Define, Measure, Analyze, Innovate, Control

By

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Abstract

Many companies today have implemented six sigma programs using the Define, Measure, Analyze, Improve, Control (DMAIC) methodology. In general, these initiatives have been very successful at keeping a company operating at peak efficiency. However, many companies have found that most of the benefits come in the first year or two after six sigma implementation. This is because six sigma is statistically based and it is most effective at optimizing existing operations. Once a process is operating at near optimal conditions, process improvements are required to sustain a stream of benefits. Incremental improvements are relatively easy to identify. Breakthrough improvements require innovation. Innovative problem solutions that are implemented through six sigma result from traditional brainstorming methods or simply through serendipity. This paper describes a structured method to generate a large number of innovative solution options, which can serve as an effective front end to six sigma.

Six Sigma and Diminishing Returns

Many companies find that their returns on six sigma decline over time (see Figure 1). Some speculate that this results from a loss of commitment, a Hawthorne effect or a structural failure of six sigma itself.

A more rational explanation can be found in the very nature of problems and solutions. We can consider problems at one of five levels as shown in Figure 2.
Level 1 problems are Inspection problems. The answer to the problem is known. No innovation is required. For example, if a chemical reaction is off spec and we know that raising the temperature 5 degrees will get back on spec.

Level 2 problems are Engineering problems. In this case we don’t know the answer but we know how to get it. We know how to do the calculations or run models. Multiple options may need to be evaluated. While the problems are more complex and more than one solution is possible, there is minimal innovation involved. For example, if we are to design a system to pump 100 gallons of water per minute to the top of a building, there is some room for creativity, but the design alternatives are generally known.

Level 3 problems are Research problems. In this case, the existing problem solutions are inadequate or there are no known solutions. In this case we apply the scientific method.

1. We first define the problem.
2. Then we develop hypotheses to resolve the problem.
3. Then we design experiments to test the hypothesis. We run the experiments and gather data.
4. We evaluate the experimental results to validate the hypothesis.

If the hypothesis is validated then a solution has been found. If not then steps 1-4 are repeated until an adequate solution is found. This is a trial and error process. Multiple solutions are possible and no adequate solution is guaranteed. Developing a new catalyst with superior yield and selectivity is one example.

Over 90% of the problems we face are solved with solutions at Levels 1 and 2. These solutions are quick and relatively easy to implement, but their financial impact is typically incremental.
Level 3 problems can take a long time to develop and implement but they often produce significant results or paradigm shifts. So, when a company starts a new six sigma effort, it develops level 2 solutions that quickly float to the surface and are effectively implemented with traditional engineering tools. But once this low-hanging fruit has been picked, the high impact Level 3 solutions become more elusive. Most of the problem solutions implemented in six sigma projects are at level 2. The result: an apparent decline in six sigma productivity.

How do people naturally solve creative problems? The process usually goes something like this.

1. Define the problem
2. Analyze the problem to understand cause and effect
3. Abstract a principle that was used to solve an analogous problem
4. Combine this principle with the resources available in the current problem to form an hypothesis
5. Mentally test the hypothesis for applicability

Our ability to generate creative options for solution is depicted in Figure 3.

As we gradually accumulate knowledge about a problem, we increase the number of solution options. However, time is a limited resource. Six sigma projects are to be completed in a few months at most. What is needed is a method to quickly analyze a problem to understand cause and effect followed by a structured algorithm to rapidly generate potential solutions.
Pretium Methodology for Structured Innovation

Pretium Innovation has developed a simple but extraordinarily effective method for innovative problem solving as shown in Figure 4.

Fig. 4. Pretium’s Methodology

The first step is a Situation Assessment. Here we gather information about the problem. What is the problem we need to solve? Why do we think this is a problem? What are the consequences of not solving the problem? Who will benefit from solution of the problem? What limitations and constraints do we face? How can we tell when the problem is solved?

Following this, we build a function model of the system that contains the problem. The concept of function models was developed by Charles Bytheway at General Electric in 1965. Bytheway built on the work of Lawrence Miles, the father of Value Engineering. The technique Bytheway developed was called Function Analysis System Technique or FAST. Pretium has adapted and extended FAST. Function models are used to deconstruct problems and reveal cause-effect relationships. In building function models, we consider two types of functions, useful and harmful as shown in Figure 5.
Useful functions are shown in green and harmful functions are shown in red. The arrows connecting the functions describe their relationship. A solid arrow means that the first function produces the second function. An arrow with a short line through the shaft means that the first function counteracts the second function. There are eight basic relationships that can exist as shown in Figure 5. In any function model, there are only three things we can do to improve system functioning.

- Improve a useful function
- Reduce or eliminate a harmful function
- Resolve a contradiction.

A contradiction exists when one useful function produces a second useful function and also produces a harmful function as shown in Figure 6.

Contradictions are particularly interesting and valuable. Engineers love to compromise or optimize around contradictions. However, if we can find a way to resolve the contradiction such that compromise is no longer required, then we have an innovative and often high value solution.

The third step in our process is Guided Innovation with TRIZ. TRIZ is the Russian acronym for Theory of Inventive Problem Solving. This theory was first developed by Genrich Altshuller in 1946. At the time, Altshuller was a patent agent in the Soviet Navy and he saw a lot of patents, both foreign and domestic, come across his desk. He began to question whether invention was the result of creative genius alone or was there a structure or method by which inventions were made? Altshuller studied about 200,000 patents looking for structure in the inventions. Of the 200,000 patents he examined, he identified about 40,000 that embodied innovations. A further study of these 40,000 odd patents revealed 40 patterns of invention. These patterns are themes or abstractions that recur many times. Altshuller believed that these patterns could be the basis for an innovation algorithm.

In December 1948 Altshuller wrote a letter to Joseph Stalin addressed “Personally to Comrade Stalin.” He told Stalin that there was chaos and ignorance in the USSR’s approach to innovation and that he had discovered a theory that could make the Soviet people the most
innovative people in the world. Altshuller was in fact a patriot but his actions were treated as treason. Two years after he wrote to Stalin, he was arrested and sentenced to 25 years in prison. He was transferred to Siberia’s Gulag where he worked as a logger and he also worked in the Varkuta coal mines. Throughout his incarceration, he continued to develop his TRIZ theories. A year and a half after Stalin’s death, amnesty was granted to many political prisoners and Altshuller was released.

Over his lifetime, Altshuller developed a number of innovation algorithms including ARIZ-71, ARIZ-77 and ARIZ-85. Virtually all of this work went unnoticed in the West because of the cold war. With the advent of Perestroika and the fall of the Soviet Union, Altshuller’s work became recognized throughout the world. In 1992 the leading TRIZ scientists in the world relocated to the United States. TRIZ now has over 50 years of research and development and has been used to solve thousands of inventive problems in a wide variety of disciplines.

There are four fundamental concepts in TRIZ, which are essential to understanding and using TRIZ. The first concept is “contradiction”. We have already seen how contradictions manifest themselves in function models. When Altshuller studied his initial group of patents, he was looking for inventive solutions to problems. Altshuller observed that most technical problems contain at least one contradiction. For example, in producing high density polyethylene (HDPE) resins for use in detergent bottles, it is necessary for the bottles to have good environmental stress crack resistance so that the bottles will not crack and leak due to the chemical activity of the detergent. Adding a comonomer such as butene or hexene to the resin can increase environmental stress crack resistance. It is also necessary for the bottles to have good sidewall stiffness so that cases of bottles can be stacked on top of each other during shipment and storage. Flexural modulus (stiffness) decreases as comonomer level is increased. The contradiction as shown in Figure 7, is that we want the comonomer content to be high so that we have good environmental stress crack resistance, but we want the comonomer to be low so that we have good sidewall stiffness.

An engineering solution to this problem seeks to compromise or optimize by finding an acceptable balance of useful and harmful effects. An inventive solution, by contrast, resolves the contradiction. Because inventive solutions resolve contradictions, they have a greater economic potential than engineering solutions and will often result in paradigm shifts in a product or industry. Not all contradictions can be resolved, however. In this case we have a
paradox. Because resolution of contradictions is at the heart of the TRIZ approach to problem solving, it offers the best method for identifying inventive problem solutions.

The second concept in TRIZ is “ideality”. Research of the worldwide patent library and other sources of inventive achievements have revealed the following general pattern: Technological systems tend to evolve in the direction of increasing ideality. In other words, systems become smaller, less costly, more energy efficient, pollutes less, and so on. We can define ideality as the ratio of a system's useful functions to its harmful functions.

Functions are activities, actions, processes or operations related to your system. A system's useful functions include the following:

- primary useful function – the purpose for which the system was designed
- secondary functions – other useful outputs that the system provides in addition to the primary useful function
- auxiliary functions – functions that support or contribute to the execution of the system's primary useful function, such as corrective functions, control functions, housing functions, transport functions, etc.

A system's harmful functions include all harmful activities associated with the system such as the cost to design it, the space it occupies, the noise it emits, the energy it consumes, the resources needed to maintain it, manufacturing costs and so on. The best solution to a problem is one that advances a system on its evolutionary path toward ideality. Therefore, ideality should always be kept in mind during problem solving, like a beacon that guides problem solvers to the best solution. This is exactly what Leonardo da Vinci was expressing when he said, "Think of the end before the beginning." He understood the importance of envisioning an ultimate, ideal goal.

The third concept in TRIZ is "resources". Resources are properties or attributes that provide us with the ability to increase system ideality. There are six classifications of resources.

- Functional – the capability of a system or its surroundings to perform additional functions including super-effects.
- Fields – any kind of energy, action or force available in the system or its environment. This includes mechanical, thermal, electrical, chemical, magnetic or electromagnetic fields.
- Information – additional information about the system that can be obtained with the help of dissipation fields, matter or fields passing through the system.
- Substances – materials that make up the system and its surroundings.
- Space – free, unoccupied space existing in the system and its surroundings.
- Time – time intervals before the start, after the finish, and between cycles of a technological process, which are partially or completely unused.

The importance of resources is quite simple. We must have resources to solve a problem. If we can resolve contradictions using available resources, then we will increase the ideality of the system. TRIZ specialists look very hard for available latent and derived resources that can be
employed to improve useful functions, reduce or eliminate harmful functions or resolve contradictions.

The fourth concept in TRIZ is inventive principles. In Altshuller's original work he identified 40,000 patents that embodied inventive solutions, solutions that resolved one or more technical contradictions. This heroic work was done in a time when computers and databases were a thing of the future. Altshuller looked at the resources employed to solve these inventive problems and examined the trends toward ideality. From this study he developed 40 inventive principles. The inventive principles are themes or abstractions found in inventions that are repeated over and over. Altshuller determined that the inventive principles could be applied to solve a broad spectrum of inventive problems and he developed an innovation algorithm, a step-by-step procedure to generate inventive problem solutions. There is some debate today about how many fundamental inventive principles there are. At Pretium we use a practical set of inventive principles as an aid in brainstorming.
Sample Problem

Let's consider a sample problem to illustrate how Pretium's Methodology can be used to accelerate the realization of benefits from six sigma. High purity copper sheet is produced electrolytically by placing a source of raw copper and a high purity starter sheet into an electrolyte and then applying a direct current. Figure 8 shows one example of electrolyte tanks.

![Electrolytic Copper Process](image)

Figure 8

Figure 9 shows the pure copper sheets being extracted from the electrolyte tanks.

![Electrolytic Copper Process](image)

Figure 9

As current is increased, the production rate of purified copper increases. However, as current increases, pores begin to appear on the surface of the copper sheets. When the sheets are removed from the electrolyte, some electrolyte becomes trapped in the pores and after the water evaporates from the pores, black spots appear on the surface resulting in a quality defect.
To counteract this problem, a high pressure washing system is used to rinse electrolyte from the pores. Our mission is to consider projects to reduce operating cost, improve quality, increase throughput and/or reduce the capital cost to install an electrolytic copper process.

We could attack this problem with the six sigma DMAIC process: Define, Measure, Analyze, Improve, Control. The project progress might look like this.

Define: Identify the customer, define internal and external critical to quality criteria (CTQC), build a business case for improvement, define measures of success, develop a project schedule.

Measure: Define the major steps in the process, identify key input variables, identify key output variables, determine if measurements are reliable by running gage repeatability and reproducibility. The flow chart might look like Figure 10.

Analyze: Measure process baseline capability ($C_p$), conduct regression analyses on key process variables, conduct a failure modes and effects analysis (FMEA), conduct hypothesis testing using ANOVA.

Improve: Identify critical to success independent variables, conduct designed experiments (DOE) to establish causality and define quantitative relationships between critical input and output variables. Determine optimum settings for key input variables (KIVs) and key output variables (KOVs).

Control: Document optimum process settings, establish out-of-control action plans to bring the process into a state of optimal control, document changes in ISO procedures, train all plant personnel in operating changes, and calculate benefits.

At the end of this six sigma project, we would know things like the following.

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*The ISA Process And Its Contribution To Electrolytic Copper*, Presented at the Rautomead Conference, Scotland, UK, August 1999 by Wayne Armstrong, Copper Refineries

Figure 10
• Maximum current level at which we can operate and still produce in-spec product
• Optimum washing time, pressure and flow rate
• Process set points required to optimally run the process
• Capital cost reductions that result from reduction of excesses in equipment
• Maximum operating profit expected given quality parameters

Six sigma works to understand variation in a process and reduce cost (operating and capital) by reducing controllable variation and maximizing profit by developing correlations between key input and output variables. The process as defined is now running as well as it can be run, given the existing process design. In the course of studying the operation of the process, some process improvement ideas may occur to the engineers involved based on their experience and subject matter expertise. These can lead to add-on six sigma projects to change the underlying process design. But how can we systematically develop these process improvement ideas?

Enter Pretium’s Methodology for Structured Innovation

Situation Assessment in Pretium’s methodology might proceed much like the Define step in six sigma. Function modeling, however, represents a departure. A function model of the process might look like Figure 11.

![Function Model for Copper Refining](image)

The primary model is built by asking “How” and “Why”. We start with the primary function, “Purify Copper”. Notice that this function is the combination of a verb and a noun. Charles Bytheway said that functions should always be the combination of a verb and a noun. Then we ask how do we Purify Copper? The answer is by Supplying Electrolyte, Supplying Electric...
Current and Supplying Raw Copper. Moving against the direction of the arrows in Figure 11 we ask “How”. The validity of the logic can be tested by moving in the direction of the arrows and asking Why. Why do we Supply Electrolyte? To Purify Copper. Why do we Supply Electric Current? To Purify Copper. Why do we Supply Raw Copper? To Purify Copper.

After the primary function model is built we examine each function and as “When”? When this function is performed are there any consequential functions good or bad that occur? When we Supply Electric Current the High Current Produces Pores. The Pores Contain Electrolyte. The Electrolyte Oxides the Surface. To counteract the Oxidised Surface we Wash the Sheets to Eliminate Oxidation. How do we Wash Sheets? By Supplying High Pressure Water. How do we Supply High Pressure Water? By Supply Water to Nozzles. How do we Supply Water to Nozzles? By Pumping Water. And finally, when we Supply High Pressure Water we Clog Nozzles and Create Down Time. When we Pump Water we Create Energy Cost.

There are many places we could attack this problem to improve process performance. The Function Model provides and aid to identify high value opportunities. We can begin by examining the contradictions as shown in Figure 12. If we had a magic wand and we could make the contradiction disappear, how valuable would that be?

Evaluating Contradictions

- Contradiction 1: Pumping Water Supplies Water to the Nozzles but Create Energy Cost. We wave our magic wand and we can pump all the water we want and consume zero energy (this is the “Ideal” situation). Looking at the cost sheets we see that these pumps do consume power but it is not all that much, so we will pass on working on this contradiction for now.
- Contradiction 2: Spraying High Pressure Water Washes the Sheets but it also Clogs the Nozzles. Waving our magic wand we see that the value of eliminating this contradiction depends on how often the nozzles clog. If they clog once or twice per year, we would not
worry about this. If the clogs weekly, then this problem solution has greater opportunity for improvement.

- **Contradiction 3:** Supplying Electric Current produces Purify Copper but it also Creates Pores. By waving our magic wand here we could increase the current very high thus increasing production rate and never produce a pore. Making this contradiction disappear would be tremendously valuable. So, this is our primary focus for brainstorming.

One of the main benefits of Function Models is to focus the team on the highest value opportunities.

Next, we conduct a structured brainstorming session using TRIZ inventive principles. Our selected contradiction is shown in Figure 13.

A team of subject matter experts trained in the application of TRIZ Principles considers ways to resolve this contradiction. Contradictions can often be resolved by a Separation in Time, Space, Structure or Condition as shown in Figure 14. We separate the root function in the contradiction into two states such that in State 1 we produce the Useful Result and in State 2 we counteract the harmful Result.
Figure 15 shows an example of Separation in Space. I can produce a pair of glasses such that I can see things far away but then I may not be able to see things close up. We could compromise or optimize and produce a pair of glasses that is slightly out of focus for distance and close up. Bi-focals are an example of separation in space. In one location we have a lens to see things far away and in another location we have a lens to see things up close.

![Resolve the Contradiction](image)

Figure 15

Figure 16 shows an example of Separation in Time. If a plane has a large wing area it can fly slowly while landing but the large wing creates drag when the plane is flying at high speed. Again we could compromise by using a moderate size wing. Planes like the F-14 have movable wings such that during one time period (landing and take off) the wing area is large but when flying at high speed the wing area is small.

![Resolve the Contradiction](image)

Figure 16

Figure 17 shows an example of Separation in Structure. If a sailboat is designed with a narrow beam it is fast but the narrow beam results in instability. Again we can compromise by designing the boat with a hull that sacrifices some speed in exchange for some increased stability. A catamaran is an example of separation in structure. If we look at the entire width of a catamaran (i.e. the system level) it has a broad beam. If we examine each hull (i.e. the subsystem level) it has a narrow beam. Catamarans are both fast and stable. In the past boats...
entered in the Americas Cup Race were all mono-hull boats. Today all of these boats are catamarans.

Figure 17

Figure 18 shows an example of Separation upon a Condition. Turning on a light can illuminate a dark area. But if we don’t turn the light off during daylight hours we waste energy. A photocell is an example of separation on Condition. Under condition 1 (light is absent) the photocell switches on. Under condition 2 (light is present) it switches off.

Figure 18

In a Structured Brainstorming session we would consider all of the separation principles to see what ideas might result to resolve the contradiction at hand. In the case of the contradiction selected in Figure 13 let’s look at Separation in Time. There are six different inventive principles embodied in Separation in Time as listed below.

- Preliminary Action - Perform a necessary function in advance
- Hide - Temporarily hide the system from a harmful action
- Use Pauses - To resolve incompatibility of functions, conduct one function in pauses of the other
• Dynamicity - Change the characteristics of the system or process in time
• Rushing Through - "Rush through" a harmful or risky process
• Post Process Time - Use time after a process

The Dynamicity principle suggests here making our process dynamic by changing the level of current over time. The Rushing Through principle suggests raising the current very high during the first time period and then dropping it in the second time period near the end of the production cycle. This idea is graphically shown in Figure 19.

![Figure 19](image_url)

In our brainstorming session, this idea would be accepted along with all others at face value. Later, we will validate these concepts. Any idea such as this one will raise questions. One engineer might say, “This is a great idea. It will reduce the time required to produce high quality sheets and could greatly reduce or eliminate pores.” Another engineer might say, “Nonsense. I don’t think this idea will do anything but produce big pores faster.” It will be obvious that some ideas can be successfully implemented. Others will require some evaluation. In this case the idea in Figure 19 was shown to be very effective.

Once the idea has been validated, other questions arise such as.

• How high should we set the current?
• How long should we hold it at a high level?
• How low should we set the current?
• How long should we hold it at the low level?
• How much can we reduce the creation of pores?
• How much pressure do we need to clear the pores?
• How long should we wash the sheets?
• Others questions?

These questions are all appropriate for six sigma analysis. Once the level 3 Idea has been implemented the subsequent problems can be solved at Level 2.
As it turns out, this idea does have a dramatic effect on the copper production process. It reduces operating cost, increases throughput and reduces capital cost. It is the triple crown of ideas! A significant portion of the existing process can be eliminated as shown in Figure 20.

While this idea might have come out of a traditional six sigma project, it is more likely that we would have found the optimum current level, optimum washing pressure, time and flow rate, and generally, run the existing process at peak efficiency. Front ending six sigma with Pretium's Methodology provides a structured innovation process that dramatically increases the probability that a high impact solution will emerge. In this way, the benefits of six sigma can be increased and sustained.

Conclusion

Pretium's Structured Innovation Methodology (the combination of Function Models, TRIZ and Brainstorming) can generate a large number of innovative solution concepts in a very short time. Concepts produced in this way can be used as the front end to the six sigma DMAIC process or as the creative step in design for six sigma (CDOV, DMADV, etc). This methodology is effective at finding breakthrough solutions.