TRIZ Future Conference 2006

Conceptual design using axiomatic design in a TRIZ framework

Madara Ogot *

Engineering Design Program, and The Department of Mechanical and Nuclear Engineering, The Pennsylvania State University, University Park, PA 16802, USA

Abstract

This paper explores the symbiotic relationship that can be established between axiomatic design and TRIZ, capitalizing on each method’s strengths and simultaneously minimizing their weaknesses. Through a contextual example the paper illustrates how axiomatic independence axiom principles can be utilized to select appropriate standard solutions once a physical contradiction has been identified. It concludes by showing ways to use the same AD principles to qualitatively evaluate generated designs.

© 2010 Published by Elsevier Ltd.

Keywords: Axiomatic design; Conceptual design; TRIZ;

Nomenclature: AD: Axiomatic Design; DP: Design Parameter; TRIZ: Theory of Inventive Problem Solving; FR: Functional Requirement;

1. Introduction

A broad view of the engineering design process reveals five broad steps that are generally followed: Problem identification, problem formulation, concept generation, solution evaluation, and embodiment design. This paper extends earlier work, that reviewed use of TRIZ within an AD Framework (Ogot, 2006), by looking at the reverse: reviewing the use of axiomatic design (AD) within a TRIZ framework and making implementation suggestions based on application similarities and differences found in the literature. The strength of AD lies in the problem identification and formulation steps, while TRIZ’s main strengths are problem identification (making sure you are solving the correct problem) and concept generation. With reference to Figure 1, AD divides the design process into four major domains: customer, functional, physical and process. Our discussion will focus on the relationship between the function domain and the physical domain, each defined by the design functional requirements (FRs) and design parameters (DPs), respectively. Based on two design axioms (the information and the independence axioms), AD provides an effective approach to problem formulation and clarification. The AD zig-zagging process is used to identify the FRs and the corresponding DPs relevant to the current problem. Ogot (2006) illustrated how
the TRIZ system operator in conjunction with EMS models can be used to achieve this task. Once complete AD design matrices (DM) that show the relationship between the FRs and the DPs can be constructed. 

\[ [\text{FRs}] = [\text{DM}] [\text{DPs}] \]  

(1)

for brevity the following abridged notation will be used throughout the paper,

\[ [\text{FRs}][\text{DM}][\text{DPs}] \]  

(2)

The Independence Axiom states that the AD design matrix should be at least triangular, but ideally diagonal. The later represents the ‘ideal’ design where each FR is controlled by a single DP.

\[ \text{Figure 1. Axiomatic Design domains} \]

AD, however, does not provide ample guidance on how to achieve the conceptual solutions to solve the design problem. For example, once the problem has been formulated in terms of function requirements and design parameters, and if the resulting relationship between them is found to be coupled (bad) or too complex, AD does not provide ideas on how the design could be uncoupled or simplified, respectively. TRIZ on the other hand provides numerous conceptual generation tools that could be used for this purpose.

From the TRIZ point of view, often a very large number of conceptual solution directions can be generated for the same problem using TRIZ’s numerous tools (for example, trends of evolution, technical and physical contradictions). The number of solutions and solution paths often overwhelms TRIZ users. Although proper use of the Algorithm for Inventive Problem Solving (ARIZ) can significantly help reduce this number, methods such as AD can help prioritize the suggested TRIZ solutions by giving higher priorities to those solutions that would help decouple the AD design matrix, or reduce information in the system. A holistic view of both methods shows that they have their strengths and weaknesses, but also provide avenues where, collectively, they can significantly enhance early conceptual design. In the literature most authors address consider the use of TRIZ within an AD framework, primarily to decouple/uncouple AD design matrices or develop new designs when AD design constraints are not met. For example, Ruihong et al. (2004) proposed an AD framework that incorporates TRIZ, illustrating the approach via the design of a paper machine. Similarly, Kan (2004) presents a discussion of uncoupling, coupled and decoupled AD design matrices by recasting the coupled FRs as technical or physical contradictions. The redesign of a pile driver is used to illustrate the approach. Kim and Cochran (2000) provide a comprehensive comparison of AD and TRIZ especially between ideality and AD design axioms, TRIZ contradiction concepts and their applicability in AD and su-field modeling and the AD zig-zagging process. Similar comparisons can be found in Karr (1998) and Norlund (1996). . Yang and Zhang (2000) provide a tabular comparison of the common elements between the two methods. Hu, Yang and Taguchi (2000) illustrate how the two methods can be used within a Taguchi framework to enhance robust design. Very little is discussed in the literature, however, about the use of AD within a TRIZ framework. The contribution of this paper therefore is to illustrate how AD can be used to narrow down solution choices in TRIZ when confronted with a physical contradiction (much like the way contradiction tables support technical contradictions), as well as serve as a qualitative evaluation tool for generated TRIZ concepts. For a detailed description of axiomatic design, the reader is referred to Suh (2001). Similar Savaransky (2000), Orloff (2003) can provide a detailed introduction to TRIZ.

2. TRIZ framework – AD supporting role

2.1. Simplified steps for application of TRIZ tools
A simplified flow chart illustrating the use of several common TRIZ tools is presented in Figure 2(a). It is by no means meant to be comprehensive, but used to provide a simplified framework to illustrate how AD tools can be used within TRIZ. The steps in the simplified algorithm are as follows:

1. Analyze the problem by defining the contradiction zones and creating an energy-material-signal (EMS) model (Ogot, 2005). This ensures that you understand the problem at hand and that you end up solving the right problem. In addition, at the end of this step you should have determined whether you have a physical or a technical contradiction(s). Define your Ideal Final Result.

2. If you believe you have a technical contradiction(s), formulate it in terms of the generalized engineering parameters. Once complete, use the contradiction matrices to seek the most probable design principles to solve the problem. Recall that the contradiction matrices list the most probable solutions to solve your problem. If none of the recommended design principles work, go through each of the other principles in search of a solution. If you find a solution, you are done.

3. If no solution is found from the previous step or if the problem cannot be formulated as a technical contradiction, define the problem in terms of a physical contradiction. Redefine your Ideal Final Result in terms of the physical contradiction.

4. Apply the 76 Standards/Condensed Standards (Ogot, 2003) to seek a solution. If a solution is found, you are done.

5. If not, use the separation principles to separate the physical contradictions. Apply the 76 Standards/Condensed Standards to solve the new form of the problem. If a solution is found, you are done.

6. If not, revisit Step 1, and ensure the problem was defined correctly. Seek alternate forms of the contradictions and repeat all steps until a solution is found.

Figure 2. (a) Flow diagram of a simplified algorithm for use of three common TRIZ tools and (b) with the addition of AD tools

Figure 2(b) shows where AD tools can be integrated into the TRIZ framework. Details of the integration form the thrust of the paper.

2.2. The condensed standards.
The 76 standard solutions are to a large extent, based on the substance-field modeling method. In an effort to effectively use the EMS models, the 76 standard solutions were modified and articulated in terms of EMS models. In addition, as several authors have noted the significant degree of repetition amongst the standard solutions suggested their own reduced versions (Soderlin, 2002; Orloff, 2003). Ogot (2005) also proposed a reduced set of 27 Condensed Standards. In addition to reducing the number of solutions, the Condensed Standards, (a) use the language and jargon typical in engineering design, and (b) replace the substance-field models found in the original 76 solutions with the EMS models. Further, the condensed standards reduce the five classes of classical 76 standard solutions from five classes (Improving the system with little or no change, Improving the system by changing the solution, System transitions, Detection and measurement and Strategies for simplification) to three:

1. Condensed Standards I: Improving the system with little or no change
2. Condensed Standards II: Improving the system by changing the solution
3. Condensed Standards III: Detection and measurement

The complete list of condensed standards incorporating the EMS models can be found in Ogot (2005).

2.3. Contextual example—computer hard drive

An area of concern arises when the computer is off and receives a hard external knock. Without the hard drive disk spinning, the head can be knocked off its rest position and data on the disk destroyed. In the rest position, the head is typically held in place by a magnetic latch. When the computer is powered on again, the airflow from the disk motion raises the head, and a permanent magnet/electro-magnet system situated at the arm axes of rotation (the pin) generates enough force to release the arm from the magnetic latch and move the head to wherever data needs to be written or read (Royzen, 1999). Starting with the first step in Figure 2, an EMS model of this scenario can be developed and is illustrated in Figure 3 (Ogot, 2003). In the model, one can track the sequence of events (the flow) from when the computer chassis receives a hard knock to the point where there is damage (harmful effect) to the disk surface by the read/write head. In the figure, the magnetic field is shown to be insufficient, and therefore an area of the concern that would be addressed. In addition, several resources that would be available in the system are included in the diagram.

An obvious solution is to use a stronger magnetic latch. This, however, may present its own problem by making it difficult for the arm to be released during start-up. The two scenarios are modeled in Figure 4, where the top slot in the multiple scenario symbols represents the hard knock scenario, and the lower slot the computer start-up (Ogot, 2003). Note that by increasing the magnetic strength of the latch, a desirable effect is achieved in response to reduction of damage from external knocks, but it also produces an undesirable effect during system start up. With reference to Figure 2, a technical contradiction may not be as appropriate as the next step, physical contradictions. One could state that:

**Physical contradiction #1:** The strength of the magnetic field in the magnetic latch needs to be **strong** to hold the latch in place when the computer is turned off to prevent the read write/head from damaging the disk surface, yet the field should be **weak** to allow arm release on computer start-up.

With reference to Figure 4, one could simply increase the strength of the voice coil (the electro-magnet) that controls the arm. This would provide enough force to overcome the larger magnetic field in the latch. The downside of this solution is that (1) a larger voice coil adds significant cost to the hard drive, and (2) reduces the sensitivity/performance of the coil – required to accurately, and rapidly position the arm (and by extension the play head) at different positions over the disk surface. This solution yields yet another physical contradiction:

**Physical contradiction #2:** The strength of the voice coil needs to be **high** to overcome the stronger magnetic latch, but needs to be **low** to provide desired sensitivity and performance.

Two solution paths are therefore available: (1) search the standard/condensed solutions or (2) use the separation principles first, and then if necessary search the standards. A cursory look at the standards may be intimidating at first class due to the large number of choices and possibilities. Unlike the 40 design principles, there is no contradiction table to provide a small sub-set of ‘best/likely’ solutions. Can AD principles therefore be used to serve this purpose?

2.4. Opportunities for AD in the TRIZ framework
For the contextual example, three functional requirements can be defined:

1. FR1 – Passively hold arm in place when power off
2. FR2 – Release arm on power on
3. FR3 – Control arm during computer use

![Figure 3. EMS model of hard drive when the computer is turned off. A hard knock on the computer dislodges the arm resulting in the head damaging the disk magnetic surface](image)

Further, two design parameters can be identified:

1. DP1 – Strength of permanent magnet (PM)
2. DP2 – Electro-Magnet (EM) in arm controller

A possible AD design matrix can then be constructed with the form

| FR1 – Passively hold arm | X | DP1 – PM Strength |
|--------------------------|---|------------------|
| FR2 – Release arm        | X | DP2 – EM in arm controller |
| FR3 – Control arm        | X |                   |

(3)

The ‘X’ s indicate which DPs influence which FRs. For example from Equation 3, the following observations can be made:

1. FR2 is influenced by two DPs
2. DP1 influences two FRs (FR1 and FR2)
3. DP₂ influences two FRs (FR₂ and FR₃)
4. The matrix is not square, i.e., it can never be diagonal or triangular and therefore never satisfy the independence axiom is left in its present form.

From an AD perspective, the design matrix must first be converted to a square matrix by either adding a DP or by removing an FR. Removal of an FR would adversely affect the desired functionality of the device, making the addition of a DP necessary. The resulting expression would therefore take on the form

\[
\begin{array}{ccc|c}
\text{FR}_1 & \text{Passively hold arm} & X? & ? & \text{DP}_1 & \text{PM strength or ??} \\
\text{FR}_2 & \text{Release arm} & X? & X? & ? & \text{DP}_2 & \text{EM in arm controller or ??} \\
\text{FR}_3 & \text{Control arm} & ? & X? & ? & \text{DP}_3 & ?? \\
\end{array}
\]

(4)

Where ?? indicates that an existing DP can be changed or a new one sought where none exits, and ? indicates that an existing relationship can be changed or a new one established where none exists. In addition to making the matrix square, AD seeks to de-couple FRs and DPs. Recall that from a TRIZ perspective when addressing the problem, we were confronted with a large number of Condensed Standards from which to find a possible solution. With reference to the AD design matrix in Equation 4, and considering the need to add a DP to the problem description, a smaller subset of five standards (see Table 1) related to placing an additive in the system and that are most closely related to the desired design task is extracted and explored for possible solutions. Use of AD methodology can therefore cull the full list of standards to a smaller subset for physical contradiction design problems, much the same way the contradiction table works for technical contradictions. The placement of this AD intervention within the TRIZ framework was presented in Figure 2b.

2.5. Possible solutions

**Concept #1** – Based on Condensed Standard 1.3, a possible solution to physical contradiction #1 is to place the arm controller (and voice coil) on a spring-loaded limited rotation platform. The platform would also have an electromagnet that would work against that spring force. With reference to Figures 5, when the computer is powered off the arm is moved to the rest position by the arm controller where the strong permanent magnet holds it securely in place. On turning the computer back on, the electromagnet in the limited rotation platform is activated and moves the entire arm assembly (controller and arm) away from the permanent magnet – the electromagnet is strong enough to overcome the larger PM latch field – releasing the arm from the secured position. The arm controller then moves the arm to the active position. At the same time, the electromagnet on the rotation platform is turned off, with the spring returning the platform to its rest position. The spring also prevents any movement of the platform during the hard drives active state – that would interfere with the data transfer to the disc surface – and as well as when the hard drive is turned off. The AD design matrix for this configuration based on Equation 2 is

| #       | Solution                                                                 |
|---------|--------------------------------------------------------------------------|
| 1.1     | Without changing the system add a temporary or permanent, internal or external additive that may or may not be present in the system. |
| 1.3     | If a moderate amount of energy is insufficient, but higher energy is damaging, apply higher energy to an additive that acts on the original system. |
| 2.1     | Apply an additional energy source to the system                           |
| 2.2     | Replace or add to energy existing in the system that is difficult to control with energy that is easier to control. From the Laws of Evolution, in order to improve controllability: mechanical to thermal to chemical to electric to magnetic to electromagnetic energy. |
| 2.8     | Add ferromagnetic materials (objects or liquids) and/or electric generated magnetic fields (dynamic, variable or self-adjusting). |

Table 1. Reduced set of condensed standards that may be applicable to hard drive example
FR₁—Passively hold arm  |  X  |  DP₁—PM Strength  
FR₂—Release arm  |  X  |  DP₁—EM/Spring Platform  
FR₃—Control arm  |  X  |  DP₂—EM in arm controller  

A comparison of Equations 3 and 5 shows a significant improvement (in an AD sense) in that (1) the design matrix is now square, and (2) whereas DP₁ and DP₂ influenced two FRs each in the original design, only DP₁ influences two FRs. From the product point of view, the new design prevents damage of the disk surface due to hard knocks (strong permanent magnet), yet allows arm to be released on start up, while maintaining sensitivity of voice coil.

Concept #2 – Condensed Standard 2.2. The permanent magnetic latch, though passive as required, is always on even when the arm is required to be released. In trying to decouple the latching (passive) and unlatching actions a possible design would replace the permanent magnetic latch with a combination electromagnetic activated spring-loaded pin and latch mechanism, a possible manifestation illustrated in Figure 6. With reference to the EMS model in the same figure, when the computer is turned off, the electromagnet is activated, raising the pin. The arm then moves to the rest position at which point the electromagnet is turned off, resulting in the spring loaded pin returning to its original extended position, but this time resting in the hole in the latch attached to the arm. As a result the arm is passively held in place by the pin. On computer start-up, the electromagnet raises the pin allowing the arm controller to readily move the arm to the active position. The electromagnet is then turned off and the pin returns to its rest position. Based on Equation 4, the design matrix can be stated as

Figure 5. Schematic and EMS model of concept #1: limited rotation stage

Figure 6. Schematic and EMS model of concept #2: spring-loaded pin and latch mechanism
Similar to the first concept, a comparison of Equations 3 and 6 shows a significant improvement (in an AD sense) in that (1) the design matrix is now square, and (2) only DP2 influences two FRs.

2.6. Use of AD for qualitative evaluation

Although significantly more concepts could be developed from the condensed standards in Table 1, generated concepts #1 and #2 are used to illustrate how AD tools can be further used to perform a qualitative evaluation of generated designs. Several points where the qualitative evaluation could occur within the TRIZ framework are shown in Figure 2b. A comparison of Equations 5 and 6 corresponding to Concepts 1 and 2, respectively, shows that the two designs are similar from the AD independence axiom perspective. If one however qualifies the relationships between the DPs and FRs as either helpful (positive) or detrimental (negative) to the product function, Equations 5 and 6 are recast as Equations 7 and 8, respectively.

In Equation 7 (Concept #1), DP1 (PM strength) works counter to DP3 (EM/Spring platform) with respect to FR2 (release arm). The latter provides a negative contribution to FR2. In Equation 8 (Concept #2), both DPs contribute positively to FR2. From a qualified AD independence axiom perspective, therefore, Concept #2 represented by Equation 8 is a better design. Note that one would have to take into account all other design considerations (e.g., size, cost, complexity, etc) before settling on a final design.

3. Conclusion

Axiomatic design and TRIZ are two principle-based innovation methods that have recently gained popularity. This study illustrates how AD independence axiom principles can be used within a TRIZ framework to (1) narrow down the list of possible standard solutions to apply if a physical contradiction is present, and (2) once a set of solutions is obtained, the same principles can be used as an evaluation tool.

Acknowledgements

The author would like to thank the reviewers for the helpful comments and the US National Science Foundation for partial support of this work through grant number CCLI-Educational Materials Dev 0442944.

References

Karr, T., 1998, Synthesis of the Principle-based and other Product Development Approaches with Emphasis on Concept Generation and Evaluation. Diploma Thesis of Cand.-Ing Aachen RWTH-Aachen in the WZL. Kim, Y-S and Cochran, D.S., “Reviewing TRIZ from the Perspective of Axiomatic Design”, Journal of Engineering Design, vol. 11, no. 1, pp. 79-94.
Norland, M., 1996, An Information Framework for Engineering Design based on Axiomatic Design”, Ph.D., Thesis, Stockholm: Royal Institute of Technology.

Ogot, M. (2005) “Problem Clarification in TRIZ using Energy-Material-Signal Models”, Journal of TRIZ in Engineering Design, Vol. 1, No. 1, pp. 27-39.

Ogot, M., (2006) “A Framework for Conceptual Design with Axiomatic Design and TRIZ”, TRIZCON2006, Milwaukee, WI.

Orloff, M., (2003) Inventive Thinking through TRIZ: A Practical Guide, Springer, Berlin.

Royzen, Z., (1999), “Tool, Object, Product (TOP) Function Analysis”’, TRIZ Journal, no. 9.

Ruihang, Z., Runhua, T. and Guozhong, C., “Case Study in Axiomatic Design and TRIZ: A Paper Machine”, TRIZ Journal no. 3, 2004.

Savaransky, S., (2000) Engineering of Creativity: Introduction to TRIZ Methodology of Inventive Problem Solving Boca Raton: CRC Press.

Soderlin, P., (2002), “TRIZ The simple way” TRIZ Journal, no. 2.

Suh, N.P. (2001) Axiomatic Design: Advances and Applications New York: Oxford University Press.

Yang, K. and Zhang, H., (2000) “A Comparison of TRIZ and Axiomatic Design”, TRIZ Journal, no. 8.