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AXIOMATIC DESIGN AND TRIZ: COMPATIBILITIES AND CONTRADICTIONS

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ABSTRACT

The paper examines Axiomatic Design in the light of its possible links to an evolved version of the Theory of Inventive Problem Solving, TRIZ. The paper highlights incompatibilities between the the Independence Axiom and the Ideality concept contained within TRIZ, but also several areas of mutually beneficial integration between the two methods – at philosophical, methodological and working tool levels.

Keywords: Axiomatic Design, TRIZ

1 INTRODUCTION

TRIZ (1, 2) offers a high level philosophical construct, plus a wide-ranging series of tools and methods to help designers and inventors to solve problems in creative and uniquely effective ways. For the most part these methods have evolved independent of many of the design strategies developed outside Russia. TRIZ-based research work taking place at the University of Bath includes activities to compare and contrast TRIZ with some of these non-TRIZ methodologies. The aim has been to produce tools and techniques coherently combining the best features of each method.

The paper focuses on Axiomatic Design (AD) concepts and ideas and their possible relationship with TRIZ; firstly from the perspective of how TRIZ might benefit designers more accustomed to AD methods, and then looking more closely at how Axiomatic Design might be usefully applied within a TRIZ context. The paper explores somes of the compatibilities and contradictions between Axiomatic Design's **analytical** design Axioms and the powerful design solution-**generating** capabilities of TRIZ. The discussion takes place through use of case studies from The Principles of Design and real world case study examples taken from a range of application arenas from pizza boxes to automobile wheel covers to next-generation aircraft undercarriage design.

The paper ends by proposing means of overcoming the contradictions between the two design approaches to create a sum greater than the individual parts.

2 THE DESIGN PROCESS

Put body of the paper here. The simplest – most superficial connection between TRIZ and Axiomatic Design comes from the map of the design process (Figure 1) found in The Principles of Design (3), into which TRIZ may be seen to fit exactly into the 'Ideate and Create' activity. Undoubtedly TRIZ offers designers and problem solvers in general considerably more in the form of substance than the usual instruction to 'now go and brainstorm some ideas' (also known as the 'insert miracle here' instruction in some circles) found in just about every other available method.

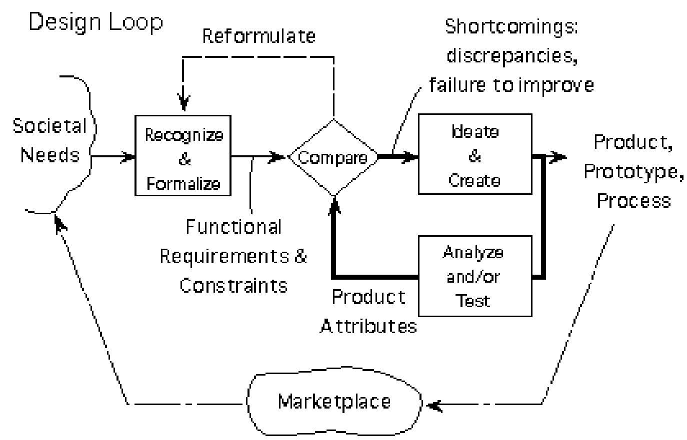

Figure 1.Schematic of Design Process.

At a slightly deeper level, the two methods have in common the basic guiding principle of distillation and codification of excellence into a deployable form. TRIZ's scope has been somewhat wider, taking in the systematic analysis of close to 2 million examples of engineering success, plus large proportions of known physical, chemical, biological, mathematical, and business success, plus several hundred person-years study of the psychological aspects of creativity. Consequently its findings have been somewhat more comprehensive. As illustrated in Figure 2, the include a hierarchy of philosophical concepts widening out to a complete systematic innovation process, which in turn contains a broad array of different tools and strategic for problem solving in its multitudinous forms.

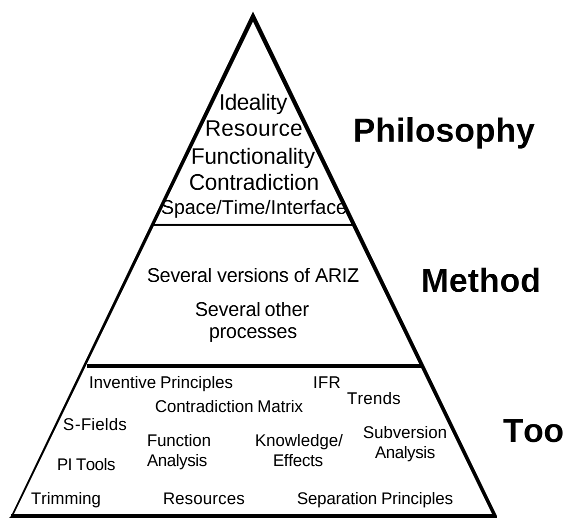

Figure 2.Schematic of Overall TRIZ Structure.

It is at the broad philosophical level that we may find the first area of incompatibility between TRIZ and Axiomatic Design. Both methods recognise the importance of function and functionality in the systems we design, but then have different views of what defines 'good'ness. In terms of the Independence Axiom, 'good'ness is measured by one-to-one, independent mapping between functional requirements (FRs) and design parameters (DPs). In simplified terms, 'one bit for every function'. TRIZ on the other hand, having studied the manner in which systems evolve (and hence the directions designers evolve the systems they design) suggests evolution tends towards an end-point (called 'Ideal Final Result') in which the ideal system delivers the function, but doesn't exist (or rather, more specifically, has zero cost or harm).

In terms of the well-worn faucet example, AD identifies the 'good' design as the one where the two functions 'control temperature' and 'control flow' are delivered by one lever with two independent motions. In terms of the TRIZ Ideal Final Result, the 'good' solution is the one where we obtain the functions, but there is no faucet. If this sounds rather abstract, what is likely to happen to help achieve this goal is that something (from the Resources part of TRIZ) already in the bigger picture system (from the Space/Time/Interface part of TRIZ) – like the sink unit, like the pipe-work, like the sink-top – takes on the function of the faucet. In TRIZ terms also, comes the image of hierarchical system structures in which components at the bottom end of the hierarchy gradually disappear as their function is taken on by things higher up the hierarchical chain.

The net result of this evolutionary direction is that as higher level systems take on more functions the one-to-one mapping of FRs to DPs may well not apply. Or; evolution towards increasing ideality says that it is possible to do better than one-to-one. Or, to put it another way, although the Independence Axiom represents a good 'rule', it is not – in TRIZ terms – an Axiom.

3 FUNCTION AND ATTRIBUTE ANALYSIS

Put body of the paper here. Put body of the paper here. Put body of the paper here. Put body of the paper here. Put body of the paper here Before leaving faucets to discuss some of the compatibilities between AD and TRIZ, it is probably instructive to examine how the faucet design problem would be handled from a TRIZ perspective. A common (although not compulsory) start point to the creative design process is the construction of a function and attribute analysis (FAA – Reference 4) model of an existing system.

AD unfortunately resorts to matrix algebra as the principle mechanism for determining the independence of functions (unfortunate because 'matrix algebra' and 'designer' seem to mix like oil and water in around 95% of cases). FAA modelling seems to offer a rather more visual perspective on whether designs are coupled or not, and it is that we will focus on now in order to elicit the useful rules that Axiomatic Design offers during use of the Trimming part of the TRIZ toolkit.

For the standard, coupled faucet design, a simplified FAA model would look something like the image reproduced in Figure 3.

The first thing we look to from this figure is what are the factors that show us that the design is coupled and therefore doesn't meet the Independence rule? The answers to this question are twofold:

1) the main product (a known amount of warm water) is produced through a combination of other things, and,
2) there are multiple (in this case two) control actions

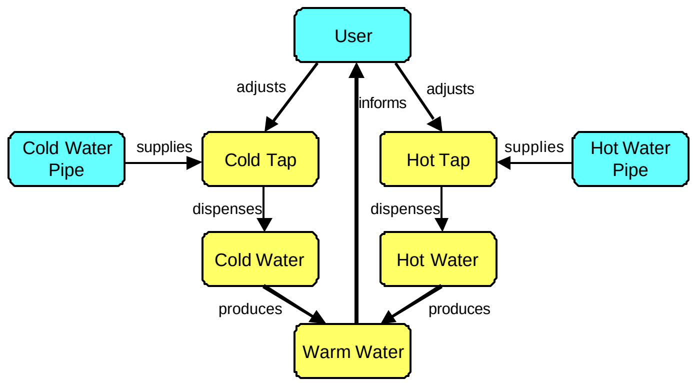

Figure 3.Simplified FAA Model of Hot and Cold Tap System

The second useful rule to take from this example and therefore from Axiomatic Design, is that after we have successively trimmed the system – see Figure 4 showing the equivalent FAA model for the mixer tap – we should continue to endeavour to maintain independence between the functional requirements. In other words, at least one of the two answers above, should no longer be true – so that either the product comes from one thing, or there is one control action, or both.

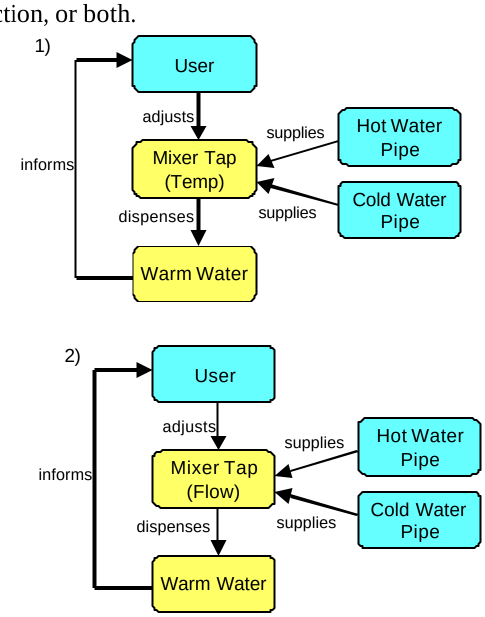

Figure 4.Schematic of Overall TRIZ Structure.

Note also how to truly reflect what happens in the mixer tap, the FAA model is drawn at two different times – the usual mode of operation being that the user first adjusts the faucet to the right temperature, and then adjusts for desired flow rate. In TRIZ terms, independence has been achieved by separating the two functions in time – i.e. the two functions happen sequentially and not in parallel.

Strict examination of the Independence rule suggests that the two FRs are actually only independent insofar as we have made this separation in time. If we think about the two functions being delivered in parallel, as far as the control signals heading back to the brain from the faucet are concerned, the two functions are most definitely coupled, no matter what the matrix algebra suggests. The usual response of most practically oriented faucet users seems in fact to be to uncouple the flow and temperature functions by setting flow rate to maximum (higher level functional requirement: 'fill sink in the shortest time possible') throughout the process of adjusting the temperature.

Meanwhile, let us now explore some of the other compatibilities and contradictions between AD's **analytical** design rules and the powerful design solution-**generating** capabilities of TRIZ using some design cases from The Principles of Design.

3.1 A SIMPLE EXAMPLE - REDUCTION OF MATERIALS COST

Suh discusses the case of a major US instrument maker looking to reduce the cost of the impact-grade polystyrene it used each year (Reference 3, pp30-31). Seeing that material cost for the parts under consideration constituted 75% of the manufacturing cost, Suh describes how the R&D team at the company was asked to devise a means of reducing cost of materials by 20% without sacrificing the mechanical properties of the part.

As in the large majority of other approaches, Suh also sees problem definition as the key to achievement of successful design. In Suh's terms, problem definition is an iterative process centred on the definition and optimisation of the Functional Requirements of a design.

In the case in question, Suh derives two FRs:-

FR1 = reduce the material cost by 20%
(i.e. reduce the material usage by 20%)
FR2 = toughness of the plastic part to equal or exceed that of the original part.

In terms of synthesizing possible solutions to the problem, the book offers little to detail how the 'ideate and create' black box derived viable solutions other than by stating that the designers tried a few different ideas (e.g. 'insert fillers', insert very small fillers') and eventually came up with the idea of 'microvoids'. The description in the book very much implies that the 'process' of discovering the solution was a somewhat nebulous affair.

At this point, then, it is very interesting to introduce how TRIZ might have been usefully deployed in reaching such a design solution:-

Contradictions - the problem of how to reduce the amount of material being used, while maintaining strength should hopefully immediately suggest a design contradiction and hence the use of Altshuller's Contradiction Matrix. The Matrix suggests 'Parameter Change', 'Curvature Increase' and 'Preliminary Action' as means used by others to inventively solve this QUANTITY OF SUBSTANCE versus STRENGTH technical contradiction. The first two suggestions in particular point immediately to a void-based solution (e.g. 'curvature increase should suggest the idea of making 'bubbles'/voids in the material smaller).

Evolutionary Trends - even more encouraging is the 'space segmentation' evolution trend spotted by Altshuller and his team - Figure 5 - i.e. a trend in which voids are introduced into a structure in ever smaller fashion:

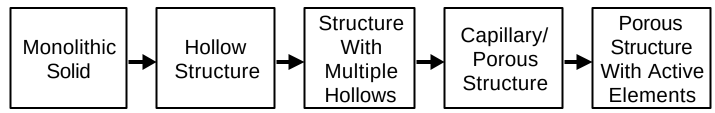

Figure 5.TRIZ `Space segmentation' Evolution Trend.

In both instances, TRIZ has vividly replaced the somewhat nebulous ideation stage in the reference description with a systematic solution synthesis.

Once derived, Suh demonstrates (albeit extremely briefly) how the Axioms may be used to determine that the microvoids solution is a good one and, perhaps more importantly (in Chapter 6) how the axiomatic approach may be used to quantitatively establish the most appropriate size and volume fraction of microvoids for the detailed, final solution. In this way, Suh's approach may be seen to be complementary to TRIZ: TRIZ equals synthesis tool, Axiomatic design equals analytical tool.

3.2 THE WRIGHT BROTHERS AND THE FREEZER DOORS

Problem definition is everything. According to Suh, the key to successful problem definition is the formulation and minimisation of Functional Requirements (FRs). He cites birds' wings as an example. Birds' wings have to satisfy many FRs; vertical take-off, horizontal take-off, climb, dive, cruise, hover, pitch, yaw, roll, retract, provide thermal insulation, etc. Initial human attempts at flight looked to mimic the bird wing design. They failed to recognise that not all of the bird wing FRs were necessary to achieving flight and hence they failed to fly. Suh suggests that the genius of the Wright brothers was in minimising the number of FRs to only those necessary for near-horizontal take-off, slow cruise speed and limited need for change in direction.

In many senses, this minimization of FRs is a solid test of 'good' design. It is however not the whole story. It is not the whole story for two important reasons:-

1) It fails to recognise evolutionary trend towards increasing 'value' or 'ideality'; minimising the number of FRs might be the only way to achieve *any* form of solution – as was the case with the Wright brothers - but as capability increases, so we will seek to introduce more FRs in order to increase customer 'value'. For example, sticking with the case of wing design, think of the evolution from the Wright brothers fixed wing, to simple flaps, to complex multi-flap designs, to swing wing aircraft, to smart structures, etc (NB note also TRIZ's 'Dynamisation' trend – Figure 6.)

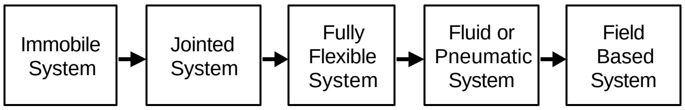

Figure 6: TRIZ 'Dynamisation' Evolution Trend

2) It fails to recognise the 'delight' aspects when a customer buys a product to do one thing and later finds out it can also do something else as well. When we reduce the FRs to a minimum (or simply define them inappropriately) - as in Suh's example of freezer door design (Figure 7); where the Requirements are reduced to 1) minimise energy (cold air) loss, and, 2) provide good access - we may well actually be shutting ourselves off from a significant sector of the actual customer base.

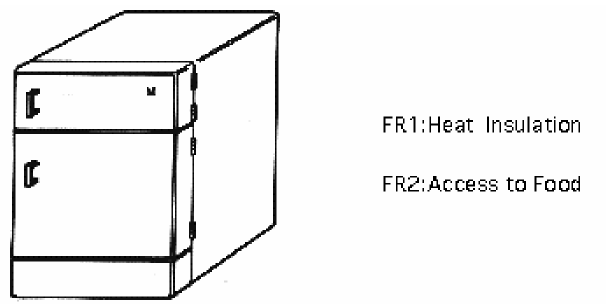

Figure 7: Nam Suh's 'Bad Design' Freezer

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Of course, the freezer design case cited in The Principles of Design is merely used as a convenient demonstration of his idea of Functional Requirements. In the real world of very high levels of competition and consumer choice, however, when he describes the vertical hinged door as 'bad design' because it does not meet his FRs, he is failing to recognise that they actually might well not be the most important requirements. Or that a very large proportion of freezers sold are of the vertically hinged variety.

The 'customer delight' aspect is also interesting. "Good design is about giving customers what they want. Great design is about giving customers what they didn't expect" to quote Tom Peters (Reference 4). A great example of a product which turned out to offer customers something they didn't expect is the AV-8B (Harrier) vertical take-off and landing (VTOL) aircraft. The Harrier was – and, thirty years later, still is – a great aircraft. At least a small part of it's longevity is due to the realisation some considerable time into it's service life that if pilots used the swivelling nozzles during flight (as well as for the initially designed vertical-to-horizontal flight transition functional requirement), they were able to produce manoeuvres capable of defeating just about any kind of enemy threat: 'Vectoring In Flight' – VIFing – an unexpected additional functional capability.

Problem definition continues to be the single greatest challenge facing designers. Apart from the recognition of the importance of function, AD does not appear to have much to offer in this regard. The TRIZ 'Ideal Final Result' philosophy, as discussed earlier is a rather more effective and practical alternative in most instances, although, as we shall see later, the appropriate definition of FRs can offer new problem solving insights in certain regards.

3.3 WHEEL-COVERS

The Principles of Design also contains many examples of use of the Axiomatic design analysis approach. While the main purpose of the examples is to demonstrate the underlying principles of the AD methods, they, unfortunately, do not always demonstrate his stated belief in the importance of effective problem definition. The example of the wheel-cover design (pp289-93) is one such case. More interesting than simply providing a demonstration of how the axiomatic approach may be used to find a good ('right') answer to the wrong question, however, is the role it might help to play in highlighting both the power inherent in the TRIZ methodology and the future potential for integration between the two approaches.

The example comes from work done at General Motors. Back in the early 80s, the designers at GM had a problem with wheel covers. GM wheel covers at the time were held on by simple spring clips. The problem the designers faced was that, if spring force was too small, the wheel covers fell off, and, if the spring force was too high, vehicle owners found it difficult to remove the cover when a wheel change was required. Suh's book describes the high degree of scientific rigour and customer focus employed by the GM designers during the search for a problem solution: They conducted a series of sophisticated customer trials using wheel covers with different spring forces and systematically measured how satisfied the customers were with each of the different cases. The results are summarised in Figure 8. Very simply, they found that 100% of customers were satisfied from the perspective of ease of cover removal if the force required to remove the cover was 30N or less, and that 100% of customers were happy that their wheel-covers wouldn't fall off if the retention force was 35N or more.

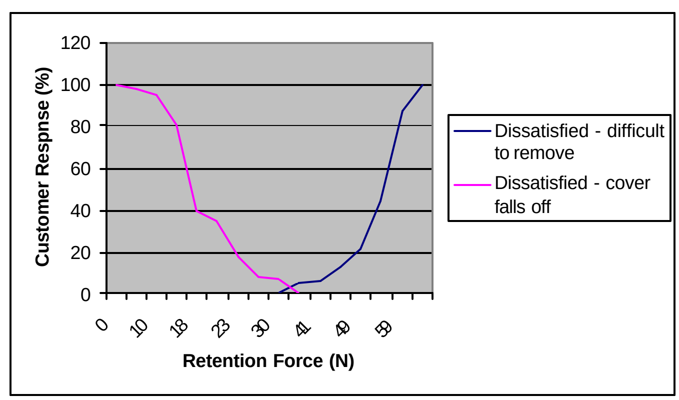

Figure 8: Wheel Cover Retention Force Design Point Selection

As well as being customer focused scientists, the example shows how the GM designers were very much cast in the non-TRIZ 'design is a trade-off' mind-set. Given the customer data, the 'design-is-a-trade-off' mindset says that the 'optimum' spring retention force needed to be somewhere between 30 and 35N. Being scientists, they also recognised that mass-production would mean some statistical variation in the achievable spring force. The

Functional Requirement for the wheel cover spring design, therefore, became '*Provide a retention force of 34±4N*'.

In non-TRIZ terms, they had done the best they could. In effect they had come up with a solution which was 'optimum' because it dis-satisfied the minimum number of customers. In fact, their data had shown that a 34±4N solution would dis-satisfy somewhere between 2 and 6% of their customers. Or, put another way, probably somewhere around 100,000 per year.

The AD analysis of the problem is subsequently somewhat complex, but nevertheless shows how the approach was able to best tune the design variables to achieve the defined Functional Requirements.

TRIZ, on the other hand, would immediately identify the GM wheelcover problem as a design contradiction. The TRIZ approach is built on a 'design without compromise' philosophy. It is about eliminating contradictions rather than accommodating them. The contradiction present in the wheelcover case is a Physical Contradiction. It is a physical contradiction because the wheelcover retention force is required to be be HIGH (to retain the cover) AND LOW (to make it easy to remove). Altshuller's analysis of the patent database has allowed him to see how inventors across all industries and specialities have successfully eliminated such contradictions. Specific TRIZ Inventive Principles, then, recommended to solve problems of the wheelcover type, include:-

- 'Preliminary Action' (e.g. push-and-twist type wheel covers)
- 'Skipping' (e.g. eliminate the spring and use some other means of holding the wheelcover – e.g. Peugeot sometimes use the wheel-nuts to hold the cover as well as the wheel)
- 'Discarding and Recovering' (e.g. eliminate the spring altogether – e.g. alloy wheels (the wheel is the wheel-cover))

In other words, the GM designers were using AD to optimise the wrong design. The 'right' design – according to TRIZ – is the one which eliminates the trade-offs rather than seeking to balance between them. The 'Contradictions' part of TRIZ provides designers with a systematic approach to finding means of eliminating those contradictions.

The Axiomatic approach may have some use in **analyzing and optimizing** the conceptual solutions derived from TRIZ in some cases. In a simple case like the wheel-cover, it is perhaps difficult to see what additional benefits the Axioms might bring. Moving along to look at the AD/TRIZ connection story from the perspective of how Axiomatic Design might be usefully applied to help produce a 'better' TRIZ solution, we can see that this need not always be the case.

3.4 PIZZA BOX

US patent 5,472,139 is a commonly cited example amongst TRIZ users of the 'geometric evolution of linear constructions' technology evolution trend. The patent uses the trend as the basis for contouring the base of a pizza box in order to introduce thermally insulating air-gaps between the pizza and the base of the box – i.e. a harmful planar contact surface will evolve towards aline-based contact (and ultimately towards a point-based contact). A sketch of the pizza box design is illustrated in Figure 9**.**

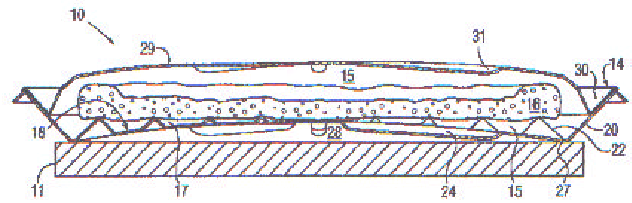

Figure 9: US Patent 5,472,139 Pizza Box

The basic idea of the patent is to improve the heat retaining properties of the box such that the pizza stays hotter for longer.

In terms of Axiomatic design, the invention sees the introduction of a Functional Requirement 'improve heat insulation' to the basic pizza box FR of 'protect pizza'.

A more complete functional analysis of the pizza-box using AD, however, might well also register the presence of a Functional Requirement to be able to slice and serve the pizza direct from the box. The 5,472,139 invention has not been conceived with this requirement fully in mind (NB despite the fact that the invention is an upgrade of a previous patent by the same inventors specifically to try and improve 'slice and serve' performance). The simple fact is that the contoured base of the box is not amenable in a sufficiently practical sense to the use of a cutter to slice in situ pizza.

The pizza box example demonstrates the importance of identifying **all** the necessary FRs to be achieved in a given design. Axiomatic Design methods, while not always able to help identify what 'all' means – Suh in fact recommends QFD for this task – can be very usefully employed to ensure the chosen FRs are independent and thus consistent with good design practice. Or perhaps it is merely sufficent that AD forces designers to give the matter of Functional Requirement definition due consideration.

4 CONCLUSIONS/FINAL THOUGHTS

It is still early days for integration between TRIZ and Axiomatic Design (applying TRIZ trends to TRIZ suggests that eventually they will join – Reference 5). Preliminary evidence, however, suggests that the analytical methods of AD do complement the synthesising capabilities of TRIZ in at least three significant areas:-

1) a very important philosophical aspect of AD is that there exists a necessary process of iteration between FR's and physical design attributes. In other words, it is not sufficient to simply define a set of Functional Requirements and then set about the process of translating them into Design Parameters. The method says that if we are to achieve 'good design' – i.e. design satisfying the two Axioms – the design parameters must be allowed to influence the form and content of the Functional Requirements.

2) As well as recognising the relationship between Functional Domain and Physical Domain, Suh further extends the AD

model to include what he describes the Process Domain (Reference 1, Section 4.10). In other words, AD demands that manufacturability issues are given appropriate consideration **during** the process of iterating to achieve the most appropriate form of the design Functional Requirements. This is an area where TRIZ is rather unspecific at this point in time.

3) Perhaps the most significant difference between AD and TRIZ becomes apparent when considering the hierarchial nature of design problems. Aspects of this difference may be seen in a previous discussion regarding the design of a helicopter particle separator (Reference 6). Basically, meanwhile, AD places careful emphasis on the importance of recognising the hierarchial nature of design and, particularly to ensure that the process of iteration between Function Requirements in the Functional Domain and selection of Design Parameters in the Physical Domain is carried out in a systematic manner.

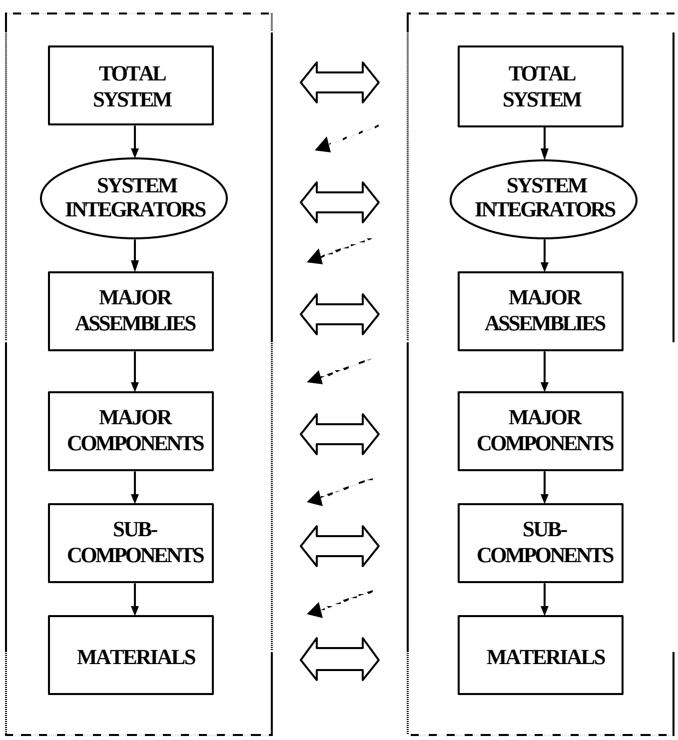

Figure 10: Hierarchial Nature of Functional Domain – Physical Domain Mapping

As may be seen in Figure 10, this systemisation occurs through an essentially top-down approach; definition of System Level FRs permits derivation and iteration of System Level DPs and then – most importantly – definition of the System Level DPs is necessary before FRs at the next level down in the hierarchy may occur; and so on right through each level of the hierarchy. In effect, AD suggests that finalisation of top level FRs can only really be achieved after each layer of the problem hierarchy has been given due consideration and iterated accordingly.

It would appear that Axiomatic Design has much to offer TRIZ in terms of providing a better understanding of both the hierarchial nature of design **and** the need to pay due attention to the inter-connections which exist between successive hierarchial layers.

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