Theoretical and Practical Aspects of Development of TRIZ-based Software Systems

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August 2005

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Abstract

The first attempt to automate TRIZ was made by Genrich Altshuller in the mid-1960s when he built an electromechanical version of the Contradiction Table with the Innovation Principles. In the mid 1980s, the emergence of personal computers allowed for the computerization of selected instruments of Classical TRIZ (principles, standards, effects) conducted under the leadership of Valery Tsourikov. Since 1989 the authors have led Kishinev TRIZ School and later Ideation International (USA) in developing and implementing their own approach to TRIZ computerization involving substantial restructuring of TRIZ, in particular:

    - Development of Ideation TRIZ (I-TRIZ) focusing on producing implementable (medium level) inventions capable of delivering maximal return on investment (ROI).
Development of Ideation processes for each application with computerization in mind, including the following basic steps:
- Collection and reorganization of information facilitating the creative process.
- Automated generation of a practically exhaustive set of directions for innovation (solutions).
- Automated process of suggesting Operators (recommendations) with statistically proven relevance to the selected directions for innovation prompting idea generation.
- Evaluation of obtained ideas and their enhancement using selected patterns of technological evolution.
- Documenting all steps and obtained ideas and results.

The work described above has resulted in the enhancement of existing tools, the development of new ones and the creation of a family of TRIZ software (TRIZSoft®), including new software systems utilized solely by Ideation TRIZ scientists to support the most sophisticated analytical services provided by Ideation like Directed Evolution™, enhancement of Intellectual Property, solving scientific problems, etc.

The suggested paper will share the experiences and main solutions to numerous problems associated with TRIZ computerization.

Acknowledgements

This work couldn’t be done without incredibly dedicated Ideation software development team lead by Sergey Malkin and in different times including Eugene Haimov, Dmitriy Bushuev, Vladimir Pevnev, Alexey Tikhonov, Vladimir Nikitenko, Eugene Subbotin, Oleg Pojidaev, Konstantin Sakirkin, Olena Malkina; Vicki Roza and Larry Cohen; and TRIZ specialists Len Kaplan, Svetlana Visnepolschi, Vladimir Proseanic and Vladimir Oleynikov.

Introduction

Why do we need TRIZ software or do we need Power Point software?

The main reasons for slow dissemination of TRIZ include but not limited to the following issues:
- Long learning curve
- Complexity of tools and methods utilization
- Psychological barriers
- Lack of full scale implementation to prove the effectiveness

Long learning curve is necessitated by the large amount of knowledge that has to be acquired from various sources and via substantial practicing before becoming a
successful practitioner. TRIZ has numerous tools of various complexity without clear
rules which tools have to be used in particular cases. Typical TRIZ knowledge includes
numerous examples and illustrations learned from others and accumulated from own
TRIZ practitioner’s experience that serve as analogies in the problem solving process and
other, mostly tacit knowledge on how successfully utilize TRIZ methods and tools.
Counterintuitive nature of TRIZ forces people think outside of the box, that is, look in
directions that are out of their comfort zone typically defined by psychological inertia.
Although certain discussion on utilization of computers to address at least some of the
problems discussed above took place in the late 1970s¹, by mid 1980s, it became obvious
that TRIZ could greatly benefit from computerization.

Since computers have been introduced, computerization of human activities allowed for
various benefits, including but not limited to expediting numerous processes and making
them more accurate (like calculations), and enabling new forms of activities (like
searching information or buying goods on Internet).

One of the most important benefits of computerization is enabling masses to perform
activities that prior to computers had been a prerogative of professionals. We have plenty
of examples when simple and effective software allowed millions of people to engage
into amazing new activities like making their own presentation slides using Power Point
software or communicating via e-mail thanks to America Online.

The natural way to invent and solve creative problems was always achieved through trial
and error, and was especially effective when applied by gifted inventors. The
methodology encompassed in TRIZ took the first step away from this "human" approach.
TRIZ has little in common with the natural human ways of creative thinking. TRIZ is an
invented method that allows one to achieve the same results as can be achieved with
“natural” creative thinking, but in another, more effective and controlled way.

Similar to TRIZ, TRIZSoft® is the next invented application by which similar results can
be achieved as with TRIZ, but in even more effective and controlled way. In fact, solving
problems with the TRIZSoft is an alternative way of inventing that is parallel to both
"natural" creative thinking and "manual" TRIZ.

¹ In 1978, in the correspondence between Zlotin and Altshuller, a project was discussed outlining
development of a TRIZ-based, computerized system that would allow users to find inventions in patent
libraries through a TRIZ analysis of a situation. For various reasons, the project was never started.
Given the above, computerization of TRIZ seems a logical and inevitable step in further evolution of TRIZ and its wide dissemination.

The first attempt to automate TRIZ was made by G. Altshuller in the mid-1960s when he built an electromechanical version of the Contradiction table with 40 Innovation Principles. The first ideas for utilizing a computer for TRIZ-based inventive problem solving occurred back in the 1970s. During the late 1980s and early 1990s, as far as we know, several teams of TRIZ specialists tried to develop such software products. *Invention Machine* software, based on Classical TRIZ and currently marketed in the USA, was developed in Minsk. The Novator Company in Moscow developed prototypes for two inventing software products: *Edison* and *Novator*. A team led by Professor Zaripov in Tashkent developed software prototype for synthesizing new technological systems through the combination of various physical effects. Other attempts were made as well, with low to moderate success.

**What kind of TRIZ software do we need or what should be computerized in TRIZ?**

The main problems associated with TRIZ computerization could be formulated as follows:

- Multiplicity of TRIZ tools without clear understanding when certain tools should be used.
- Lack of processes covering all necessary steps and tools for problem definition and formulation steps.
- Certain TRIZ tools like Algorithm for Inventive Problem Solving (ARIZ) occurred to be too complex for computerization.

Some of the problems listed above are not specific to TRIZ but rather have more general nature.

The history of software development considers two important periods:
1. "Computerization of formulas", i.e., the development of software for complex calculations according to well-defined methods, algorithms, resolving of equations, etc. At this stage, mathematicians were the project leaders; they could apply centuries of accumulated math experience.

2. "Computerization of human activities", i.e., the development of software that performs operations previously carried out by humans, such as accounting, selling airplane tickets, etc. The experience accumulated by the people who had been performing these procedures was utilized for the purpose of software development. Software analysts, software architects, and other “knowledge” engineers, i.e., people who worked with potential users and absorbed their knowledge and algorithms, became the project leaders.

Computerization of human activities is a part of automation of human activities. Studies in the history of automation show that the most repeatable mistake in the process of automation was that at the beginning, people tried to build machines that copied the human ways of doing things – first locomotives had “legs”, first sewing machines had two “hands”, etc. Historically, these first attempts have not been successful; the real success would come after old technology (process) was replaced with a new one invented with the consideration of automation. In the case of the sewing machine it was the invention of a special needle with the hole in its sharp end and utilization of two threads instead of one used in manual stitching.

Furthermore, today we are often dealing with the computerization of functions not previously even performed by people, i.e., the development of computer systems that have no non-computerized prototypes. Needless to say, in this case, before the process is computerized it has to be invented. Typical example – buying goods using Internet.

Given the above, we can conclude that the following trio has to be involved in development of a prototype-less software:

- Subject matter Expert (SME) knowledgeable in the area of activity automation takes place
- Software development expert
- Expert in methods of inventing

Computerization of TRIZ is another example of such prototype-less activity as the majority of potential users have never applied TRIZ or any other methods for systematic innovation in any form at the first place.

Evolutionary studies show that effective automation (computerization) should follow the pattern of evolution towards decreased human involvement². The pattern establishes the following steps in the process of human replacement:

- in operations
- in management/control of operations

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According to this pattern, another important issue that has to be considered in the process of automation/computerization of a human activity is its “intellectual load” that can vary from rather low for operations to highest for decision making. The “intellectual load” can also vary inside the same group – apparently some operations require more intelligence than the others. In other words, it is quite easy to replace a thousand of people with shovels with an excavator, but it will be rather difficult to replace one excavator operator with computer.

Any problem-solving process involves two main components: the problem itself and the system in which the problem exists. Typically, an inventor tries to eliminate the problem by changing the system. But experienced inventors realize that when faced with a difficult problem, it is helpful to reconsider the problem (i.e., change the problem statement). In 1994, we suggested dividing all TRIZ tools into two groups: analytical and knowledge-base, having in mind that analytical tools operate with the problem while knowledge-base tools operate with the system.

The main purpose of analytical tools is to help develop a comprehensive set of potential problem statements based on various models of the situation and select the most promising ones for further consideration. Typical analytical tools of Classical TRIZ are ARIZ and Substance-Field (SF) Analysis.

Knowledge-based tools represent the best practices on addressing various types of problems suggesting ways for the system transformation that can eliminate the problem and include 40 Inventive (Innovation) Principles with Contradiction Matrix, Separation Principles, 76 Standard Solutions, Collection of Effects, patterns/lines of technological evolution and selected powerful inventive examples.

Below one can see the mapping of the tools of Classical TRIZ on the Traditional Innovation Process.

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3 Ideation Methodology educational materials (Ideation International Inc, 1995).
As one can see from the picture above, classical TRIZ tools don’t provide complete coverage of the entire process, focusing around ideas generation and concept development stage.

The main classical TRIZ tools that could be computerized with the estimation of their “intellectual load” are listed below:

<table>
<thead>
<tr>
<th>Tool type</th>
<th>Name</th>
<th>“Intellectual load”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analytical</td>
<td>ARIZ</td>
<td>Highest</td>
</tr>
<tr>
<td></td>
<td>SF Analysis</td>
<td>High</td>
</tr>
<tr>
<td>Knowledge-based</td>
<td>Patterns/Lines of Evolution</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td>Separation Principles</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td>76 Standard Solutions</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td>40 Inventive Principles and Matrix</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Collection of Effects</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Selected Inventive Example</td>
<td>Low</td>
</tr>
</tbody>
</table>

Obviously, the table above doesn’t look surprising given the number of successful enough attempts to computerize 40 Inventive Principles and Contradiction Matrix and failed attempts to computerize ARIZ or SF Analysis. Another conclusion – knowledge-based tools are much easier for computerization than analytical ones. At the same time, analytical tools of classical TRIZ are not sufficient to support all stages of the innovation process (see the picture above) and are very difficult to computerize.

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5 Invention Machine Corporation had successfully computerized numerous knowledge-based tools like 40 Inventive Principles, 76 Standard Solutions and Effects (Phenomena) but failed in the case of ARIZ.

6 Earlier versions of ARIZ contained a special chapter helping in problem definition using control questions based on system approach. G. Altshuller excluded this chapter starting from ARIZ-1982 because it didn’t meet his requirements for rigorousness.
Given the above, the following tasks had been formulated and had to be resolved before any computerization could take place:

- Develop new analytical tools that would be able to support problem definition and formulation stages and that could be easy to computerize.
- Create a new integrated knowledge-based tool including all accumulated TRIZ knowledge to avoid multiplicity of tools and confusion.
- Create a universal process that will allow all problems be treated in the same way.

All three tasks listed above had been successfully completed between 1989 and 1992 and resulted in the development of the following modules:

- Two new analytical tools, including
  - Innovation Situation Questionnaire®
  - Problem Formulator®
- An Integrated Knowledge-based tool named System of Operators

These new modules allowed for significant simplification of the TRIZ problem solving map (compare two pictures below).

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To support the process above, the main modules of the software should perform the following functions:

<table>
<thead>
<tr>
<th>Module</th>
<th>Function description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Innovation Situation questionnaire</td>
<td>Collection and reorganization of information about the situation and the system facilitating the creative process.</td>
</tr>
<tr>
<td>Problem Formulator and System of Operators</td>
<td>▪ Visualization and automated generation of a practically exhaustive set of directions for innovation (solutions).</td>
</tr>
<tr>
<td></td>
<td>▪ Automated process of suggesting Operators (recommendations) with statistically proven relevance to the selected directions for innovation prompting idea generation.</td>
</tr>
<tr>
<td>Concept development</td>
<td>Consolidation of ideas into concepts</td>
</tr>
<tr>
<td>Evaluation</td>
<td>Evaluation of obtained ideas and their enhancement using selected patterns of technological evolution</td>
</tr>
</tbody>
</table>

New ideas, solutions, concepts, etc., may be found in any stage of the problem solver’s work; the Ideation Problem-Solving Process supports this in the following ways:

- Filling out the ISQ often helps change the user's point of view, reminding the user of information he/she had not previously linked to this problem. This activity, as well as structuring the information about the problem, sometimes helps the user to find the solution even in this early stage.

- Consideration of the Directions for Innovation formulated by the software sometimes allows for the revealing of new approaches not previously considered; sometimes these problems are easy to resolve.

- Applying the Operators and examples-analogs for problem solving is the major stage for the revealing of new ideas.

- The improvement of ideas and the solving of secondary problems by applying Operators and Lines of Evolution prompts new ideas and solutions, as well.

In addition to the above, the software generates a list of ideas and full report of work.

**Using TRIZSoft**

Ten years of experiments enabled the most effective ways of using TRIZSoft to be identified, both for individual work and teamwork.

**Individual Work**
• The step-by-step solving of problems of average to high complexity through the application of the entire Ideation Problem-Solving Process.

• The solving of simple problems through the application of the Express Process.

While working with the software, the user accumulates experience and repeatedly uses his/her own materials (diagrams, ideas, etc.) For example, diagrams made for one problem might be applicable, with some editing, for other problems related to the same system; ideas and solutions that occurred, but were not used in one situation, might be useful for other problems. This means that while working with the software the user creates his/her own “creative library.”

TRIZSoft allows remarks, comments, examples to be added to the software screens by the user, allowing for partial "customization" of the software.

**Team Work**

TRIZSoft is most effective if used with teams consisting of at least two experts. This is due to the fact that discussion among team members allows for a more precise description of the problem situation in the Diagram, as well as a better understanding of Directions and recommendations, etc. The Ideation Brainstorming mode is highly recommended for teamwork.

**Assessment of the effectiveness of the TRIZSoft™ Support for Problem Solving**

**Generation of concepts**

While using TRIZSoft with the Problem Formulator, the user can regard any problem situation as a combination and interaction of useful and harmful functions. The average problem situation is usually "sliced" into 50 – 100 functions (boxes); a complex situation might comprise thousands. In the preliminary formulation mode, the software formulates one problem for each function (plus additional problem statement for contradictions); this means that 100 to 300 problems are formulated when analyzing the average situation.

For each problem, the software suggests between five and twenty Operators, where each is a potential recommendation for resolving the problem situation. As a result, the user obtains several hundreds of recommendations aimed at resolving the problem. We are confident that this represents a practically exhaustive set of concepts; there is no reason to increase this number; to the contrary, the subsequent steps of the problem-solver’s work are aimed toward reducing this number by selecting the most effective Directions/concepts.

**Attention:** TRIZSoft completely modifies the traditional approach taken in inventive problem solving; instead of activating a search for variants of solutions, the user’s focus

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is directed to a selection of variants, which is close to “usual” engineering work. It is safe to assume that there are two approaches to improving and evolving systems:

- **Rooster Approach:** The search for a pearl through trials of variants; this approach is used in many methods of problem-solving, the difference is in the ways the trials are made.

- **Gold Prospector’s Approach:** Generating many potential directions and concepts, then rejecting some according to specified criteria, as in sluicing the gold ore; this is the TRIZSoft approach.

**Selecting Directions/concepts**

The first step in this selection is made during the process of analyzing the Directions; this selection is aimed at rejecting Directions that are either of little interest for problem-solving or do not meet the goals of the particular project. Usually, from 2/3 to 9/10 of Directions are rejected at this step.

The second step in the selection process is made while working with Operators; this selection is aimed at rejecting those recommendations which either cannot be provided with the necessary resources, or which result in secondary problems that are too complex to be dealt with. Usually, from 1/2 to 9/10 of the remaining recommendations are rejected at this step. As a result, from one to several dozen Directions/concepts remain for resolving the average problem situation.

According to our experience, the solutions that are plausible for the customer begin to appear during the first stage of work.

**Assessment of Time Consumption of the Problem-Solving Process**

Problem solving through the Trial-and-Error method seems like an instant process: there was no solution, then it occurred as a result of circumstance and rare coincidence. However, it can take weeks, months, or even years before the next solution occurs.

Tedious work is the price to be paid when utilizing TRIZSoft. It typically takes from 5 to 15 minutes to find one solution, whether the solution is plausible or not. However, there is no pause between the occurrence of solutions, and a TRIZ specialist can find about 20 – 50 solutions per working day. For the average problem, the probability is high that a plausible solution will be among the first dozen ideas.

**TRIZSoft® Suite**

Based on considerations above we have developed a suite of TRIZ based software as follows (see more detail history in Appendix 2):

Inventive Problem Solving (IPS):
- Eureka on demand – introductory level software
- Ideation Brainstorming (IBS) – medium level software
- Innovation Workbench (IWB)® - professional level software\(^9\)
- Knowledge Wizard (KW) – professional level software for non-technical problems

Anticipatory Failure determination (AFD)®:
- Ideation Failure Prediction
- Ideation Failure Analysis

Also, the following two software are in development:
- Directed Evolution ®software
- Intellectual Assets Management software

Software for IPS support the following steps of the innovation process:

<table>
<thead>
<tr>
<th>Process steps</th>
<th>IPS Software</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Eureka</td>
</tr>
<tr>
<td>Problem definition</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Problem formulation (modeling)</td>
<td>Function modeling</td>
</tr>
<tr>
<td>Idea generation and concept development</td>
<td>Limited set of Operators</td>
</tr>
<tr>
<td>Evaluation of results</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Conclusions**

1. Computerization of TRIZ is an inevitable evolutionary step; it follows the powerful trend of utilization of informational technologies for computerization of human’s activities facilitating word processing, graphic design, information search and others.
2. Computerization of TRIZ is absolutely necessary step in wide TRIZ dissemination demonstrating the depth of TRIZ knowledge and power of its tools.
3. TRIZ couldn’t be computerized as it was – it had to be restructured; tools that are difficult to computerize had to be modified and/or replaced with the ones that provided similar results using more computer-friendly approaches.
4. A suite of TRIZ based software (TRIZSoft®) has been developed including eight programs (two are in development) to support all TRIZ applications (Inventive Problem Solving, Failure analysis and prediction, Directed Evolution and Validation and Enhancement of Intellectual Property).

\(^9\) A brand new version IWB 2005 has been recently released.
References


3. Ideation Methodology educational materials (Ideation International Inc, 1995)


Appendix 1: The history of TRIZSoft™ development

The Kishinev TRIZ School embarked on the development of software based on theoretical research aimed toward the re-engineering of so-called “classical” TRIZ. A brief chronology of this software development is listed below:

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1978</td>
<td>A project was outlined for developing a TRIZ-based, computerized system that would allow users to find inventions in patent libraries through a TRIZ analysis of a situation. This project was discussed in correspondence between Zlotin and Altshuller; it was never performed.</td>
</tr>
</tbody>
</table>
- The first prototype software for forecasting, called Cassandra”, including a special module for forecasting evolution of systems for measurement and control, was built |
| 1992 | - The first hypertext prototype, called "Inventor Toolbox" (later renamed the Innovation Workbench System, or IWB®) was completed in April  
- The first DOS prototype of Problem Formulator® was completed |
| 1993 | - First presentation of the IWB® in the U.S.  
- First integrated DOS version of the IWB® |
<p>| 1994 | First IWB sold in the U.S. |
| 1995 | Development and sales of the Eliminator™ and Improver™ software products |</p>
<table>
<thead>
<tr>
<th>Year</th>
<th>Events</th>
</tr>
</thead>
</table>
| 1996 | • Development of the "Opershow" system for modeling TRIZ logic  
• Development of a graphical Problem Formulator®  
• Development and sales of IWB® for Windows  
• Development and sales of Ideator® software |
| 1997 | Development and sales of the Anticipatory Failure Determination (AFD®) software |
| 1998 | Development and sales of the IWB® for Windows-95 |
| 1999 | Development of Knowledge Wizard™ software |
| 2001 | • Introducing basic TRIZ e-learning course software  
• Introducing IWB Master program with embedded e-learning  
• Introducing Ideation Failure Analysis and Failure Prediction software with Problem Formulator®  
• Start of development of Directed Evolution® software |
| 2002 | • Introducing Ideation Failure Analysis and Failure Prediction software with e-learning  
• Introducing an integrated system of software and educational materials TRIZSoft®  
• Development of software for solving scientific problems (not completed)  
• Development of a chemical module for the IWB software (not completed) |
| 2003 | • Integration of ISQ® and PF® into software for managing resources for the Stage Gate system |
| 2004 | • Introducing Ideation Brainstorming software  
• Introducing Eureka on Demand software |
| 2005 | • Introducing IWB 2005 – a brand new version with numerous user friendly features  
• Introducing Ideation brainstorming software 2.3 with the new interface  
• Introducing Eureka on Demand 2.1 with the new interface |

**Appendix 2: Containment ring case study**

**Innovation Situation Questionnaire**
Brief description of the situation
The engineered system, which is designed to contain the fragments resulting from an impeller burst of a maximum-speed fan, consists of the following: a fan, fan shroud (which controls the direction of the air stream), and an armor-steel containment ring. The problem to be solved is that the ring is too heavy and must be reduced in weight by 50%.

Working with typical problems: Operators for reducing weight:

Ideas generated at this stage:

Idea # 1
Vary the thickness of the ring tube, reducing the thickness where permissible.
Idea # 2
Determine where the ring usually breaks and reinforce those places.

Detailed description of the situation

Supersystem - System - Subsystems

System name
The following systemic levels can be considered:
- Containment ring
- Fan
- Air conditioning system
- Aircraft
- Testing of ring
For the **ring**, the problem is:
the ring must be strong to withstand the impact of the impeller fragments, and the ring should not be heavy.

For the **fan**, the problem is:
the impeller can burst, but fragments should not fly away.

For the **air-conditioning system**, the problem is:
the impeller can be broken, but the air should be conditioned.

For the **aircraft**, the problem is:
the impeller can burst, but neither people nor equipment should be harmed.

For **testing the ring**, the problem is:
the ring's ability to capture flying fragments should be tested, but it is difficult to move the heavy ring back and forth.

Idea # 3
Make the ring as an assembly made of light-weight parts that are easy to move for testing purposes.

We can influence two systemic levels: the ring and the fan assembly. Let's select the fan assembly as the system to be considered.

**System structure**
The fan assembly consists of the following elements:
- fan
- motor
- shaft
- motor support
- containment ring
- connectors or support to keep the ring

**Supersystems and environment**
Other parts of the air conditioning system:
- pipes
- heat exchanger
- airflow distributors

Other systems located nearby:
- aircraft covering
- equipment

Other system interacting with the fan and air conditioning system:
- electrical power supply
- air supply
- exhaust air removal
- vibration dampers

Conditions around the system:
- indoor conditions
**Systems with similar problems**

Similar problems exist in many other areas where weight and mechanical strength are critical issues, as well as other systems for protection against flying parts. We do not have any information about how these problems have been addressed.

**Input - Process - Output**

**Functioning of the system**

The primary useful function of the fan is to supply (move) air for the air conditioning system.

The fan rotates quickly and moves air. The air is conditioned so that the aircraft cabin can be supplied with conditioned air.

**System inputs**

Fan assembly inputs:
- voltage
- intake air flow

**System outputs**

Fan assembly outputs:
- output air flow
- noise and vibration

**Cause - Problem - Effect**

**Problem to be resolved**

Reduce the weight of the ring by 50%.

The primary harmful function of the given system (the fan assembly) is that impeller fragments fly away if the impeller bursts.

**Mechanism causing the problem**

The containment ring must be strong to contain the flying fragments - for this reason the ring is thick and, as a result, heavy.
The cause of an impeller burst is as follows: Rotation of the fan results in centrifugal forces that "pull" the parts of the impeller. The strength of the impeller material can be compromised by material defects and fatigue. As a result, the impeller can burst, causing the impeller fragments to fly off. Due to the high speed at which the fan rotates, the flying fragments carry high energy and can harm people and other parts of the aircraft.

**Undesirable consequences if the problem is not resolved**
The high weight of the ring makes it difficult to carry out the routine tests required by the FAA.

The "dead weight" of the aircraft equipment is also high.

If the weight problem is resolved at the expense of the ring's strength, the result will be inadequate protection from the flying impeller fragments, which in turn can result in death and/or damage.

**Other problems to be solved**
Use an alternative method to contain the fragments.

Make the impeller unbreakable.

Others (see the problems on different systemic levels in the beginning of the ISQ).

**Past - Present - Future**

**History of the problem**
The increased requirements for conditioning the air are met using a higher velocity airflow, but this means that the rotational speed of the fan increases. As a result, an impeller burst becomes more probable and the danger from the flying fragments increases. Because the energy of the flying fragments is increased, the ring must be stronger. As a result, the ring is heavier.

Idea # 4
Provide high airflow with low rotational speed of the fan. Perhaps utilize several slow fans instead of one that rotates quickly.

Known attempts to reduce the ring thickness resulted in a reduction in strength.

**Pre-process time**
Time before the fan is turned on.

**Post-process time**
Time after the fan is turned off.

**Resources, constraints and limitations**
Available resources

Substance resources
- Material of containment ring
- Material of fan impeller
- Other objects around
- Airflow

Field resources
- Mechanical forces
- Airflow energy
- Electrical energy
- Magnetic field (motor)

Space resources
- Space inside the ring
- Space outside the ring

Time resources
- Time during which the fan is not operating
- Time when the fan is operating
- Time before the impeller bursts
- Time after the impeller bursts

Informational resources
- No special resources

Functional resources
- Rotation

Allowable changes to the system
- Drastic changes are allowed.
- Any reduction in strength is unacceptable.

Constraints and limitations
- Cost increase of no more than 5%
- About two weeks for new design
- One year for implementation

Criteria for selecting solution concepts
- Weight reduction of at least 30%

Problem Formulation and Brainstorming
Idea # 5
Find an alternative way to obtain \textit{Fan rotates quickly} that offers the following: provides or enhances \textit{Fan moves air} does not cause \textit{centrifugal forces pull parts of impeller} and \textit{High energy of fragments}.

Resolve the contradiction: The useful \textit{Fan rotates quickly} should provide \textit{Fan moves air} and avoid \textit{centrifugal forces pull parts of impeller} and \textit{High energy of fragments}.

Find an alternative way to obtain \textit{Fan moves air} that does not require \textit{Fan rotates quickly}.

Find a way to eliminate, reduce, or prevent \textit{centrifugal forces pull parts of impeller} in order to avoid \textit{Impeller burst} under the conditions of \textit{Fan rotates quickly}.

Idea # 6
Reduce the mass of the fragments to reduce damage.

Find a way to eliminate, reduce, or prevent \textit{High energy of fragments} in order to avoid \textit{Damage to the aircraft} under the conditions of \textit{Fan rotates quickly}.

Find a way to eliminate, reduce, or prevent \textit{Damage to the aircraft} under the conditions of \textit{High energy of fragments} and \textit{Fragments flying away}.

Find a way to eliminate, reduce, or prevent \textit{Impeller burst} in order to avoid \textit{Fragments flying away} under the conditions of \textit{centrifugal forces pull parts of impeller} and \textit{Impeller's material is not strong enough}.
Find a way to eliminate, reduce, or prevent Fragments flying away in order to avoid Damage to the aircraft under the conditions of Impeller burst.

Find a way to eliminate, reduce, or prevent Impeller's material is not strong enough in order to avoid Impeller burst under the conditions of Material defects.

Find a way to eliminate, reduce, or prevent Material defects in order to avoid Impeller's material is not strong enough.

Find an alternative way to obtain Ring is thick that offers the following: provides or enhances High mechanical strength does not cause Ring is heavy.

Resolve the contradiction: The useful Ring is thick should provide High mechanical strength and avoid Ring is heavy.

Find a way to eliminate, reduce, or prevent Ring is heavy under the conditions of Ring is thick.

Find an alternative way to obtain Test convenience that is not influenced by Ring is heavy.

Find an alternative way to obtain High mechanical strength that offers the following: provides or enhances Ring contains fragments does not require Ring is thick.

Idea # 7
Perform testing without removing the ring.

Find an alternative way to obtain Ring contains fragments that offers the following: eliminates, reduces, or prevents Fragments flying away does not require High mechanical strength.

Idea # 5
Utilize a "weak" ring that will absorb energy as it is destroyed.

Selected Directions and ideas generated with working with Operators recommended by the software to address selected directions
Idea # 7
Find a way to eliminate, reduce, or prevent Impeller burst in order to avoid Fragments flying away under the conditions of centrifugal forces pull parts of impeller and Impeller's material is not strong enough.

Idea # 8
Improve the mechanical strength of impeller blades
Idea # 12
Use styrofoam or similar substance to absorb flying pieces.

Idea # 13
Explode the ring the moment the impeller bursts. Use the explosion wave to create a counteracting force.
Idea # 9
Use foam or foam-like material to absorb energy. Apparently, we need a special type of foam such as metal foam. We can also consider other fillings that can absorb energy.

Idea # 10
Define the least dangerous directions and redirect the fragments in these directions.

Idea # 11
Distribute the harmful energy between more of the fragments.

Idea # 14
Create a special pathway (spiral) to trap the fragments and to reduce their energy while traveling through the spiral route (see ideas # 22 and 24). Also, see idea # 26: absorb the energy.

Resolve the contradiction: The useful factor *Ring is thick* should provide *High mechanical strength* and avoid *Ring is heavy*. 
Idea # 15
Make a thin ring that has reinforcing ribs. If the ribs are placed on the internal surface of the ring, flying fragments will lose much of their energy smashing into the ribs.

Idea # 16
Use a multi-layer ring: additional strengthening rings, rings having different hardness and elasticity, rings which have a gap in between them, filling the gap with an energy-absorbing material.

Idea # 17
Replace the ring with an airbag that inflates when the impeller bursts.

Idea # 3
Make the ring as an assembly made of light-weight parts that are easy to move for testing purposes.

Idea # 18
Change the ring thickness or strength or other containment capabilities the moment the impeller bursts.

Find a way to eliminate, reduce, or prevent Ring is heavy under the conditions of Ring is thick.

Idea # 19
Vary the thickness of the ring tube, reducing the thickness where permissible.

Idea # 20
Reduce the energy of the fragments by reducing their weight (i.e., help the impeller break into smaller pieces). This will allow the ring to be made less strong and thus lighter.

Idea # 21
Introduce preliminary stress. For example, use additional rings which have been pressure-fitted to create a force directed toward the inside of the ring.
PM Idea # 22
Use thermal treatment to harden the ring material.

Idea # 23
Use light and strong alloys

Idea # 24
Use light and viscous alloys capable of absorbing the impact.

Idea # 25
Use light and elastic alloys capable of absorbing the impact.
Idea # 26
Use special reinforcing threads (fibers) such as those found in bullet-proof vests.

Idea # 27
Use an airbag that inflates when the impeller bursts.

Find an alternative way to obtain *Test convenience* that is not influenced by *Ring is heavy*.

Idea # 28
Make the ring as an assembly made of light-weight parts.

Idea # 29
Disposable ring - consider that the ring will be destroyed while absorbing all the energy of the fragments.

Idea # 30
Consider various types of support while transporting the ring.

Idea # 31
Learn the details of the transporting process and look for the ways to reduce the number of liftings.

Find an alternative way to obtain *High mechanical strength* that offers the following: provides or enhances *Ring contains fragments* does not require *Ring is thick*. 
Idea # 32
Make a thin ring that has reinforcing ribs. If the ribs are placed on the internal surface of the ring, flying fragments will lose much of their energy smashing into the ribs.

Idea # 33
Make the ring corrugated in two planes.

Idea # 34
Determine where the ring usually breaks and reinforce those places.

Idea # 35
Internal ribs with sharp edges can counteract flying fragments, breaking them into smaller pieces.

Idea # 36
Use thermal treatment to harden the ring material.

Idea # 37
Use a multi-layer ring: additional strengthening rings, rings having different hardness and elasticity, rings which have a gap in between them, filling the gap with an energy-absorbing material.
Idea # 38
Make the ring out of separate layers so that if cracks develop inside they will not spread.

Idea # 39
Use a multi-layer ring with elastic bonds between strong layers.

Idea # 40
Use metal-concrete or some other composite material.

Idea # 41
Create inner stresses inside the ring: This can be done using wiring, banding, double ring structure, etc.

Find an alternative way to obtain Ring contains fragments that offers the following: eliminates, reduces, or prevents Fragments flying away does not require High mechanical strength.

Idea # 42
Explode the ring the moment the impeller bursts. Use the explosion wave to create a counteracting force.

Idea # 43
Disintegrate the fragments.

Idea # 44
Utilize special geometrical shapes to create traps for the fragments. For example, make the ring in the form of spring.

Idea # 45
Create a combination of pressurized air and liquid to counteract the fragments.

Idea # 46
Use a counteracting explosion.
Idea # 47
Create a safe pathway for the fragments.

Idea # 48
Introduce strong fibers in the impeller blades that are capable of holding the fragments after the impeller bursts.

Develop Concepts
We can categorize the obtained ideas into the following groups:
1. Strengthening the ring via
   - changing the ring material structure:
     - creating inner stresses (wiring, banding, press-fit) (#41, 21)
     - introducing special reinforcing threads (fibers), using metal-concrete or other composite materials (# 26, 40, 48)
     - special thermal treatment for hardening the ring material (# 22)
     - using a multi-layer ring with layers with different properties (elasticity, hardness, gaps filled with energy-absorbing materials) (# 37)
   - changing the ring's shape:
     - vary the ring thickness to best accommodate the situation (# 1, 2)
     - create various reinforcing ribs (# 15, 32)
     - use two-plane corrugations (# 33)
2. Increasing the ring's energy-absorbing properties via
   - changing the material structure:
     - using foam and/or foam-like materials (metal foam, honeycomb, wiring, brushes) (#5, 45, 9, 29)
     - using a multi-layer ring with layers capable of moving relative to one another to absorb extra energy
   - b) changing the ring's shape:
     - spiral or other traps that can slow down the fragments (#44)
3. Reducing the mass/energy of the flying fragments to reduce damage and allow the ring's mechanical strength to be lowered via
   - changing the ring's material structure to make it capable of breaking into smaller pieces (# 6, 11, 43)
   - introduce ribs with sharp edges capable of breaking fragments into smaller pieces (# 15, 32, 35)
4. Improve testing convenience, including:
   - perform the test without removing the ring (# 7)
   - make the ring dismountable and transport parts of the ring rather than the whole thing (# 3, 28)
   - consider various types of special support during ring transport (# 30)
5. Strengthen the impeller blades to eliminate the need for the ring (#48)
6. Define or create a safe pathway for the fragments (# 10, 14, 47)
7. Change the principle of operation of the ring, including:
   - replace the ring with an airbag that inflates the moment the impeller bursts (# 17, 27) or change its thickness (# 18)
• explode the ring to create a counteracting force (# 13, 42) and/or break the fragments into smaller pieces
8. Replace the impeller with a safer method of providing air (# 4)

Evaluate Results

Meet criteria for evaluating concepts
The following concepts were selected:

For short-term:
1. Multi-layer ring
2. Ring with ribs

For mid-term: Explosive ring.

For long-term: Blades with fibers (wire) inside to keep pieces in place.

The short-term idea of utilizing a multi-layer ring creates a subsequent problem - the increased cost associated with manufacturing the different layers and with the final assembly of the ring.

We therefore have a subsequent problem - reduce cost.

Idea # 49
Instead of manufacturing several layers and assembling them later, use surface hardening of the internal and external surfaces of the ring. Hardening the inner surface will allow the ring to better counteract the fragments. Hardening the outer surface can create additional inner stresses that in turn increase the ring's overall strength. Together, these measures should allow the weight of the ring to be reduced without sacrificing its containment capabilities.