The 4.5 Sigma Wall

Using TRIZ to Exceed Fundamental Limits

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There is much interest across a wide variety of different industries in the principles and goals operating under the “6 Sigma” label. Essentially, the underlying mechanisms by which 6 Sigma seeks to achieve target levels of quality are built on the solid principles of optimisation. The MAIC phase of 6 Sigma (Measure Analyze, Improve, Control) parallels the “Plan-Do-Check-Act” phase of earlier quality improvement methodologies.   In some applications, optimisation techniques have been applied to achieve impressive results. (Reference 1,2)

More often than not, however, these same techniques do not deliver the stated target levels of performance. This type of shortfall is related to the fundamental dynamics of system evolution uncovered during TRIZ research. This research has shown that all systems eventually hit fundamental limits dictated by the emergence of one or more limiting contradictions. (Ref. 3,4) Organisations often experience these fundamental limits via continuous improvement initiatives that progressively consume more and more resources to achieve smaller and smaller levels of improvement. It is observed that for many manufacturing systems this situation is reached at or around 4.5 Sigma quality levels. In situations like this, where the fundamental capability of a system is inconsistent with the desired target, optimisation is not the appropriate strategy; something else is required. (Ref. 5.)

The typical response to the 4.5 to 6 Sigma inconsistency has been to introduce ‘Design for 6 Sigma’ initiatives. While often at least partially successful in achieving the stated quality goals, it is usually the case that the quality goals have been achieved at the expense of some other aspect of the design. In other words, designers have achieved 6 Sigma quality by compromising on some other feature (cost, adaptability, performance) of the system. In TRIZ terms, this type of design-by-trade-off is simply yet another form of optimisation, and therefore can never offer a true answer to the problem at hand since there is no fundamental research into the causes of the problem, and no change to the system to remove those causes.   The conceptual breakthrough of TRIZ, that compromise (the term is used interchangeably with “contradiction”) is not a solution to the problem, has not yet been incorporated into the fundamental practice of Six Sigma, although some of the major teaching organizations are starting to recognize TRIZ as a contributing system in their DFSS methods. (Ref. 6)

In uncovering the mechanics of system evolution, TRIZ has demonstrated that in situations where system capability and target are fundamentally inconsistent or where designers find themselves in a trade-one-parameter-for-another vicious circle, the only real options involve either a change to the target (a not uncommon strategy in many organisations when the going gets tough) or a change to the system. TRIZ research has further identified three principal mechanisms by which the required system changes can be achieved systematically and reliably. These are illustrated in Figure 1. The figure denotes the importance of the s-curve in determining whether a system can or cannot achieve a desired level of capability. One of the unfortunate but nevertheless fundamental aspects of the s-curve is that when we are plotting the ‘actual’ (we will describe why this word is important in a later section) curve for a system, the maturity plateau at the top of the curve is indeed fundamental. Put simply, systems will hit a point beyond which no amount of optimisation will result in additional increase in value or ideality or whatever performance metric we chose to plot up the vertical axis.

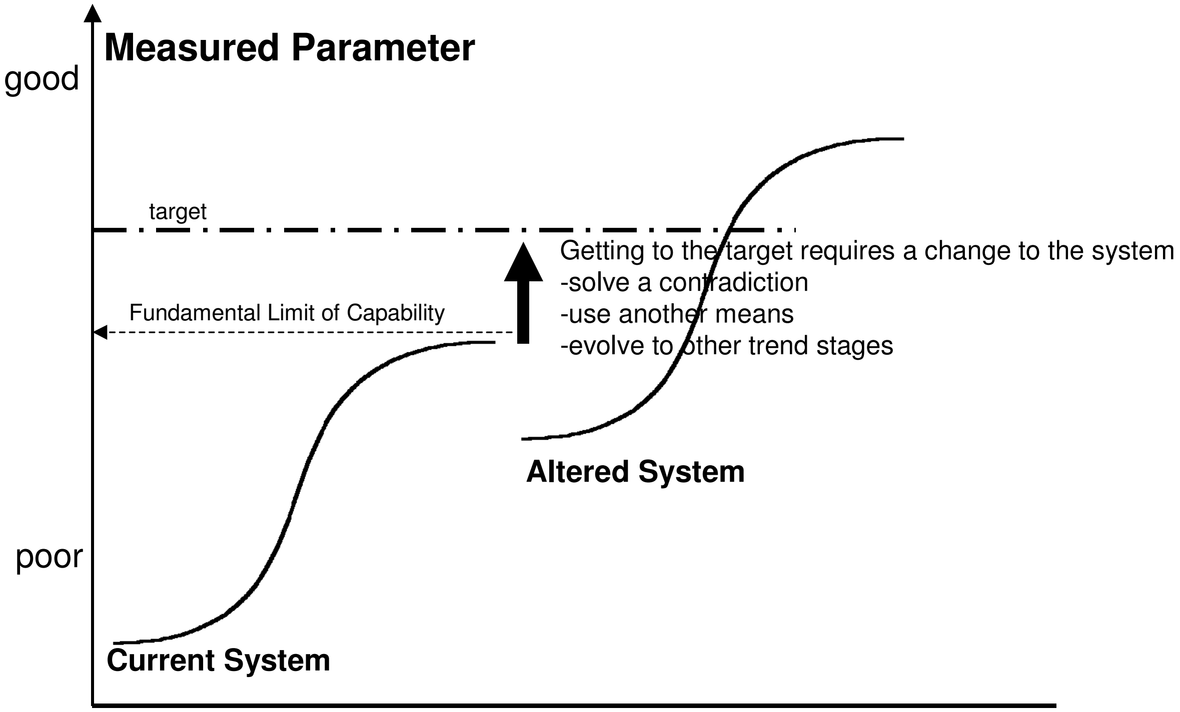


Figure 1: Three Mechanisms for Changing a System

It is important to recognise at this point that when we say ‘change the system’ here that we are not necessarily implying that the entire system – and all of the learning that has enabled it to get to the capability that it has – needs to be dispensed with, but rather to recognise the hierarchical nature of systems, and the fact that it may just be one sub-element of the overall system that is requiring to be changed. Figure 2 illustrates the hierarchical nature of s-curves. By plotting the complete hierarchy for a system and making judicious estimates of the relative maturity of each of the sub-system elements, it becomes possible to identify which parts of a system are preventing the overall system from improving towards the desired target performance level. Reference 10 describes some of the key means of identifying the position of a system along its current s-curve.

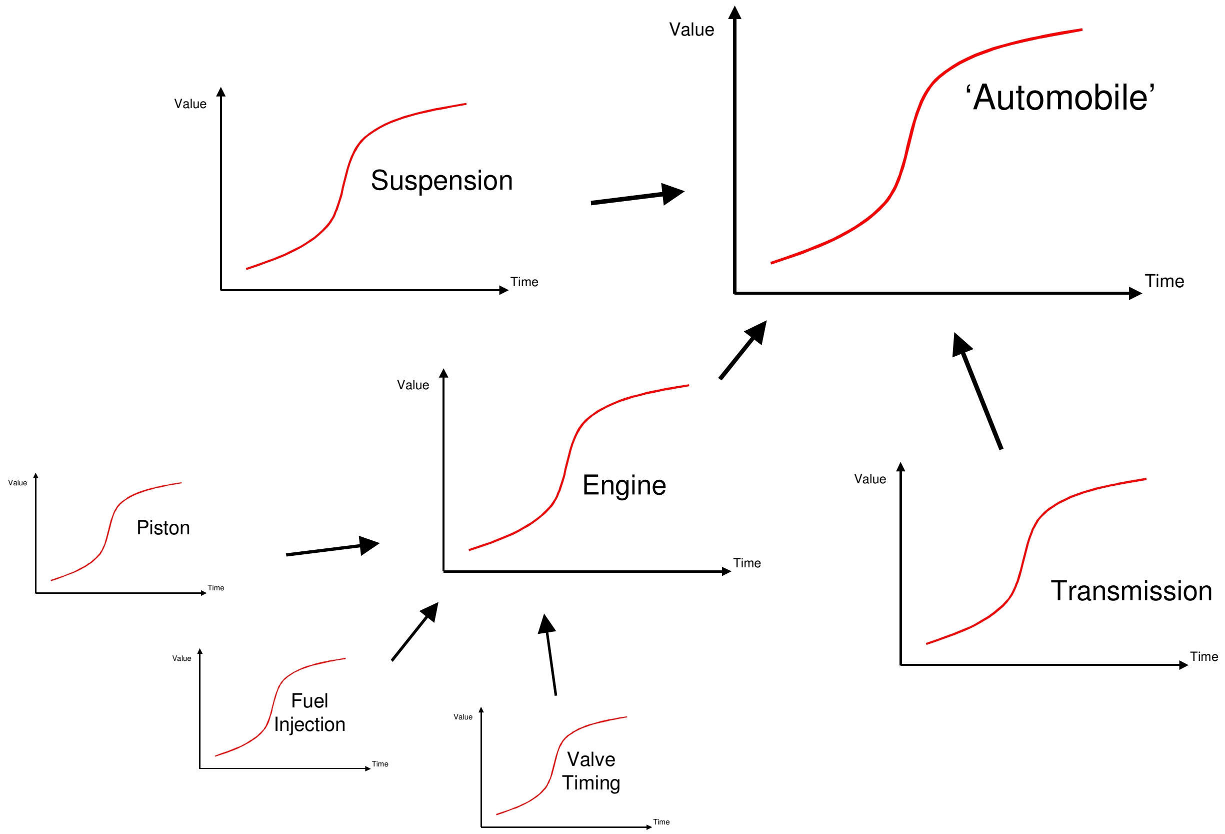


Figure 2: S-Curve Hierarchy For an Automobile. Each component or sub-system is typically at a different point along the S-Curve.

In order to demonstrate the three mechanisms in action and their potential impact on the DFSS paradigm, we will examine three case studies. Each case study is intended to illustrate

- How and why optimisation failed to achieve the breakthrough to the Six Sigma level performance
- How TRIZ methods remove the fundamental contradiction that prevented previous solutions from succeeding, and revealed the strategy that would lead to success in reaching the next level of performance

The case studies comprise:

- A re-design of an unreliable multiple hole-drilling manufacture operation
- A re-design of a heat exchanger brazing operation
- An assessment of the consequences of traditional Western 'acceptable/ unacceptable' manufacture strategies versus the Eastern 'head for the optimum' paradigm.

Before we discuss these cases, however, it is worthwhile devoting a few more words to a discussion about the importance of s-curves in the whole Six Sigma and DFSS arena.

S-Curve Dynamics

There are two aspects of s-curve dynamics that need to be considered in relation to the Six Sigma subject. The first involves the three ways that a system can reach, or appear to reach, the plateaued maturity phase of the S-curve. These three are:

1. **True maturity:** The system has reached limits based on the properties of the materials or the nature of the technical phenomena being used.

2. **False maturity:** The system stopped developing because the organization stopped spending money (or the equivalent in time and personnel resources) on development. If no work is being done, no change in the system will happen.

3. **Stalled progress:** Unresolved conflicts at the sub-system level.

Types 1 and 3 both call for changes in the fundamental system or one of its sub-systems in order to make progress toward higher levels of quality. Type 2 is observed frequently in organizations that are paying “lip-service” to improvement, but not investing the needed resources. The only cure for false maturity is a change in management philosophy, accompanied by a change in management behaviour. Since the Six Sigma system involves extensive management education as well as technical education for improvement, there is a good possibility that type 2 can be avoided or counteracted in companies that are using Six Sigma as their improvement strategy. From the perspective of the remaining discussions in this paper, we will only consider situations of the first and third type.

The second important aspect of s-curve dynamics involves the relative positioning of one curve to the next. Here there are essentially two possible scenarios – as illustrated in Figure 3. Both patterns shown in the figure are possible in the case of new system development.

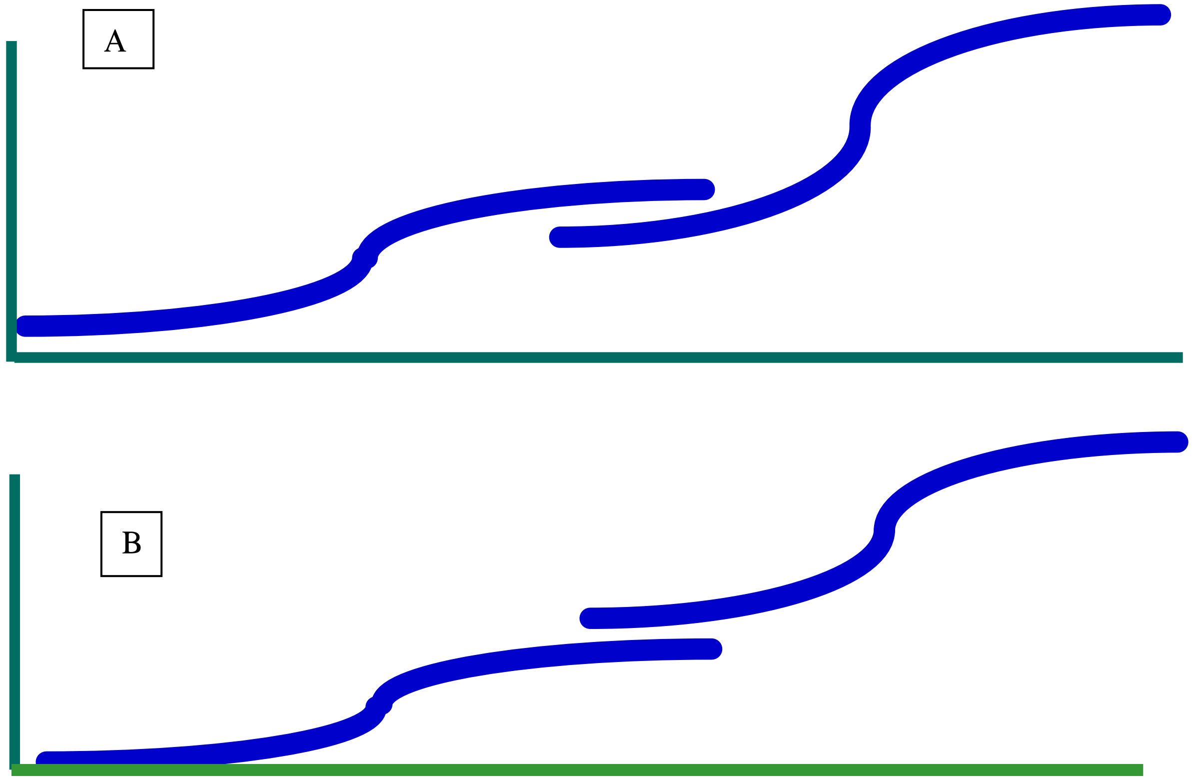


Figure 3: Stages of evolution, showing that the new system may be either inferior (A) or superior to the old (B). It is a critical business decision whether to introduce the new product to the market in condition A, where it has high potential but inferior performance. (Ref. 8, 9, 14.)

We must also remember that the relative positioning of adjacent curves along the y-axis is very much dependent on the needs (and perceived needs) of every individual customer of the system. Different customers can have very different views concerning whether a new system is inferior or superior to the old one. Within this paper, we are primarily concerned with case B situations – where the new way of doing things is immediately superior to the old for all customers, although it is worth mentioning that in many senses in the other A situation, it is the job of the designer to accelerate the design towards maturity by pushing key design parameters towards the limits of capability. This is particularly the case at the bottom (component) end of the s-curve hierarchy.

Case Study 1 – Hole Drilling Operation

The first case examined during the research fro this paper involved a final hole drilling operation in a high value, high duty aerodynamic component. In all, the operation required the simultaneous forming of a row of 20 holes along a thin edge of a component. The function of the holes was to permit the flow of air from an internal cavity used to cool and otherwise protect the component. A schematic of the design is illustrated in Figure 4. The diameter of the holes was around 0.002" and the chosen method of production was electro-chemical drilling (ECD). Immediately after launch, the defect rate of the process was around 5%. The defects were primarily caused from two mechanisms; the first due to small variations in the position of the internal cavity (which was produced via an investment casting route) that meant the holes did not fully break through into the cavity, and the second was a drift in the direction of the holes as they were being formed. This second mechanism was believed to be due to the very small diameter of the tooling used to form the holes coupled with the very difficult to machine nature of the component material.

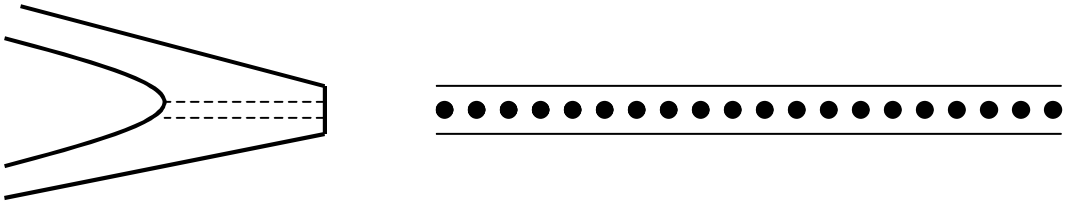


Figure 3: Hole Drilling Operation – Design Detail

Attempts to improve the defect rate in the manufacture cell involved a series of experiments to vary the parameters that could influence the problems. These included varying the speed of the operation, temperature, amount of chemical agent, flow rate of the chemical agent, etc. At the end of the process to optimise these parameters, the process was delivering an average defect rate of 4.5%. This after the efforts of a three person team working for about a month.

At this point, it was decided that in order to achieve a more acceptable defect rate it was necessary to change some aspect of the design itself. Implicit in this decision was a recognition that the manufacture process had hit some kind of limit. When examining the design, it became clear that the designer was quite heavily constrained and had already pushed the limits of performance of the system quite hard. An exercise to re-design the system to enable easier manufacture seemed to be stymied at almost every corner:

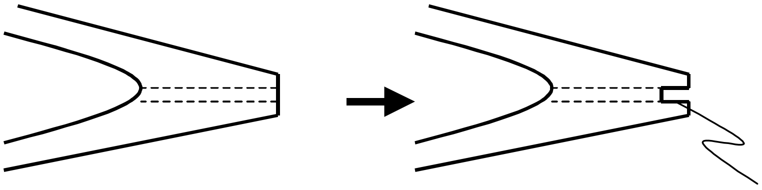
- Bigger holes would have improved the problem, but bigger holes would have necessitated a broader edge on the component – which would have made the aerodynamic performance substantially worse – or would have reduced the amount of material present at the edge, and hence give insufficient strength properties.
- Reducing the number of holes would have reduced the cooling performance of the system; potentially leading to impaired life of the component.
- Drilling the holes sequentially instead of simultaneously, although increasing the control over the production of each hole, represented a serious increase in the time to produce each component.

This heavily constrained situation necessitated the location of some under-utilised resource in the system. As it turned out, such a resource turned out to be the pressure in the cavity inside the component available to drive the cooling air out of the holes. This resource enabled the designer to re-specify the holes with an oval rather than round shape. The oval shape enabled fewer holes to be drilled in order to achieve the correct amount of cooling flow during operation of the component, and also permitted the production of a tool that was theoretically more robust than the original one. On the other hand, the tool was now more expensive to produce, the pressure loss through the holes was increased (meaning the available margin was now used up), and, as it turned out, the impact on the drift problem was close to zero. At the end of this design and validation exercise, the manufacture process was capable of producing a defect rate of around 2%. Around two person years of activity had been devoted to the re-design and validation process.

From a TRIZ perspective, the designers had simply moved the trade-offs present in the existing system from one place to another; the thing they were worrying about (manufacture waste) had improved, but only at the expense of several other parameters. The whole situation was indicating the fact that the process was hitting some kind of fundamental limit, and that even several more re-optimisation activities would not deliver the desired defect rate. From that same TRIZ perspective, if the system was going to improve, it was going to have to change.

It was decided that there was clearly a conflict (or series of conflicts) confounding the attempts of designer and manufacturer alike from achieving the desired improvement. A form of root contradiction analysis (Reference 11) was conducted in order to try and identify the key limiting features of the system. After a two-hour session, it was determined that the conflict involving the drift of the tool versus the length of the hole to be drilled was the one that was limiting the advance of the system. Focusing on the tool, this conflict was translated into one involving an object generated harmful factor versus length (of moving object). The Inventive Principles suggested by the Contradiction Matrix for this particular conflict were – 17, 15, 16 and 22. Each was studied in the context of the drift problem, and several viable ideas were generated and subsequently compared to the constraints present on the problem (not least of which was a desire to not have to commission a completely new machine tool). The initially un-promising sounding Principle 16 ‘Partial or Excessive Actions’ turned out to be the source of a solution that, once implemented (actually in combination with an input generated from Principle 17) enabled the process to achieve a situation whereby, without any additional optimization of the process, no defective operations have since been produced (as the process has not as yet been called upon to produce a million of these components, we shall deem the outcome to be consistent with a 6 sigma target).

Of further note is that the solution employed – schematic shown in Figure 4 (Inventive Principle 17 input not shown for commercial reasons) – not only eliminated the defect problem, but also resulted in more effective cooling of the edge of the component and lower cooling air pressure loss. These in turn later enabled an exercise to re-optimise the cooling flow supply in order to achieve benefits in other parts of the system. In other words, the new solution presented a new resource that could be exploited elsewhere.. at least until the overall system or some other part of it hit another limit.



continuous groove machined along edge of component acts to reduce length of hole and also support tool during drilling operation

Figure 4: Before and After View of Chosen Solution

Case Study 2 – Heat Exchanger Brazing Operation

In this case, the target of the project was the improvement of the operations to braze 40 tubes onto an end plate of a simple shell-and-tube heat exchanger. The brazes needed to produce an airtight seal between tube and shell. This seal needed to remain intact over prolonged periods of operation of the heat exchanger – during which considerable thermal and mechanical stresses were imposed on the join. After the brazing operation and subsequent heat treatment on all 40 tubes was completed, the system was put through pressure and stress testing cycles prior to final assembly into the complete system. The net braze defect rate (either due to non-air-tight sealing or cracking under stress) was just under 1%. With 40 pipes per heat exchanger, this equated to a defect rate of one in three on the assembly.

All attempts to re-optimise the process (through re-training of the operators, to production of new jigs and fixtures, to experiments on the type of braze filler used) had had little impact on the overall defect rate. This suggested that the system was hitting some kind of fundamental limit. Analysis of the system from the TRIZ perspective this time began by constructing an evolutionary potential radar plot (Reference 12) for the pipe and end plate used in the brazing operation. A summary plot is reproduced in Figure 5.

Commercial considerations prevent us from discussing too many of the details of this case study, but basically, the radar plot was used to demonstrate that although the system had hit a limit that seemed to be fundamental, the system as a whole still possessed a considerable amount of untapped potential. The system was, in other words, at a stalled progress stage in its evolution. The basis for improving the defect rate of the system was to select those area of untapped potential that fit the constraints present in the problem (which primarily related in this case to a lack of funds for capital equipment and the limited skill-set of those conducting the joining operation.

One of the trend directions not previously exploited in the design was the one pointing towards increasing dynamisation. In situations like this brazing operation, the idea of increasing the flexibility within a system runs counter to the instincts of most people – the prevailing logic in many brains being that if something is cracking and failing, the problem should be solved by increasing the strength and stiffness of the structure and certainly not to travel in the other direction. Overcoming this instinct, and incorporating ideas generated from the untapped geometric and surface segmentation evolution potential contained in the initial design resulted in a very elegant design that not only made it effectively self-sealing over a very wide range of individual ways of brazing the joint, but thanks to the increased flexibility in the overall system, was also able to self-release any stresses that would otherwise have been able to accumulate in the system.

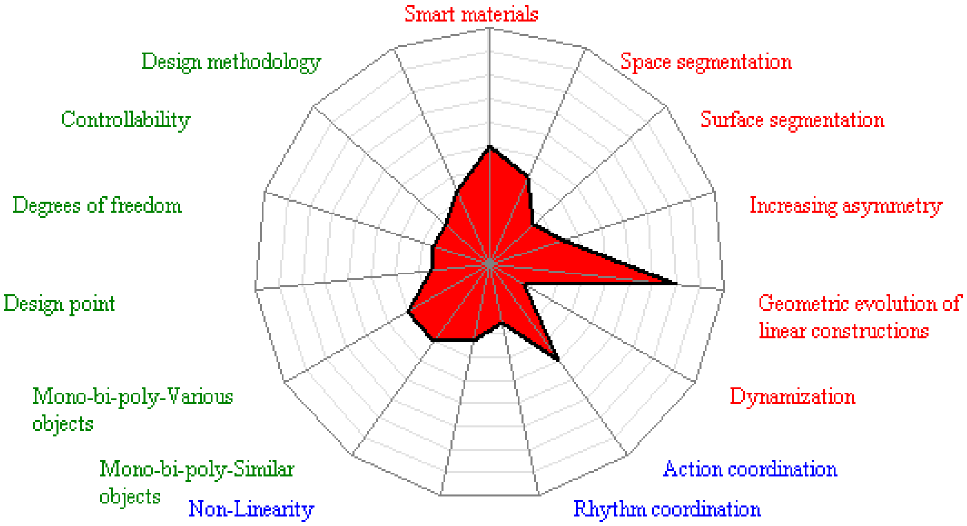


Figure 5: Evolutionary Potential Radar Plot for Tube/End-Plate Brazing Operation

After the analysis, the net defect rate for the tube-to-end-plate brazing operation had fallen to a level of 0.0003%.

To date, the change has complicated the initial manufacture of the tubes (but only because the modified design has not yet been optimized), but this was compensated for not only by the improved manufacture defect rate, but also by a considerable reduction in in-service failure of the heat exchangers.

The trend jumps suggested by the radar plots represent steps towards increasing ideality, and the directions that others have successfully taken in order to overcome conflicts and contradictions within systems. The considerable amount of untapped potential in most systems made apparent by the construction of these plots – particularly at the component and sub-system levels – should cause us to recognize that a) there are many situations where systems are in a stalled progress situation rather than being at a truly mature level, and b) if we think of untapped evolutionary potential as under-utilized resources, most systems are some considerable distance away from using things to the maximum possible advantage.

Case Study 3 – Acceptable versus Optimum Manufacture Strategies

This third case study is actually rather more general in nature than the preceding two. The interest in this case came from an investigation into some of the implications of the subtle but profound differences in philosophy between Eastern and Western manufacture paradigms.

These two paradigms are summarized in Figure 6. Typically in the West, engineering drawings are specified with tolerances. These tolerances denote limits within which a component is deemed ‘acceptable’, and outside which it is not. The Eastern philosophy, although it typically also features acceptable/not-acceptable limits, tends much more towards aiming at a specific optimum value of a parameter. The Western response to a need to improve the reliability of a system in this kind of acceptable/not-acceptable scenario is to work progressively on the system to reduce the tolerance band. This is done most typically through strategies of optimization whereby improvement in quality usually comes at the expense of something else in the system getting worse – for example production time, need for higher cost alternative production processes, and quite possibly, increased defect production rate.

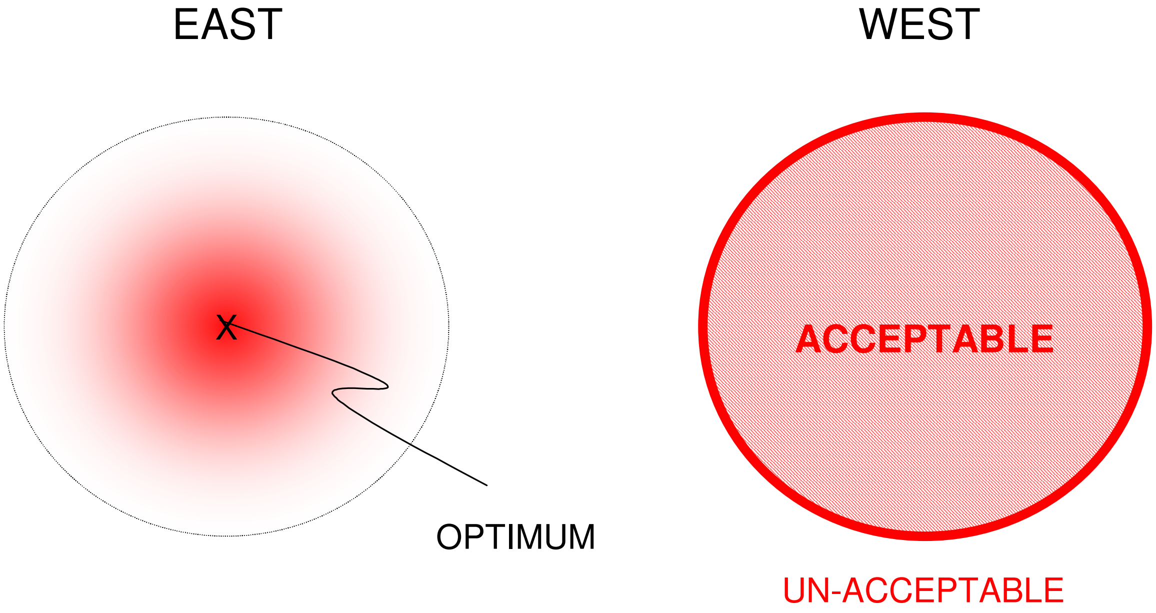


Figure 6: East versus Western Manufacture Tolerance Paradigms

There appears in fact to be some kind of philosophical disconnect between the parallel desire to reduce variation **and** reduce defect rates. This disconnect should also take into account the fact that humans are not six sigma animals, and that just about any production process involving a human operator will find it extremely difficult to achieve Six Sigma levels of defect production. This is analogous to the joke about the factory of the future being staffed by one man and one dog; the man is there to feed the dog, while the dog is there to stop the man from touching any of the machines.

Merging this thought with the TRIZ trend towards increasing ideality, and the ultimate need to get systems to do things ‘for themselves’, a brief study was conducted in order to examine the global state of the art in relation to manufacture systems that purport to be able to self-align, or self-correct or self-compensate, or self- anything that might successfully point us in the direction of an ideal final result of zero tolerance bands and zero defect production. The results of those findings are summarized in Figure 7

The data was generated via an analysis of manufacture-related patents granted in the US over the period 1996-2002. In effect, the analysis represents a subset of the self-x patents described in more detail in Reference 13.

Rather than picking one of these solutions over other ones, we merely suggest that interested readers visit one of the on-line patent websites and conduct searches on the words ‘self’ (preferably in the title) and ‘manufacture’, plus their synonyms to examine for themselves some of the existing solutions on offer from those inventors and problem solvers that have been working with this kind of ideal final result oriented objective in mind. In essence, these solutions represent the third means of allowing us to jump from a mature or stalled system to another. By using the word ‘self’ as a guide, we can be more certain that the new system we might jump to will be one that is immediately superior to the one we are looking to leave behind.

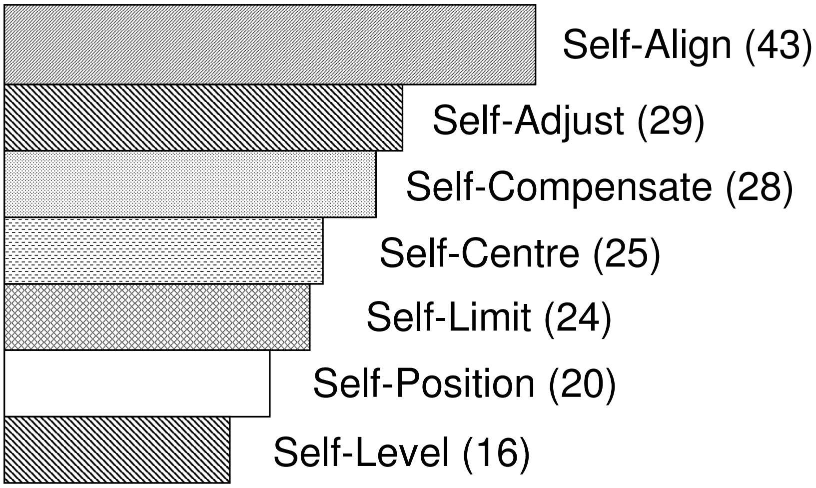


Figure 7: Manufacture-Related ‘Self-X’ Patents

Final Thoughts

In a Six Sigma deployment, typically, a series of black belt projects will start when a product, service, or system is in the growth phase, or somewhat after, and will be focused on improving a parameter other than the functional capability parameter. For example, in a project that dealt with synthesis of a chemical, the improvement project dealt with decreasing the cost of the waste treatment. In a system that records data at very high speed and very high accuracy, the improvement project dealt with increasing the number of cycles of use for each data storage device. For a consumer home appliance, the goal is increased customer satisfaction with better answers to questions faster, but the long-term goal is customer satisfaction by anticipating customer questions and not needing to answer them after they occur.

This focus on the peripheral improvements, rather than the fundamental functions of the system, can frequently lead to perception of false maturity, and mis-use of the patterns of evolution data. The evolutionary potential concept is beginning to demonstrate for just about all of the inventions and systems being analysed (Reference 13) that because so few companies and inventors are aware of all of the trend possibilities, there is considerable untapped potential. Thus even those systems we believe to have reached genuine maturity, when we try to plot the evolutionary potential for those systems, we invariably find that there are one or more trends that have so far not been fully-exploited. Once the concept becomes more visible, this phenomenon may be expected to disappear, but in the meantime, the general message that appears to emerge from the research and case studies described in this paper is that there are insufficient instances of genuine maturity to try and correlate Six Sigma performance to a position on an s-curve.

Conclusions

Some of the important underlying philosophical systematic innovation concepts are fundamentally limiting. Optimisation strategies are often also - despite what our 'common-sense' tells us – misguided and ultimately dangerous. Breakthrough improvement requires breaking with the fundamental limiting flaws of the original system concepts. Using TRIZ technology evolution insights coupled with the Six Sigma discipline for improvement provides a pathway to lasting system improvement that removes both the technical and management roadblocks seen in other systems.

The first two case studies have highlighted the differences between trade-off based optimisation and breakthrough innovation solutions in achieving Six Sigma performance levels in two manufacture operations. They have hopefully also served to suggest that the TRIZ trends, contradictions and knowledge tools can play an important role in achieving the breakthroughs necessary to allow systems to advance beyond fundamental limits.

The third case study has hopefully at least suggested the value of working towards design solutions that solve Six Sigma (and other) type problems by them**selves**. In the first case study, for example, one of the problems still left in the system is that the drilling operation still contains no feedback to suggest whether a hole has properly broken through into the cavity or not. Essentially the operation is still one of pointing a tool in the right direction, hoping we chose the right direction and hoping that the tool stays travelling in that direction. If the tool could work out for itself what the right direction was, and how to prevent itself from deviating from that direction, we would have a fundamentally stronger manufacture process that would almost inevitably be truly Six Sigma in nature.

References:

1. Samuel, P. "*Design for Six Sigma*." ASQ Conference on Six Sigma, 2001. Harry, M and Schroeder, R. *Six Sigma: The Breakthrough Management Strategy Revolutionizing the World's Top Corporations.* ASQ Quality Press, 1998.
2. Domb, E.R. "*Increase Creativity to Improve Quality: TRIZ and the Baldrige Award Criteria*." TRIZCON99. Domb, E.R. "*Using TRIZ in a Six Sigma Environment*." TRIZCON2001. Rantanen, K, and Domb, E.R. *Simplified TRIZ.* CRC Press, 2002. Chapters 12 and 14.
3. Mann, D.L, and Dewulf, S. "*Evolutionary-Potential™ in Technical and Business Systems*" TRIZ Journal, June, 2002
4. Mann, D.L. and Mitchell, I. *TRIZ Technology Evolution*, Proceedings of ETRIA TRIZFUTURES2002.
5. Smith, L. ASQ Six Sigma Forum, http://www.asq.org/pub/sixsigma/past/vol1_issue1/evolution.html
6. Six Sigma Academy, BMG, Juran Institute
7. G.S. Altshuller. *Creativity as an Exact Science.*
8. Geoffrey Moore. *Jumping the Curve* and *Riding the Tornado*
9. C. Christensen. *The Innovator's Dilemma*

10. Mann, D.L., *Hands-On Systematic Innovation*, CREAX Press, 2002.
11. Mann, D.L., *Root Cause Analysis Paralysis*, TRIZ Journal, May, 2002.
12. Mann, D.L., Dewulf, S., ‘*Evolutionary Potential*’, in Ref. 10.
13. Mann, D.L., *Ideality and Self-X, Part 1*, TRIZ Journal, February 2003.
14. Domb, E.R. “*Strategic TRIZ and Tactical TRIZ- Using the Technology Evolution Tools*” TRIZ Journal, January 2000.,