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Using a TRIZ Framework for Systems Engineering Trade Studies

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ABSTRACT

Identifying and appropriately resolving system tradeoffs or effectively evaluating alternatives is a key deliverable of systems engineering. Without proper resolution, system performance is hindered, or suboptimal technologies are chosen. TRIZ, the Theory of Inventive Problem Solving, offers tools and methods to identify and resolve tradeoffs (which it terms *contradictions* or *conflicts*). TRIZ recognizes that fundamental performance limits arise when one or more unresolved tradeoffs exist in a system. According to TRIZ, eliminating or reducing the effects of the conflicts is necessary to move to improved system performance. This paper presents a TRIZ Trade Study framework that is useful to identify system conflicts, both across alternatives and within a technology, and at various levels of requirements decomposition, to compare options and optimize how the system performs. The framework was developed to perform a trade study between alternative pharmaceutical production systems, and merges traditional trade study methodologies with classical TRIZ. Specifically, traditional pharmaceutical manufacturing development and manufacturing were traded against an emerging and proposed approach, QbD (Quality by Design). Given TRIZ is scalable and useful to a variety of systems, the application of the TRIZ Trade Study Framework is also broadly applicable across system scale and domains. © 2012 Wiley Periodicals, Inc. Syst Eng 15: 355–367, 2012

Key words: TRIZ; systems engineering; fundamental limits; tradeoff analysis; trade studies; QbD; pharmaceutical

1. INTRODUCTION

The INCOSE Systems Engineering Handbook describes a Trade Study as “a process for comparing the appropriateness of different technical solutions” [Haskins, 2006, p. 7.5]. The ability to discern between alternatives is considered a key systems engineering thinking skill for engineers [Frank, 2006].

Trade studies are needed at all phases of systems engineering, from setting requirements to selecting alternative approaches, and for optimization analysis [Vanek, Jackson, and Grzybowski, 2008]. At the requirements stage, trade studies are useful to identify and resolve system constraints. These constraints can be identified by such traditional tools as the QFD (Quality Function Deployment) *House of Quality*, specifically the *Requirements Correlation Matrix* [Hauser and

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Clausing, 1988; Haskins, 2006; Hari, Kasser, and Weiss, 2007].

Trade studies are also useful to make informed choices among alternative designs in order to select the most cost-effective solution that meets customer needs, and can contrast/compare technical solutions for systems [Squires, Larson, and Sauser, 2010]. This paper will illustrate that TRIZ (the Theory of Inventive Problem Solving) is also useful for trade studies, especially as related to performance optimization. TRIZ is complimentary to QFD [Hua et al., 2006] and provides an objective means of comparing alternatives.

The Russian inventor Genrich Altshuller began to develop TRIZ in 1946. Altshuller observed common patterns in patents across inventions, which he summarized in abstracted engineering features and inventive principles. TRIZ facilitates the identification and resolution of technical problems based on prior solutions already identified. The idea is that someone somewhere has already solved a variation of the current problem. In addition, TRIZ theory indicates that fundamental performance limits arise when one or more unresolved tradeoffs exist in a system. Specifically, it enables the systems engineer to identify requirement contradictions that limit desired performance, which are synonymous with tradeoffs [Shahbazpour and Seidel, 2007].

This paper presents a TRIZ Trade Study Framework, and leverages classic TRIZ tools. Examples are provided from the research related to an emerging approach to pharmaceutical development and manufacturing presented in Blackburn, Mazzuchi, and Sarkani [2011] and described in the following section.

2. AN EXAMPLE MANUFACTURING SYSTEM TRADE STUDY

Manufacturing systems are viewed as systems, each with its own architecture [Maier and Rechtin, 2000], and are recognized as needing to be evaluated by trade studies [Blanchard and Fabrycky, 2006; Shahbazpour and Seidel, 2007]. Papers have expressed the usefulness of TRIZ to help address manufacturing system tradeoffs, although reviewed literature lacks specificity [Shahbazpour and Seidel, 2007].

The case study used herein involves identifying pharmaceutical manufacturing production system conflicts and comparing traditional development and manufacturing methods to an emerging new solution for the industry, QbD (Quality by Design). This occurred at the top-level system architecture (as opposed to subsystems), but includes general process and technologies within the proposed and traditional systems. Detailed results of the author's research as related to QbD are presented in Blackburn, Mazzuchi, and Sarkani [2011].

As an introduction to the QbD case study that used the TRIZ Trade Study Framework, current pharmaceutical manufacturing methods rely on release product testing and secondary quality control measures. International Council on Harmonisation (ICH) defines Quality as "[t]he suitability of either a drug substance or drug product for its intended use. This term includes such attributes as the identity, strength, and purity" [ICH, 2005, p. 8]. From a systems engineering perspective, the National Airspace System (NAS) *System Engineering Manual* (Version 3.1) defines Quality in the context of a trade study as being "measured by the degree to which the project objectives are satisfied" [NAS, 2006, p. 4.6-19].

The traditional approach to pharmaceutical development and manufacturing has been referred to as QbT (Quality by Testing) [Kenett and Kenett, 2008] or Quality by Inspection [Perez and Puigdomenech, 2009]. That is, quality assurance emphasis is on *testing* versus *designing* for quality. However, the literature review and subsequent research indicate there is a significant gap between pharmaceutical production sigma capability and supplied quality. While the pharmaceutical industry supplies high-quality products exceeding 5 sigma, its production processes consistently perform at a lower rate, ~2.5 and 3.5 sigma [Blackburn, Mazzuchi, and Sarkani, 2011]. The research provided evidence that the gap exists due to a systems fundamental limit having been reached under the QbT paradigm. Fundamental limits are eventually reached (according to TRIZ theory) whenever unresolved conflicts exist in the system (which can be distinct from true limits based on scientific laws). These are apparent limits, but persist until conflicts are resolved.

The emerging QbD approach is proposed to eliminate system contradictions that impede improved performance. QbD is defined as "a systematic approach to development that begins with predefined objectives and emphasizes product and process understanding and process control, based on sound science and quality risk management" [ICH, 2005, p. 20]. It is more generally defined as a "holistic, systems-based approach to the design, development, and delivery of any product or service to a consumer" [Berridge, 2005, p. 1]. It emphasizes acquiring a mechanistic understanding of product CQAs (Critical Quality Attributes) in relation to CPPs (Critical Process Parameters) and material parameters. It includes developing a Design Space that provides a normal operating area in which quality product is assured. QbD allows for flexible processes (versus fixed-parameter processes currently part of QbT) that utilize control strategies that can react to changing inputs to ensure consistent outputs. Process Analytical Technology (PAT) is an emerging technology to support the Control Strategy. PAT is a "system for designing, analyzing, and controlling manufacturing through timely measurements (i.e. during processing) of critical and performance attributes of raw and in-process materials and processes with the goal of ensuring final product quality" [FDA, 2004, p. 7].

The trade study concluded that QbD is more efficacious in eliminating pharmaceutical production system contradictions than traditional approaches. It also evaluated the extent to which QbD, as it is expressed in contemporary literature, eliminates system contradictions and recommended additional scope. TRIZ was found to be useful to identify contradictions for this example, and using TRIZ offers systems engineers fresh tools to perform robust trade studies within traditional phases.

3. AN INTRODUCTION AND OVERVIEW OF TRIZ

TRIZ began to appear in the West in the 1980s, and is evolving to be an inventive problem-solving approach for any system

[Stratton and Mann, 2003]. The Russian title for TRIZ transliterated to English is ***T**eoriya **R**esheniya **I**zobretatelskikh **Z**adatch* [Low et al., 2002]. TRIZ (often pronounced *trees*) is an acronym from the Russian, translated as the "*theory of inventive problem solving*," an approach to solving problems systematically, creating innovation by identifying and eliminating system conflicts or contradictions [Stratton and Mann, 2003; Harvard Business Press, 2009].

3.1. TRIZ Background

TRIZ follows a scheme of abstracting a problem to identify an abstracted solution [ReVelle, 2002] and offers abstracted inventive principles to solve problems based on a prior solution. Savransky [2000, p. 24] estimates that "about 95% of the inventive problems in any particular field have already been solved in another field." Mann [2002, p. 2] makes the case that TRIZ's "generic problem solving framework . . . allows engineers and scientists working in any one field to access the good practices of everyone working in not just their own, but every other field of science." Savransky [2000, p. 339] describes this as accumulating and condensing "all respective human knowledge and then" applying "it to solve inventive problems."

3.2. TRIZ Premises

When Genrich Altshuller studied trends in patents, he discovered that innovation is not a random process, but is governed by learnable principles [Savransky, 2000; Silverstein, DeCarlo, and Slocum, 2007]. Based on the patterns he observed in patents, he later developed an approach that described conflicting features with mapped solutions. Specifically, his study identified 39 engineering or desired parameters and 40 inventive solutions to apply when one or more parameters conflict, which are addressed more fully later in this paper [see also ReVelle, 2002; Stratton and Mann, 2003]. TRIZ is based on three premises as follows [ReVelle, 2002; Stratton and Mann, 2003]:

1. Ideality or Ideal Final Result (IFR): The ultimate goal is to design a system with no harmful functions. IFR is useful to describe what the desired final system state should be, enabling the identification of system contradictions that will prevent success. This is a similar concept to backcasting, which begins by describing a future desired state and works backwards to identify approaches to link the future state to the present [Holmberg and Robert, 2000]. Like backcasting, IFR looks at the ideal and inquires what it will take to reach it.
2. Contradictions (or conflicts): It is necessary to eliminate (wholly or partially) a system contradiction to achieve improved system performance. A *physical* contradiction occurs when an aspect of a system needs to be in opposite states (e.g., hot vs. cold). A *technical* contradiction occurs when a desired feature conflicts with another (e.g., heavy but fast).
3. Resources: Maximize the utility of current resources prior to introducing any additional complexity or resources to the system.

First, IFR can be useful to mitigate the impact of PI (Psychological Inertia), where it might be difficult for the systems engineer to innovate beyond his or her normal experience. Altshuller viewed PI as a barrier to innovation [Low et al., 2002]. PI relates to the likelihood that one will limit the solution space inside a known or comfortable paradigm, or define a solution path defined by his or her paradigm [ReVelle, 2002]. PI has been described as "the sum of one's intellectual, emotional, academic, experiential, and other biases" [Silverstein, DeCarlo, and Slocum, 2007, p. 33] and "the effort made by a system to preserve the current meta-stable state or to resist change in that state" [Savransky, 2000, p. 6]. Starting at the ideal state and working backwards can stimulate new and innovative thinking. Keaney's Value Focused Thinking reflects a similar approach—it is intended to systematically generate superior solutions and short circuit the trade process [Keeney, 1996].

Expanding on point 2, Altshuller held that an inventive problem by definition includes at least one contradiction and the inventive solution to be identified must (at least in part) eliminate the contradiction to improve performance [Stratton and Mann, 2003]. Savransky makes the point that "the most effective inventive solution of a problem is one that overcomes some contradictions." [Savransky, 2000, p. 60]. However, he suggests the problem is unresolved while contradiction(s) remain.

Third, focusing on maximizing current resources avoids adding additional cost and complexity to the system, which can also trigger undesired emergent behaviors. This principle relates to maximizing the utility of resources, described as "any substance, space, or energy that is present in the system" [ReVelle, 2002, p. 405]. Specifically, maximize the utility of current resources prior to introducing any additional complexity or resources to the system. This is in stark contrast to the Western practice of investing capital to overcome problems, which can add significant complexity. That is, engineers might be willing to "pay for the effect required—in terms of machines, expenditure of time, energy, space, etc." [Savransky, 2000, p. 80]. Automation or software can also be overused to compensate for poor system performance. However, TRIZ practitioners prefer to avoid adding complexity to solve a problem, and only add design elements when current resources are exhausted [ReVelle, 2002].

3.3. TRIZ Relevance to Trade Studies

Point 2 (from the previous section) is particularly relevant to trade studies. Using the findings from patent patterns, TRIZ offers abstracted inventive principles to solve problems. By aligning abstracted engineering or desired features with already successful principles as observed in patents, system contradictions can be eliminated. The TRIZ inventive principles used to overcome contradictions are based on observations of millions of patents (in an abstracted form), as opposed to other idea generation heuristics that are derived by trial and error.

3.4. TRIZ Relationship to Heuristics

Early on, Alexander et al. [1997, p. 2] noted that "each pattern describes a problem which occurs over and over again in our environment, and then describes the core of the solution to that problem, in such a way that you can use this solution a million times over, without ever doing it the same way twice" [Haskins, 2008]. Haskins noted [2008, p. 3] that "patterns are able to capture what experts know and to share that knowledge with others in a narrative literature format that is both informative and informal. When a pattern is applied, the expertise of an experienced designer or engineer is reused, as opposed to being reinvented or rediscovered." Although there are many SE patterns that can be mined, TRIZ abstracts patterns from solutions to problems from millions of patents, and is in essence a type of pattern language.

Other heuristics have been described as involving "choice, hunch, knowledge, and a lot of creativity but lack a systematic approaches. They possess inherent drawbacks" in that they are inefficient and an optimum solution is not assured [Shirwaiker and Okudan, 2008]. While TRIZ does not absolutely guarantee the optimal solution, it does afford the designer the opportunity to apply principles most often used to resolve similar problems.

In a broader sense, TRIZ as a practice includes axioms that can be related to axiomatic design, and TRIZ is recommended as a primary approach for solution development [Frey et al., 2007]. For example, derived axiom corollaries [White, 1998] relate to one or more of the TRIZ inventive principles (e.g., *decoupling parts* is similar to *#1 Segmentation*). Other axiomatic corollaries [Suh, Bell, and Gossard, 1978; White, 1998] relate to TRIZ principles such as conserving materials/energy, utilizing symmetry, and simplification.

4. SYSTEMS ENGINEERING AND TRIZ

The utility of TRIZ is starting to gain some degree of recognition in systems engineering (SE), but the literature (in the specific context of SE) remains thin. For example, a search returned only 13 titles that contained references to TRIZ in this journal. However, all the papers support the use of TRIZ tools and methods as described in this section.

First, the papers support the use of the classic 40 TRIZ inventive principles to resolve observed contradictions [Schulz et al., 2000; Frey et al., 2007; Bonnema, 2011]. The papers also reference the classic TRIZ 39 desired features.

Papers also make application-specific references to TRIZ in the context of SE. One paper made an application specifically to reducing part count [Frey et al., 2007]. Another indicated TRIZ as a tool to improve the systems architecting outcomes [Bonnema, 2011]. A recent paper (also related to system architecture) references TRIZ as an innovation method to support requirements analysis [Lai et al., 2011]. Others make the point that a characteristic of architecting is the use of heuristics [Maier and Rechtin, 2000]—TRIZ is a heuristical approach to innovation.

Others reference TRIZ in the context of innovation and invention [Fricke et al., 2000; Browning, Fricke, and Negele, 2006; Clausing and Katsikopoulos, 2008]. Schulz recommended TRIZ during *concept generation* to resolve conflicts among critical parameter interrelations and referenced TRIZ's laws of technological evolution [Schulz et al., 2000]. They continued in their paper to indicate that TRIZ supports a "high probability of creating breakthrough superiority of function performance" [Schulz et al., 2000, pp. 197–198] There are additional examples in other literature of practical applications of TRIZ tools to support innovation, such as from Filmore and Thomond [2005], Zhao and Zhang [2009], and Chen and Chen [2010].

In the application of the TRIZ Trade Study Framework, this paper will use the classic TRIZ Contradiction Matrix and to some degree the Separation Principles. The following section presents the framework and additional explanation.

5. THE TRIZ TRADE STUDY FRAMEWORK (TTSF)

The TRIZ Trade Study Framework (see Fig. 1) uses two classic TRIZ tools/methods (Separation Principles and the Contradiction Matrix), but within steps that are similar to traditional systems engineering trade study processes. Typical steps include identifying the objective, differentiating alternatives, weighting and scoring, and looking for sensitivities [Yilmaz and Ören, 2009]. TRIZ tools and methods have been shown to be useful when integrated with others [Hipple,

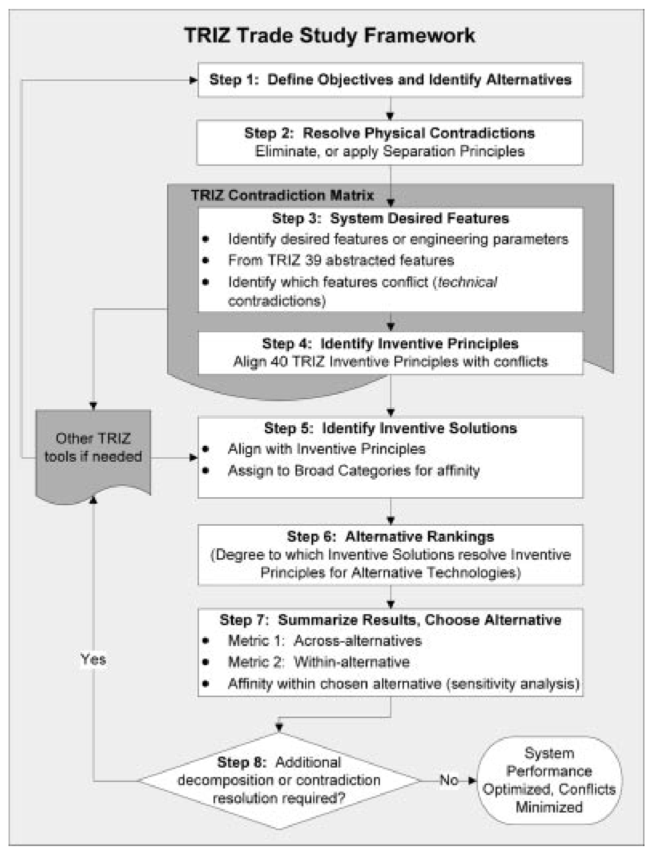

Figure 1. TRIZ trade study framework.

2003]. The ultimate goal of the trade study is cost-effective optimization [Sage and Rouse, 2009], although the TRIZ framework example herein focuses primarily on the performance optimization aspect.

The TRIZ Trade Study Framework primarily leverages the TRIZ Contradiction Matrix. The matrix is a table that aligns desired system or technology features with potentially contradicting features. At the intersection, it identifies *Inventive Principles* most frequently applied to eliminate contradictions in patents as a means to move to improved performance. This approach can be used to resolve requirement conflicts (such as can be identified in a QFD House of Quality *roof*). In addition, it enables the comparison of design alternatives.

Although the Contradiction Matrix was one of the earliest tools, and other methods have been developed to facilitate creative inventiveness (such as ARIZ, inventive standards, and anticipatory failure), it remains one of the most popular. The application of the standard inventive principles are especially considered useful [Livotov, 2004], remain a part of newer tools, and are used in 98% of all TRIZ projects [Livotov, 2004; Frenklach, 2007]. Literature and conferences continue to support its use for contemporary applications [Kang, 2004; Moehrle, 2005b].

In addition, the application of the contradiction matrix has not only been shown in the literature to apply to small-scale mechanical systems, but also is broad in scope and scalable in application. Papers have illustrated how TRIZ is applicable to a wide range of industries, applications, and scale, such as product/component-specific application, then to machinery, on to broader manufacturing, and to supply chains. It is also applicable to a broad range of industries such as aerospace (airplane, jet engines, satellite design, etc.), automotive, textiles, public transportation, medical practices, and other general business. It has also been shown to be applicable to information technology/computer science, semiconductors, and even the social sciences and politics [Mann and Domb, 1999; Bariani, Berti, and Lucchetta, 2004; Moehrle, 2005a; Frey et al., 2007; Shahbazpour and Seidel, 2007].

In summary, the scope is broad and scalable, in that problems, solutions, and patterns of technical evolution are "repeated across industries and sciences" and "innovations used scientific effects outside the field where they were developed" [Shirwaiker and Okudan, 2008, p. 34]. Others confirm similar applications and the scalability and broad application of TRIZ [Stratton and Mann, 2003; Cascini and Rissone, 2004; Shirwaiker and Okudan, 2008].

In the context of a trade study, the standard TRIZ desired features are helpful by narrowing down most applicable inventive principles. The desired features are similar to figures of merit [Daniels, Werner, and Bahill, 2001; Henry et al., 2005] in that they represent desired, but abstracted performance goals. Further, the desired features (as variables) form a design vector [Ross and Hastings, 2005], as they represent the possible solutions (in an abstracted form) found in patents. Finally, the combination of contradictions and inventive solutions represent patterns, and the inventive solutions heuristics.

Heuristics are useful to systems architecting. Maier and Rechtin [2000] noted several heuristics useful to systems architecting, most of which relate to the process of architecting, but some relate to design problems and can be associated with TRIZ Inventive Principles. For example, they mention partitioning elements for independence, which is similar to principle *#1 Separation* or *#2 Segmentation*.

6. THE TRIZ TRADE STUDY FRAMEWORK (TTSF)—A PRACTICAL APPLICATION EXAMPLE

The TRIZ Trade Study Framework steps are further described in the following and are contrasted with traditional SE trade study approaches. The framework focuses on the aspects of alternatives that represent conflicts that prohibit meeting customer performance needs. Application examples are provided from the QbD research [Blackburn, Mazzuchi, and Sarkani, 2011].

6.1. Step 1: Identify Objectives and Define Alternatives

As with most trade studies, begin with identifying objectives. Then describe technical solution alternatives at the given level of abstraction or decomposition. This requires enough understanding to identify desired features, as well as *physical contradictions.*

6.2. Step 2: Resolve Physical Contradictions

When possible, eliminate physical contradictions prior to technical contradictions. Where that is not possible, TRIZ offers *Separation Principles* to separate the action in space or time to minimize the effect of the physical contradiction. *Separation in time* "aims at separating contradicting physical properties by not fulfilling both of them at the same time," and *separation in space* "aims at separating contradicting physical properties by fulfilling each at another location" [Schulz et al., 2000, p. 20]. They also suggest *separation between system and components* which "aims at separating contradiction physical properties by fulfilling one on the system level and the other on the component level" (p. 20).

Physical contradictions were observed initially in the research example. For example, in QbT, there is a need to rely on people to complete documentation to ensure quality. But given that people make errors, it is desirable to provide solutions that do not depend on people in their operations. Efforts have been made to automate paper-based processes, but human error persists. To overcome this, the research recommended reducing the reliance on documentation for quality assurance, and instead demonstrate the control strategy maintains the process within the design space [Blackburn, 2011]. Therefore, the physical contradiction effect is minimized.

After identifying and resolving *physical* contradictions, the next step is to identify *technical* contradictions. This begins by first identifying system desired features or parameters (see Table I).

6.3. Step 3: System Desired Features

Identify the desired features or engineering parameters for the system. This can be at any level of abstraction. See TRIZ

Table I. Classic TRIZ Desired Parameters or Features

#	Desired Feature	#	Desired Feature
1	Weight of moving object	21	Power
2	Weight of stationary object	22	Waste or Loss of energy
3	Length of moving object	23	Waste or Loss of substance
4	Length of stationary object	24	Loss of information
5	Area of moving object	25	Waste or Loss of time
6	Area of stationary object	26	Amount of substance
7	Volume of moving object	27	Reliability
8	Volume of stationary object	28	Measurement Accuracy
9	Speed (object velocity or rate of a process)	29	Manufacturing Precision
10	Force	30	Harmful factors acting on object (e.g. external harms)
11	Tension, pressure	31	Harmful side effects (e.g. harmful factors generated by the object)
12	Shape	32	Manufacturability (or ease of manufacturing)
13	Stability of object (System wholeness or integrity, wear, etc.)	33	Convenience of use or ease of operation
14	Strength	34	Reparability or ease of repair
15	Durability of moving object or Duration of Action	35	Adaptability or versatility
16	Durability of stationary object or Duration of Action	36	Device complexity
17	Temperature	37	Complexity of control or difficulty of detecting and measuring
18	Brightness (Illumination Intensity)	38	Level or extent of automation
19	Energy spent by moving object	39	Productivity
20	Energy spent by stationary object		

references for the details of the 39 abstracted features that were tabulated from the extensive patent review [Tennant, 2003; Silverstein, DeCarlo, and Slocum, 2007], and which are generally described in Table I.

Table II provides a specific example of a conflict from the QbD pharmaceutical production system research. Here, *#29 Manufacturing Precision* is a desired feature, which reflects the need to produce product within tight specifications to ensure patient safety. Specifically as related to emerging QbD, product Critical Quality Attributes must remain within the predefined Design Space. However, it can conflict with feature *#33 Operational Ease*. That is, the level of precision needed to produce a pharmaceutical product can lead to undesired operational complexities that can in turn lead to emergent problems.

This is tabulated in Table II, structured to list first the desired feature, followed by an unabstracted explanation (*Desired Feature, Explained).* This is followed by the third column, or the abstracted *Conflicted Feature.* The final column describes the unabstracted *Conflict*, and the prescribed *Inventive Principles* from the Contradiction Matrix.

6.4. Step 4: Identify Inventive Principles

The next step is to identify the TRIZ inventive principles associated with the conflict or contradiction. Table III lists the standard 40 inventive principles—see TRIZ references for more detail [Tennant, 2003; Silverstein, DeCarlo, and Slocum, 2007].

Inventive principles 1, 32, 35, and 23 have been observed in patents as popular solutions to eliminate system contradictions when these two abstracted desired features conflict. These inventive principles are acquired from the TRIZ Contradiction Matrix, an excerpt from which is shown in Figure 2—see TRIZ literature for the full standard Contradiction Matrix [Tennant, 2003; Silverstein, DeCarlo, and Slocum, 2007] or the noted Internet link.[1]

Table II. System Conflict Example

Desired Feature, Abstracted	Desired Feature, Explained	Conflicting Feature	Conflict Described & (Inventive Principles)
29 - Manufacturing Precision	Need to keep CQAs (Critical Quality Attributes) in the Design Space	33 - Operational Ease	(-) Requiring precision can lead to operational complexities (1,32,35,23)

[1]The reader is referred to the following link for an interactive Contradiction Matrix online, http://triz40.com/, or the *TRIZ Journal* for the Contradiction Matrix at www.TRIZJournal.com. Referenced with permission.

Table III. Classic TRIZ Inventive Principles

#	Inventive Principle	#	Inventive Principle
1	Segmentation	21	Skipping or rush through
2	Separation	22	Turn harm to benefit
3	Local Quality	23	Feedback
4	Asymmetry	24	Intermediary carrier or process
5	Merging or combining	25	Self-service, utilize waste resources
6	Universality	26	Copying
7	Nesting dolls (inside another)	27	Disposables
8	Counter-weight or Antiweight	28	Replace mechanical system
9	Preliminary counter-action	29	Pneumatics or hydraulics
10	Preliminary action	30	Flexible films or membranes
11	Beforehand cushioning	31	Porous materials
12	Equipotential	32	Optical (color) changes
13	Invert action	33	Homogeneity
14	Spherical shapes	34	Recycling
15	Dynamism or Dynamics	35	Physical or chemical properties or parameter changes
16	Partial or excessive action	36	Use phase changes
17	Moving to another dimension	37	Leverage thermal expansion
18	Mechanical Vibration	38	Strong oxidants
19	Periodic Action	39	Inert environment
20	Continuity of useful action	40	Composite materials

This combination of Inventive Principles for a given conflict are related to a trade space, or the space of design options possible [Ross and Hastings, 2005]—in the case of TRIZ, these are the abstracted design options most popular to resolve the system contradiction. Next, practical *Inventive Solutions* are identified and aligned with the *Inventive Principles.*

6.5. Step 5: Identify Inventive Solutions

Each abstracted inventive principle is then described and aligned with an application-specific Inventive Solution. This technique is also useful for the purposes of team brainstorming tradeoff solutions, and can help in overcoming psychological inertia. From this example, inventive principle *#1* is selected for illustration, which is *Segmentation*, further de-

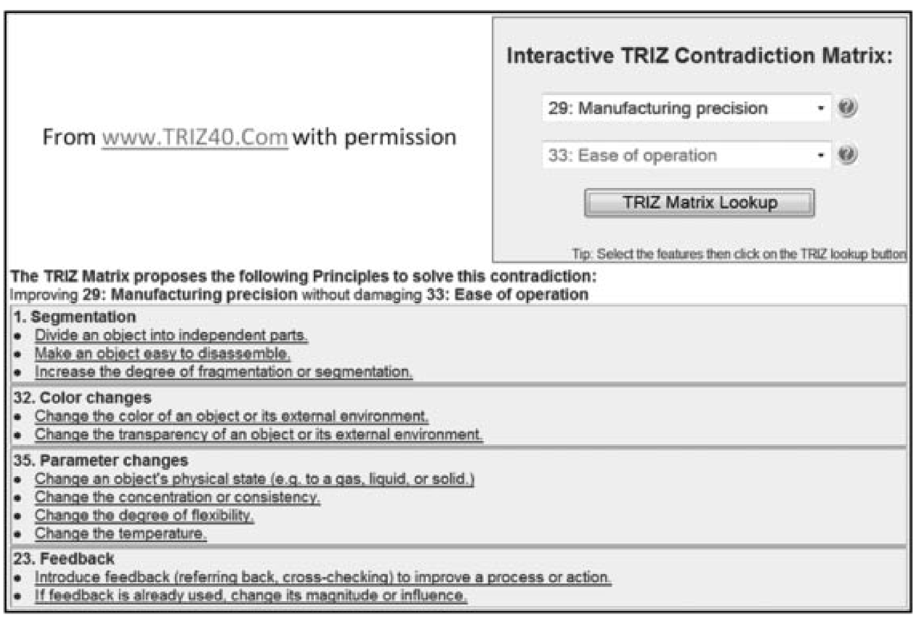

Figure 2. Contradiction Matrix example**.** Portions (for clarity) extracted from a screenshot from www.TRIZ40.com with permission, © SolidCreativity 2004–2011.

Table IV. Inventive Principles and Conceptual Solutions with Ranked Comparison Example

Inventive Principles (Abstracted)	Conceptual Solutions	Broad Category	QbT Status	*QbT Score*	QbD Status	*QbD Score*
1. Segmentation						
Divide an object into independent parts.	Divide operation into discrete units for monitoring purposes	Engineering Design	Medium	2	High	3
Make an object easy to disassemble.	SMED	Engineering Design	Medium	2	Medium	2
Increase the degree of fragmentation or segmentation.	Divide operation into discrete units for monitoring purposes	Engineering Design	Medium	2	High	3

scribed as three subprinciples (divide into independent parts, make easy to disassemble, or increase degree of fragmentation or segmentation). Table IV provides an example of identifying and aligning Inventive Principles with Conceptual Solutions, as well as comparing alternative design approaches. Table IV also enables a tradeoff analysis of QbT (Quality by Testing, or the traditional pharmaceutical production model) and QbD (Quality by Design).

Note the headings in the Table IV. The first is *Inventive Principles* as identified by TRIZ to resolve the system contradiction. *Conceptual Solutions* relate application-specific system design elements to the abstracted principle. The other columns are described in the following section.

6.6. Step 6: Alternative Rankings (Scoring)

The third column in Table IV contains Broad Categories of solutions, useful for later affinity/categorization of Inventive Solutions, followed by rankings or scores. Shown is an example for Engineering Design. Other categories in the study included PAT, Development, and others as noted later in Figure 4. Categories will vary depending on the system in question.

In traditional Systems Engineering (SE) trade studies, scoring functions are useful to "characterize, quantify, and provide a common basis for analyzing a stakeholder's preference with regard to a given . . . figure of merit" [Daniels, Werner, and Bahill, 2001, p. 4].

With the method proposed herein, the scoring is less subjective than some approaches. Here, the aligning technologies are evaluated and contrasted. In this example, the degree to which QbT and QbD scope includes the Conceptual Solution is ranked (in the *Status* columns). For this example, *High* indicates the conflict is currently resolved in industry or is highly addressed in the literature as a significant element of QbD; *Medium* indicates the conflict is addressed but not highly resolved; and *Low* indicates there is little if any resolution or reference in the literature with regard to QbD considerations, or it is significantly underdeveloped for the specific application. In other SE trade studies, the measure could indicate the degree to which the alternative includes the Conceptual Solution. The scoring numerically permits later summarization. *High* is given a 3 score, *Medium* 2, and *Low* 1. Note that this is essentially an ordinal scale and is used only to equate narrative rankings to numeric for purposes of comparing alternatives as described in the following.

6.7. Step 7: Summarize Results and Choose Alternative

The steps above are repeated for all system contradictions and are summarized. For the QbD example, the research used spreadsheets to assemble, summarize, and graph the results. The summarization is useful to compare alternatives, and score and weigh the degree to which an individual alternative is efficacious to eliminate system contradictions. These are further described by the following metrics.

6.7.1. Metric 1—Across-Alternative Comparison

This section and the following can be compared to traditional SE scoring and weighting. For traditional weighting methods, Daniels, Werner, and Bahill [2001] point out that there are many methods available, such as a ratio method, a tradeoff method, swing weights, rank-order centroid techniques, Analytic Hierarchy Process, tradeoffs, balance beam, judgments, and lottery questions [Keeney and Raiffa, 1976; Edwards, 1977; Saaty, 1980; Watson and Buede, 1987; Buede, 2000; Daniels, Werner, and Bahill, 2001]. The TRIZ Trade Study Framework also includes a ranking scheme useful to evaluate alternatives.

The first metric calculates the percent of the contradictions that have at least one *High* ranked Conceptual Solution. Percentages for *Medium* and *Low* maximum levels per contradiction are also tabulated. This allows an evaluation across alternatives and facilitates technology selection. That is, an alternative that addresses more conflicts with effective inventive solutions suggests that better system performance [Savransky, 2000] will be achieved by that alternative.

See Figure 3 for a compilation of the metrics for both alternatives. In Metric 1a, note that for QbT only about 3% of the conflicts have one or more inventive solutions with a high degree of development, while QbD returned 68% (Metric 1b). That is, for QbD, 68% of the conflicts have one or more *High*-ranked conceptual solutions. That suggests QbD is the more desired solution (at least from the perspective of addressing customer performance needs; however, other factors such as cost and schedule should be considered.)

6.7.2. Metric 2—Within-Alternative Evaluation

Metric 2 calculates the average ranking of all Conceptual Solutions within each alternative. Using the numeric equivalents, each contradiction resolution is ranked by averaging the scores and standard rounding. Altshuller held that an inventive problem by definition includes at least one contradiction and

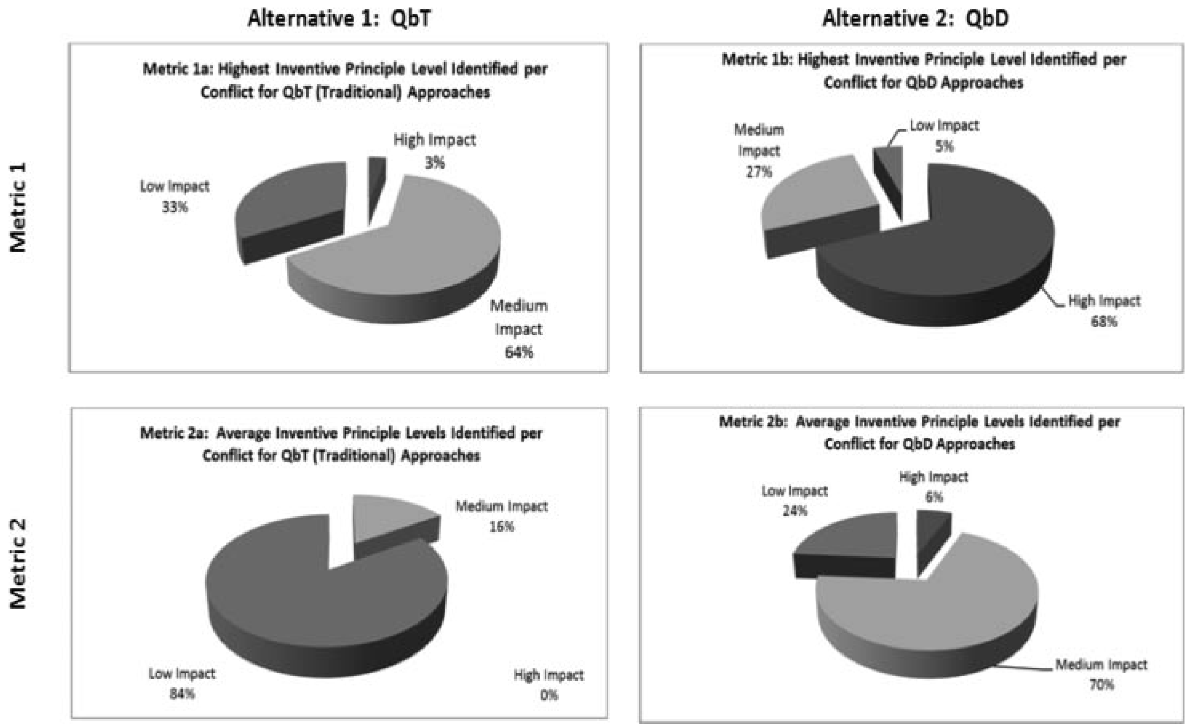

Figure 3. Tradeoff metrics.

the inventive solution to be identified must (at least in part) eliminate the contradiction [Stratton and Mann, 2003]. In some cases, the contradiction might be resolved by a single *High* solution. However, in others, more than one solution could be required. This enables the systems engineer to further refine and improve the selected alternative.

Metric 2 indicates the degree to which *all* inventive solutions are resolved in a given alternative, and automatically allocates weights. For closely ranked alternatives (e.g., where Metric 1 yields nearly equivalent scores), this could be another determining measure. In addition, it indicates additional resolution or scope that could be needed for the selected technology (QbD in this example). As noted, this enables the systems engineer to focus on further refinement (i.e., resolution of tradeoffs) of the selected alternative.

Figure 3 illustrates for this example that, for QbT (Metric 2a), 84% of the contradictions have an averaged *Low* score (measured as the degree to which inventive solutions align with inventive principles), while QbD returns a predominate *Average* rating (Metric 2b). (The ordinal 1, 2, 3 scale is averaged to derive the overall score. For example, a 2.2 average score across all Inventive Solutions for a given contradiction would return a composite *Medium* rating for that contradiction.) Although QbD remains superior to QbT by including elements that eliminate system contradictions, it also indicates more refinement is needed for QbD.

6.7.3. Affinity and Sensitivity Analysis

Trade studies often include a sensitivity analysis, in that "major attributes of the system" are "driven by relatively few parameters" [Daniels, Werner, and Bahill, 2001, p. 20]. Sensitivity analysis is useful to identify the "most important parameters in a tradeoff study; often these are the cost drivers that were worthy of further investment" [Smith et al., 2007, p. 4]. Rather than use more complex methods, which Daniels, Werner, and Bahill [2001, p. 20] describes as "relative-sensitivity measures, Response Surface Methodology, and Sinusoidal Variation of Parameters," the method proposed by this framework is much simpler. This method simply affinitizes inventive solutions in logical/natural categories, and counts the frequency of occurrences, while differentiating the degree of contradiction resolution within each category.

Figure 4 illustrates the organization of Inventive Solution categories for QbD. It organizes them in a Pareto-like format, with highest counts of Inventive Solutions to the left, and also indicates the rankings. Categories will change depending on the system under evaluation. This sensitivity analysis enables the systems engineer to focus on the *vital* or *significant few* [Daniels, Werner, and Bahill, 2001; Clausing and Katsikopoulos, 2008] elements on which to improve given likely budget, schedule, and risk constraints/considerations.

As summarized in Figure 4 for the QbD example, the research [Blackburn, 2011] identified 10 categories of Inventive Solutions that aligned with TRIZ Inventive Principles. From left to right, the first is Engineering Design considerations that need to include contradiction-eliminating criteria. Next is PAT (Process Analytical Technology) as described previously, followed by Development which includes contradiction-eliminating criteria that should be considered during drug research and development. The next is Flexible Processes, or the need for pharmaceutical manufacturing production systems to adapt to varying inputs to ensure consistent

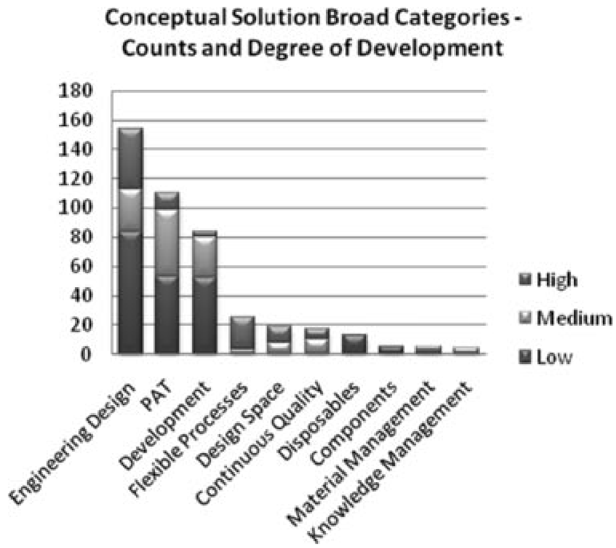

Figure 4. Inventive solution affinity and ranking.

product, followed by Design Space as described previously. Next is Continuous Quality, which relates to the need for real-time verification of quality versus completion of batch sampling and testing. The TRIZ trade study also identified Disposables used for manufacturing contact surfaces as an additional contradiction-eliminating solution, followed by the need to ensure component and raw material input attributes remain within the design space. The lowest count categories include Material Management (or the need to include QbD principles for suppliers) and Knowledge Management.

Note that in this example engineering design, PAT, and product development had the most *Low* returns *and* the highest total inventive solution counts, indicating areas of focus.

6.8. Step 8: Further Resolution

Upon selection of the desired alternative at the top-level system architecture (the system itself as opposed to subsystems), the system can continue to be developed and conflicts resolved. TRIZ can continue to be applied to eliminate contradictions at lower levels of abstraction/decomposition for problems that are not solved by classical methods. Other TRIZ methods in lieu of the classic Contradiction Matrix (such as ARIZ, Anticipatory Failure Determination, etc.) [Smith, 2001] can be applied. Also see Silverstein, DeCarlo, and Slocum [2007] for other TRIZ tools and methods not covered herein. Tradeoffs between performance, cost, and schedule should also be considered [Sage and Rouse, 2009]. The iteration continues until all economically viable system contradictions (with consideration to schedule and risk) are eliminated for the selected design alternatives.

For the case study example provided, QbD emerged as the superior alternative, and the method also identified additional areas of improvement within the QbD scope.

7. DISCUSSION AND CONCLUSIONS

Improving system performance requires the elimination of system conflicts (contradictions, or unresolved tradeoffs). Systems engineering as a practice includes comparing alternative technologies by evaluating tradeoffs against customer needs. This paper presented a framework for applying TRIZ as a trade study tool that identifies system conflicts, and determines the degree to which technology alternatives are efficacious *and* identifies areas of further trade-off resolution within the selected technology. A key advantage of the TRIZ approach is that it leverages prior knowledge, specifically as gathered by patent research, to identify system tradeoffs and identify inventive principles that can be applied to the current problem.

The implications and contribution of the TRIZ Trade Study framework are as follows: First, the comparison of alternatives using TRIZ indicates the degree to which one solution resolves the contradictions versus another. That is, the ability of the system to deliver the desired performance is indicated by the degree to which system contradictions are resolved. In addition, it provides areas of additional development needed for the chosen alternative to eliminate additional conflicts to enable improved system performance. While the TRIZ Trade Study framework leverages the classic Contradiction Matrix, it does so in a more quantitative way than observed in the literature, and advances the approach from solving concrete problems [Bonnema, 2011] to comparing and designing alternative systems.

The method was shown to be useful for the QbD example [Blackburn, Mazzuchi, and Sarkani, 2011]. It confirmed the appropriateness of the current QbD scope elements as observed in literature, but also indicated additional areas to further resolve via tradeoffs. The research [Blackburn, 2011] identified QbD scope elements that should be added or enhanced, including reducing the reliance on documentation for verification of quality, expanding QbD to Supply Chain Management, development in the area of continuous quality and continuous manufacturing, encouraged the use of disposable product contact surfaces during manufacturing, identified additional PAT technology development needed, addressed the need to embed TRIZ features in equipment design, and called for a more refined KM (Knowledge Management) concept. Higher impactive categories were also identified, such as Engineering Design (design to eliminate contradictions), PAT, and product development, indicating areas of focus for financial prioritization.

Additional areas of research recommended for the TRIZ Trade Study Framework are as follows:

- Repeat additional iterations for lower requirement decomposition levels.
- Apply to other domains and scale to further verify the usefulness of integrating TRIZ with standard trade study methodology. (For example, apply the framework to more traditional SE industries such as DoD and aerospace projects to enable further refinement and case studies.)
- Further incorporate other key trade study considerations such as schedule, cost, and risk.

- Develop software applications specifically to simplify and increase the speed of evaluation, as the example herein was applied manually using spreadsheets.

Overall, the authors found TRIZ to be useful in the application of a trade study in that it focused on prior patterns discovered in patents to maximize system performance, and reduced research bias.

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