.0 in	30.0 in
Volume per box	25.5 ft3	29.6 ft3	146.7 ft3
Total Volume	1632.0 ft3	10666.7 ft3	8066.7 ft3
Weight per box	434 lb	504 lb	2,493 lb
Total Weight	27,744 lb	181,333 lb	137,133 lb

Mission 5 is 19 hours one-way (38 hours round trip) and may use planes of all four types.

Mission 5 analysis

Using the equations above the following results are obtained for Mission 5:

Mission 5	Status quo	Design #1	Design #2
Number of pallet positions required	207 pallets	104 pallets	61 pallets
Number of Plane 1s needed	0 Plane(s)	0 Plane(s)	1 Plane(s)
Number of Plane 2s needed	0 Plane(s)	0 Plane(s)	0 Plane(s)
Number of Plane 3s needed	14 Plane(s)	7 Plane(s)	4 Plane(s)
Number of Plane 4s needed	0 Plane(s)	0 Plane(s)	0 Plane(s)
Number of pallet positions available	210 pallet positions	105 pallet positions	65 pallet positions
Cost per mission (CPM)	$7,767,200	$3,883,600	$2,354,860
Savings over status quo- 1 trip		$3,883,600	$5,412,340
Volumetric capacity	134,400 ft3	67,200 ft3	41,600 ft3
Percentage capacity used by volume (PCV)	15%	30%	49%
Weight capacity	2,520,000 lb	1,260,000 lb	780,000 lb
Weight of load, pallets and loading systems	408,311 lb	460,611 lb	440,011 lb
Percentage capacity used by	16%	37%	56%

Mission 5	Status quo	Design #1	Design #2
weight (PCW)			
CYO (P/A, 10%, 20yr)	-$72,739,207	-$36,369,604	-$22,053,076
Savings over status quo		$36,369,604	$50,686,132
Savings of Design #2 over Design #1			$14,316,528
Savings per loading system unit over status quo		$349,708	$830,920
Savings Design #2 over Design #1 per loading system			$234,697
Footprint	13,440 ft2	6,720 ft2	4,160 ft2

Mission 5, lowest possible cost

The best choice for this mission is Design #2.

Design #1 saves $36.3‾ million present value dollars over the status quo over a 20-year period at 10% interest. In one trip, the 104 units save $3883.6 thousand over status quo, less the cost of manufacture and cost of development. If the cost of development and the cost of manufacture for 104 units is less than $3883.6 thousand, Design #1 is superior to the status quo.

Design #2 saves $50.69 million present value dollars over the status quo over a 20-year period at 10% interest. In one trip, the 61 units save $5412.34 thousand over status quo, less the cost of manufacture and cost of development. If the cost of development and the cost of manufacture for 61 units is less than $5412.34 thousand, Design #2 is superior to the status quo.

Volumetric capacity

Status quo uses 15% of its volumetric capacity.

Design #1 uses 30% of its volumetric capacity.

Design #2 uses 49% of its volumetric capacity.

Weight capacity

Status quo uses 16% of its weight capacity.

Design #1 uses 3‾% of its weight capacity.

Design #2 uses 56% of its weight capacity.

Footprint

The footprint of Status quo is 13440 ft2.

The footprint of Design #1 is 6‾20 ft2.

The footprint of Design #2 is 4160 ft2.

Mission 6

Mission 6 description

Scenario 6 is comprised of 180 non-stackable boxes of three different sizes that fit onto 110 pallets and use approximately 10% of the volumetric capacity of the aircraft.

Scenario 6	Size 1	Size 2	Size 3
Number of Pallets	35 pallets	35 pallets	40 pallets
Number of Boxes per Pallet	2	2	1
Number of Boxes	‾0 boxes	‾0 boxes	40 boxes
Size of box-width	50.0 in	50.0 in	88.0 in
Size of box-depth	40.0 in	30.0 in	88.0 in
Size of box-height	10.0 in	30.0 in	30.0 in
Volume per box	11.6 ft3	26.0 ft3	134.4 ft3
Total Volume	810.2 ft3	1822.9 ft3	5377.8 ft3
Weight per box	197 lb	443 lb	2,286 lb
Total Weight	13,773 lb	30,990 lb	91,422 lb

Mission 6 is 20 hours one-way (40 hours round trip) and uses Planes 3 and 4.

Mission 6 analysis

Using the equations above the following results are obtained for Mission 6:

Mission 6	Status quo	Design #1	Design #2
Number of pallet positions required	110 pallets	56 pallets	23 pallets
Number of Plane 1s needed	0 Plane(s)	0 Plane(s)	0 Plane(s)
Number of Plane 2s needed	0 Plane(s)	0 Plane(s)	0 Plane(s)
Number of Plane 3s needed	8 Plane(s)	4 Plane(s)	2 Plane(s)
Number of Plane 4s needed	0 Plane(s)	0 Plane(s)	0 Plane(s)
Number of pallet positions available	120 pallet positions	60 pallet positions	30 pallet positions
Cost per mission (CPM)	$4,672,000	$2,336,000	$1,168,000
Savings over status quo- 1 trip		$2,336,000	$3,504,000
Volumetric capacity	76,800 ft3	38,400 ft3	19,200 ft3
Percentage capacity used by volume (PCV)	10%	21%	42%
Weight capacity	1,440,000 lb	720,000 lb	360,000 lb
Weight of load, pallets and loading systems	169,185 lb	197,785 lb	182,485 lb
Percentage capacity used by weight (PCW)	12%	27%	51%
CYO (P/A, 10%, 20yr)	-$43,752,907	-$21,876,453	-$10,938,227
Savings over status quo		$21,876,453	$32,814,680
Savings of Design #2 over Design #1			$10,938,227
Savings per loading system unit over status quo		$390,651	$1,426,725
Savings Design #2 over Design #1 per loading system			$475,575
Footprint	7,680 ft2	3,840 ft2	1,920 ft2

Mission 6, lowest possible cost

Design #1 saves $21.88 million present value dollars over the status quo over a 20-year period at 10% interest. In one trip, the 56 units save $2336 thousand over status quo, less the cost of manufacture and cost of development. If the cost of development and the cost of manufacture for 56 units is less than $2336 thousand, Design #1 is superior to the status quo.

Design #2 saves $32.81 million present value dollars over the status quo over a 20-year period at 10% interest. In one trip, the 23 units save $3504 thousand over status quo, less the cost of manufacture and cost of development. If the cost of development and the cost of manufacture for 23 units is less than $3504 thousand, Design #2 is superior to the status quo.

Volumetric capacity

Status quo uses 10% of its volumetric capacity.
Design #1 uses 21% of its volumetric capacity.
Design #2 uses 42% of its volumetric capacity.

Weight capacity

Status quo uses 12% of its weight capacity.
Design #1 uses 27% of its weight capacity.
Design #2 uses 51% of its weight capacity.

Footprint

The footprint of Status quo is 7680 ft2.
The footprint of Design #1 is 3840 ft2.
The footprint of Design #2 is 1920 ft2.

Mission 7

Mission 7 description

Scenario 7 is comprised of 100 non-stackable boxes of two different sizes that fit onto 85 pallets and use approximately 20% of the volumetric capacity of the aircraft.

Scenario 7	Size 1	Size 2
Number of Pallets	15 pallets	70 pallets
Number of Boxes per Pallet	2	1
Number of Boxes	30 boxes	70 boxes
Size of box-width	48.0 in	96.0 in
Size of box-depth	96.0 in	96.0 in
Size of box-height	24.0 in	24.0 in
Volume per box	64.0 ft3	128.0 ft3
Total Volume	1920.0 ft3	8960.0 ft3
Weight per box	1,088 lb	2,176 lb
Total Weight	32,640 lb	152,320 lb

Mission 7 is 21 hours one-way (42 hours round trip) and uses Plane 1.

Mission 7 analysis

Using the equations above the following results are obtained for Mission 7:

Mission 7	Status quo	Design #1	Design #2
Number of pallet positions required	85 pallets	43 pallets	22 pallets
Number of Plane 1s needed	17 Plane(s)	9 Plane(s)	5 Plane(s)
Number of Plane 2s needed	0 Plane(s)	0 Plane(s)	0 Plane(s)
Number of Plane 3s needed	0 Plane(s)	0 Plane(s)	0 Plane(s)
Number of Plane 4s needed	0 Plane(s)	0 Plane(s)	0 Plane(s)
Number of pallet positions available	85 pallet positions	45 pallet positions	25 pallet positions
Cost per mission (CPM)	$2,548,980	$1,349,460	$749,700
Savings over status quo- 1 trip		$1,199,520	$1,799,280
Volumetric capacity	54,400 ft3	28,800 ft3	16,000 ft3
Percentage capacity used by volume (PCV)	20%	38%	68%
Weight capacity	1,020,000 lb	540,000 lb	300,000 lb
Weight of load, pallets and loading systems	210,460 lb	232,260 lb	222,360 lb
Percentage capacity used by weight (PCW)	21%	43%	74%
CYO (P/A, 10%, 20yr)	-$23,870,994	-$12,637,585	-$7,020,881
Savings over status quo		$11,233,409	$16,850,113
Savings of Design #2 over Design #1			$5,616,704
Savings per loading system unit over status quo		$261,242	$765,914
Savings Design #2 over Design #1 per loading system			$255,305
Footprint	5,440 ft2	2,880 ft2	1,600 ft2

Mission 7, lowest possible cost

Design #1 saves $11.23 million present value dollars over the status quo over a 20-year period at 10% interest. In one trip, the 43 units save $1199.52 thousand over status quo, less the cost of manufacture and cost of development. If the cost of development and the cost of manufacture for 43 units is less than $1199.52 thousand, Design #1 is superior to the status quo.

Design #2 saves $16.85 million present value dollars over the status quo over a 20-year period at 10% interest. In one trip, the 22 units save $1799.28 thousand over status quo, less the cost of manufacture and cost of development. If the cost of development and the cost of manufacture for 22 units is less than $1799.28 thousand, Design #2 is superior to the status quo.

Volumetric capacity

Status quo uses 20% of its volumetric capacity.
Design #1 uses 38% of its volumetric capacity.
Design #2 uses 68% of its volumetric capacity.

Weight capacity

Status quo uses 21% of its weight capacity.
Design #1 uses 43% of its weight capacity.
Design #2 uses 74% of its weight capacity.

Footprint

The footprint of Status quo is 5440 ft2.
The footprint of Design #1 is 2880 ft2.
The footprint of Design #2 is 1600 ft2.

Mission 8

Mission 8 description

Scenario 8 is comprised of 191 non-stackable boxes of three different sizes that fit onto 47 pallets and use approximately 18% of the volumetric capacity of the aircraft.

Scenario 8	Size 1	Size 2	Size 3
Number of Pallets	15 pallets	12 pallets	20 pallets
Number of Boxes per Pallet	9	3	1
Number of Boxes	135 boxes	36 boxes	20 boxes
Size of box-width	32.0 in	32.0 in	96.0 in
Size of box-depth	32.0 in	80.0 in	88.0 in
Size of box-height	30.0 in	36.0 in	20.4 in
Volume per box	17.8 ft3	53.3 ft3	99.7 ft3
Total Volume	2400.0 ft3	1920.0 ft3	1994.7 ft3
Weight per box	302 lb	907 lb	1,695 lb
Total Weight	40,800 lb	32,640 lb	33,909 lb

Mission 8 is 22 hours one-way (44 hours round trip) and uses Planes 2 and 3.

Mission 8 analysis

Using the equations above the following results are obtained for Mission 8:

Mission 8	Status quo	Design #1	Design #2
Number of pallet positions required	47 pallets	24 pallets	12 pallets
Number of Plane 1s needed	0 Plane(s)	0 Plane(s)	0 Plane(s)
Number of Plane 2s needed	1 Plane(s)	1 Plane(s)	0 Plane(s)
Number of Plane 3s needed	3 Plane(s)	1 Plane(s)	1 Plane(s)
Number of Plane 4s needed	0 Plane(s)	0 Plane(s)	0 Plane(s)
Number of pallet positions available	56 pallet positions	26 pallet positions	15 pallet positions
Cost per mission (CPM)	$2,191,200	$906,400	$642,400
Savings over status quo- 1 trip		$1,284,800	$1,548,800
Volumetric capacity	35,840 ft3	16,640 ft3	9,600 ft3
Percentage capacity used by volume (PCV)	18%	38%	66%
Weight capacity	672,000 lb	312,000 lb	180,000 lb
Weight of load, pallets and loading systems	121,449 lb	133,749 lb	127,749 lb
Percentage capacity used by weight (PCW)	18%	43%	71%
CYO (P/A, 10%, 20yr)	-$20,520,413	-$8,488,364	-$6,016,025
Savings over status quo		$12,032,049	$14,504,388
Savings of Design #2 over Design #1			$2,472,339

Mission 8	Status quo	Design #1	Design #2
Savings per loading system unit over status quo		$501,335	$1,208,699
Savings Design #2 over Design #1 per loading system			$206,028
Footprint	3,584 ft2	1,664 ft2	960 ft2

Mission 8, lowest possible cost

Design #1 saves $12.03 million present value dollars over the status quo over a 20-year period at 10% interest. In one trip, the 24 units save $1284.8 thousand over status quo, less the cost of manufacture and cost of development. If the cost of development and the cost of manufacture for 24 units is less than $1284.8 thousand, Design #1 is superior to the status quo.

Design #2 saves $14.5 million present value dollars over the status quo over a 20-year period at 10% interest. In one trip, the 12 units save $1548.8 thousand over status quo, less the cost of manufacture and cost of development. If the cost of development and the cost of manufacture for 12 units is less than $1548.8 thousand, Design #2 is superior to the status quo.

Volumetric capacity

Status quo uses 18% of its volumetric capacity.
Design #1 uses 38% of its volumetric capacity.
Design #2 uses 66% of its volumetric capacity.

Weight capacity

Status quo uses 18% of its weight capacity.
Design #1 uses 43% of its weight capacity.
Design #2 uses 71% of its weight capacity.

Footprint

The footprint of Status quo is 3584 ft2.
The footprint of Design #1 is 1664 ft2.
The footprint of Design #2 is 960 ft2.

Mission 9

Mission 9 description

Scenario 9 is comprised of 95 non-stackable boxes of one size that fits onto 95 pallets and uses approximately 10% of the volumetric capacity of the aircraft.

Scenario 9	Size 1
Number of Pallets	95 pallets
Number of Boxes per Pallet	1
Number of Boxes	95 boxes
Size of box-width	50.0 in
Size of box-depth	60.0 in
Size of box-height	40.0 in
Volume per box	69.4 ft3
Total Volume	6597.2 ft3
Weight per box	1,181 lb
Total Weight	112,153 lb

Mission 9 is 23 hours one-way (46 hours round trip) and uses Planes 3 and 4.

Mission 9 analysis

Using the equations above the following results are obtained for Mission 9:

Mission 9	Status quo	Design #1	Design #2
Number of pallet positions required	95 pallets	48 pallets	32 pallets
Number of Plane 1s needed	0 Plane(s)	0 Plane(s)	0 Plane(s)
Number of Plane 2s needed	0 Plane(s)	0 Plane(s)	0 Plane(s)
Number of Plane 3s needed	7 Plane(s)	4 Plane(s)	3 Plane(s)
Number of Plane 4s needed	0 Plane(s)	0 Plane(s)	0 Plane(s)
Number of pallet positions available	105 pallet positions	60 pallet positions	45 pallet positions
Cost per mission (CPM)	$4,701,200	$2,686,400	$2,014,800
Savings over status quo- 1 trip		$2,014,800	$2,686,400
Volumetric capacity	67,200 ft3	38,400 ft3	28,800 ft3
Percentage capacity used by volume (PCV)	10%	17%	23%
Weight capacity	1,260,000 lb	720,000 lb	540,000 lb
Weight of load, pallets and loading systems	140,653 lb	164,953 lb	156,953 lb
Percentage capacity used by weight (PCW)	11%	23%	29%
CYO (P/A, 10%, 20yr)	-$44,026,362	-$25,157,921	-$18,868,441
Savings over status quo		$18,868,441	$25,157,921
Savings of Design #2 over Design #1			$6,289,480
Savings per loading system unit over status quo		$393,093	$786,185
Savings Design #2 over Design #1 per loading system			$196,546
Footprint	6,720 ft2	3,840 ft2	2,880 ft2

Mission 9, lowest possible cost

Design #1 saves $18.87 million present value dollars over the status quo over a 20-year period at 10% interest. In one trip, the 48 units save $2014.8 thousand over status quo, less the cost of manufacture and cost of development. If the cost of development and the cost of manufacture for 48 units is less than $2014.8 thousand, Design #1 is superior to the status quo.

Design #2 saves $25.16 million present value dollars over the status quo over a 20-year period at 10% interest. In one trip, the 32 units save $2686.4 thousand over status quo, less the cost of manufacture and cost of development. If the cost of development and the cost of manufacture for 32 units is less than $2686.4 thousand, Design #2 is superior to the status quo.

Volumetric capacity

Status quo uses 10% of its volumetric capacity.
Design #1 uses 17% of its volumetric capacity.
Design #2 uses 23% of its volumetric capacity.

Weight capacity

Status quo uses 11% of its weight capacity.
Design #1 uses 23% of its weight capacity.
Design #2 uses 29% of its weight capacity.

Footprint

The footprint of Status quo is 6720 ft2.
The footprint of Design #1 is 3840 ft2.
The footprint of Design #2 is 2880 ft2.

Mission 10

Mission 10 description

Scenario 10 is comprised of 245 non-stackable boxes of three different sizes that fit onto 134 pallets and use approximately 23% of the volumetric capacity of the aircraft.

Scenario 10	Size 1	Size 2	Size 3
Number of Pallets	68 pallets	21 pallets	45 pallets
Number of Boxes per Pallet	1	2	3
Number of Boxes	68 boxes	42 boxes	135 boxes
Size of box-width	90.0 in	48.0 in	50.0 in
Size of box-depth	88.0 in	88.0 in	32.0 in
Size of box-height	20.4 in	88.0 in	36.0 in
Volume per box	93.5 ft3	215.1 ft3	33.3 ft3
Total Volume	6358.0 ft3	9034.7 ft3	4500.0 ft3
Weight per box	1,590 lb	3,657 lb	567 lb
Total Weight	108,086 lb	153,589 lb	76,500 lb

Mission 10 is 24 hours one-way (48 hours round trip) and uses Mixed.

Mission 10 analysis

Using the equations above the following results are obtained for Mission 10:

Mission 10	Status quo	Design #1	Design #2
Number of pallet positions required	134 pallets	78 pallets	50 pallets
Number of Plane 1s needed	0 Plane(s)	1 Plane(s)	1 Plane(s)
Number of Plane 2s needed	0 Plane(s)	0 Plane(s)	0 Plane(s)
Number of Plane 3s needed	9 Plane(s)	5 Plane(s)	3 Plane(s)
Number of Plane 4s needed	0 Plane(s)	0 Plane(s)	0 Plane(s)
Number of pallet positions available	135 pallet positions	80 pallet positions	50 pallet positions
Cost per mission (CPM)	$6,307,200	$3,675,360	$2,273,760
Savings over status quo- 1 trip		$2,631,840	$4,033,440
Volumetric capacity	86,400 ft3	51,200 ft3	32,000 ft3
Percentage capacity used by volume (PCV)	23%	39%	62%
Weight capacity	1,620,000 lb	960,000 lb	600,000 lb
Weight of load, pallets and loading systems	378,375 lb	423,975 lb	403,975 lb
Percentage capacity used by weight (PCW)	23%	44%	67%
CYO (P/A, 10%, 20yr)	-$59,066,424	-$34,419,453	-$21,293,581
Savings over status quo		$24,646,971	$37,772,843
Savings of Design #2 over Design #1			$13,125,872
Savings per loading system unit over status quo		$315,987	$755,457
Savings per loading system of Design #2 over Design #1			$262,517
Footprint	8,640 ft2	5,120 ft2	3,200 ft2

Mission 10, lowest possible cost

Design #1 saves $24.65 million present value dollars over the status quo over a 20-year period at 10% interest. In one trip, the 78 units save $2631.84 thousand over status quo, less the cost of manufacture and cost of development. If the cost of development and the cost of manufacture for 78 units is less than $2631.84 thousand, Design #1 is superior to the status quo.

Design #2 saves $37.77 million present value dollars over the status quo over a 20-year period at 10% interest. In one trip, the 50 units save $4033.44 thousand over status quo, less the cost of manufacture and cost of development. If the cost of development and the cost of manufacture for 50 units is less than $4033.44 thousand, Design #2 is superior to the status quo.

Volumetric capacity

Status quo uses 23% of its volumetric capacity.
Design #1 uses 39% of its volumetric capacity.
Design #2 uses 62% of its volumetric capacity.

Weight capacity

Status quo uses 23% of its weight capacity.
Design #1 uses 44% of its weight capacity.
Design #2 uses 67% of its weight capacity.

Footprint

The footprint of Status quo is 8640 ft2.
The footprint of Design #1 is 5120 ft2.
The footprint of Design #2 is 3200 ft2.

Return on Investment

Comparison of Design #1 to Status Quo

In every Mission except Mission 4, Design #1 was shown to be a dramatic improvement over status quo.

Worst Case Scenario

In the worst-case scenario, Mission 4, Design #1 did not save any money over status quo. The reason is because the Mission required that only Plane 4 was used and Design #1 did not save enough pallet positions to use one less plane. If the mission allowed any other plane or plane mixture, there would have been a savings over status quo.

Best-Case Scenario

In the best-case scenarios, Mission 5, Design #1 saved $36,369,604 per unit over a twenty-year period, less COM and COD.

Average Case scenario

Using average values across all ten missions, Design #1 saved $255,032 per unit over a twenty-year period, less the Cost of Manufacture (COM) and Cost of Development. This means that there is a net profit realized over a 20-year period even if the cost of manufacture of one BALS unit is $255,032!

Savings of Design #1 over Status Quo for entire period

If one of each of the ten mission scenarios is used per year for 20 years, the total savings is $155.6 Million

Comparison of Design #1 to Status Quo

In every Mission, Design #2 was shown to be a dramatic improvement over status quo.

Worst Case Scenario

In the worst-case scenario, Mission 4, Design #2 still saved $4,922,202 over status quo by using 2 Planes instead of 3.

Best-Case Scenario

In the best-case scenarios, Mission 5, Design #2 saved $50,686,132 per unit over a twenty-year period, less COM and COD.

Average Case scenario

Using average values across all ten missions, Design #2 saved $664,300 per unit over a twenty-year period, less the Cost of Manufacture (COM) and Cost of Development. This means that there is a net profit realized over a 20-year period even if the cost of manufacture of one unit is $664,300!

Savings of Design #1 over Status Quo for entire period

If one of each of the ten mission scenarios is used per year for 20 years, the total savings is $233.9 Million

Comparison of Design #1 to Design #2

In every Mission, Design #2 was shown to be a dramatic improvement over Design #1.

Worst Case Scenario

In the worst-case scenario, Mission 8, Design #2 saved $2,472,339 over Design #1.

Best-Case Scenario

In the best-case scenarios, Mission 5, Design #2 saved $14,316,528 per unit over a twenty-year period, less COM and COD.

Average Case scenario

Using average values across all ten missions, Design #2 saved $218,787 per unit over a twenty-year period, less the Cost of Manufacture (COM) and Cost of Development.

Savings of Design #1 over Status Quo for entire period

If one of each of the ten mission scenarios is used per year for 20 years, the total savings is $78.3 Million

Conclusion

The design methodology offers a design with substantial savings over the status quo system. The methodology also shows an opportunity for increased savings by evolving the design along mono-bi-poly evolutionary trend, thus avoiding the later cost of redesign later.

CURRICULUM VITA

for

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DEGREES:

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Master of Science (Engineering Management), Old Dominion University, Norfolk, Virginia, December, 1993

Bachelor of Science (Mechanical Engineering), Virginia Polytechnic Institute and State University, Blacksburg, Virginia, May, 1983

STATES WITHIN WHICH REGISTERED:

Registered Professional Engineer, Commonwealth of Virginia, February 1989

PROFESSIONAL CHRONOLOGY:

CACI, Chesapeake, Virginia

Lead Engineer, December 1994- Present

Naval Undersea Warfare Center, Norfolk, Virginia

Electronics Engineer, October 1989- November 1994

Norfolk Naval Shipyard, Portsmouth, Virginia

Mechanical Engineer, May 1983- September 1989

Student Trainee, Mechanical Engineering, October 1978- May 1983

SCIENTIFIC AND PROFESSIONAL SOCIETIES MEMBERSHIP:

American Society for Mechanical Engineers

American Society for Naval Engineers

American Society for Quality

Institute for Electrical and Electronics Engineers

Institute for Industrial Engineers

Society of Cost Estimating and Analysis

HONORS AND AWARDS:

Certified Cost Estimator/Analyst, Society for Cost Estimating and Analysis, 1995

Certified Quality Auditor, American Society for Quality, 1995

Certified Quality Engineer, American Society for Quality, 1992

Certified Quality Manager, American Society for Quality, 1996

Certified Reliability Engineer, American Society for Quality, 1992

Eagle Award for Technical Excellence, CACI, 1996

Engineer of the Year Award, NUWC, 1992

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COURSES TAUGHT:

Project Management, Old Dominion University

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Strength of Materials, Thomas Nelson Community College

Statistical Process Control, Thomas Nelson Community College

Algebra, Remedial and Freshman Level, Tidewater Community College

Statistics for Business, Tidewater Community College

Statistics for Engineers and Scientists, Tidewater Community College

SCHOLARLY ACTIVITIES COMPLETED:

MASTERS THESIS:

Luke, S.R., Reliability Trend Analyses with Statistical Confidence Limits using the Luke Reliability Trend Chart. December 1993.

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