From trade-offs to innovation - the underlying principles of TRIZ and TOC applied.

Systematic innovation and the underlying principles behind TRIZ and TOC applied to manufacturing.

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Abstract

Innovative developments in the design of product and manufacturing systems, are often marked by self-evident simplicity, at least in retrospect, that has previously been shrouded by restrictive mental models or limited knowledge transfer. These innovative developments are often associated with the breaking of long established trade-off compromises, as in the paradigm shift associated with JIT & TQM, or the resolution of design contradictions, as in the case of the dual cyclone vacuum cleaner. The rate of change in technology and the commercial environment suggests the opportunity for innovative developments is accelerating, but what systematic support is there to guide this innovation process. This paper brings together two parallel, but independent theories on inventive problem solving; one in mechanical engineering, namely the Russian Theory of Inventive Problem Solving (TRIZ) and the other originating in manufacturing management as the Theory of Constraints (TOC). The term systematic innovation is used to convey the systemic approach to the use of common underlying principles within these two approaches. The paper focuses on the significance of Trade-off contradictions to innovation in these two fields and explores their significance to evolutionary developments in manufacturing strategy.

Keywords: Systematic Innovation, TRIZ, TOC, Constraints Management, Trade-offs, Manufacturing Strategy

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1. Introduction

The concept of trade-offs, or conflicting performance parameters is a central feature of mechanical design where speed and efficiency, or strength and weight performance conflicts are readily acknowledged. These are typically well documented and the performance trade-offs balanced in the design process to give the optimum for a particular application. What is less well known is the significance of these contradictions in the innovation process. The practice of using trade-off parameters as a focus for systematic innovation in mechanical design has only recently emerged from Russia under the name of TRIZ (The Theory of Inventive Problem Solving), but it is already attracting significant industrial interest. [1]

In the field of manufacturing it is over 30 years since Skinner [2] used the concept of mechanical design trade-offs to help acknowledge and manage conflicting performance parameters associated with manufacturing. This extract from his seminal work illustrates the mechanical analogy.

'For instance, no one today can design a 500 passenger plane that can land on a carrier and also break the sound barrier. Much the same is true of manufacturing. The variables of cost, time, technological constraints, and customer satisfaction place limits on what management can do, force compromises, and demand an explicit recognition of a multitude of trade-offs and choices.' [2]

From this and subsequent papers the strategic trade-offs associated manufacturing investment and decision making became explicitly acknowledged. The term 'manufacturing strategy' emerged with a new awareness of performance conflicts and the need to make strategic choices between competitive criteria, such as speed and efficiency or quality and cost. Since then the debate has moved on and some of the originally cited trade-offs are acknowledged to have been all but eliminated in certain sectors, with the application of developments such as JIT and TQM, now often cited as heralding a new manufacturing paradigm [3]. As a consequence some would argue the trade-off analogy with mechanical design is no longer relevant [4]. Others argue the trade-offs just change, as with mechanical systems [5,6,7], but the perceived role of trade-offs is limited to one of explicitly acknowledging their existence so that their negative impact can be minimised, rather than as a focus for innovation.

This paper aims to shed new light on this debate by exploring the deeper significance of trade-offs in mechanical design before linking the analogy to organisational improvement and innovative developments in manufacturing. The thesis of this paper is that the concept of performance contradictions has much more to offer than has been widely acknowledged to date, not only in the design of artifacts but also manufacturing strategy. The paper will outline the TRIZ and TOC perspectives on performance contradictions, demonstrating the common underlying principles, before exploring the broader significance of trade-offs in manufacturing.

2. TRIZ

Work on TRIZ, a Russian acronym for The Theory of Inventive Problem Solving, began in 1946 when Genrich Altshuller, a mechanical engineer, began to study patents in the Russian Navy. Over subsequent years his desire to structure the inventive process resulted in a range of tools and approaches based on empirical analysis. TRIZ has now been the subject of many person years of development and seen the study of over 2 million successful patents [9]. The approach has been widely taught in Russia, but did not emerge in the West until the late 1980s. The different solution systems have been derived by abstracting inventive principles from ongoing analysis of patent data. Several of these focus on contradictions or trade-offs in identifying innovative solutions.

The TRIZ methodology claims that, 'Inventive problems can be codified, classified and solved methodically, just like other engineering problems'. [8]

There are three premises on which the theory is based:

- The ideal design with no harmful functions is a goal.
- An inventive solution involves wholly or partially eliminating a contradiction.
- The inventive process can be structured.

Each of these premises will be dealt with in turn.

2.1 The ideal design with no harmful functions is a goal.

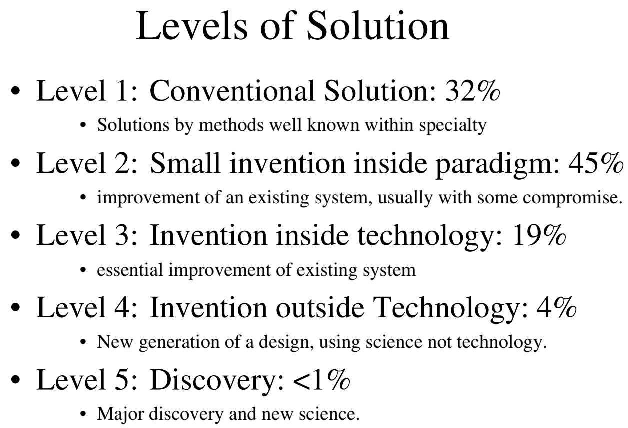
Finding the ideal solution to a needed effect or function with no additional resources or negative secondary effects is referred to in TRIZ circles as Ideality.

$$\text{Ideality} = \frac{\text{All useful effects or functions}}{\text{All harmful effects or functions}}$$

The ideal being, to achieve all useful effects or functions with no harmful effects or any use of resource. One can argue there is little new in this, as a similar emphasis on improving functionality is also evident in widely established approaches such as Value Engineering. However, the difference is that this thinking is central to TRIZ and specialist supporting tools have been developed that specifically concentrate on improving the functionality through innovation rather than the traditional cost cutting focus of Value Analysis.

2.2 An inventive solution involves wholly or partially eliminating a contradiction.

Altshuller's [9,p12] early work on patents resulted in him classifying inventive solutions into five levels. Through this work he defined an inventive problem as one containing at least one contradiction. After reviewing 200,000 patent abstracts he selected 40,000 as representative of inventiveness. The remainder he considered to involve self evident direct improvements. He then separated the 40,000 inventive solutions into five levels as shown in figure 1. Further patent work in the 60s and 70s resulted in the percentages shown in figure 1.



Levels of Solution

- Level 1: Conventional Solution: 32%
  - Solutions by methods well known within specialty
- Level 2: Small invention inside paradigm: 45%
  - improvement of an existing system, usually with some compromise.
- Level 3: Invention inside technology: 19%
  - essential improvement of existing system
- Level 4: Invention outside Technology: 4%
  - New generation of a design, using science not technology.
- Level 5: Discovery: <1%
  - Major discovery and new science.

Figure 1 levels of innovation [9]
showing the % of patents discovered in each level[10,p47]

Altshuller considered level one solutions to not be inventions but narrow improvements. Level 2 solutions involved partially eliminating contradiction but still requiring obvious compromises.

Level 3 solutions completely eliminate the main contradiction within the existing system using technology outside the field. The level of solution can be considered to cause a paradigm shift within the industry as the solution is outside the industry's range of accepted ideas and principles.

Level 4 solutions are found in science and are outside the technology's normal paradigm, involving a completely different principle.

Level 5 solutions lie beyond the confines of contemporary scientific knowledge.

Altshuler claimed his solution systems could assist innovation at levels 2-4.

2.3 The inventive process can be structured.

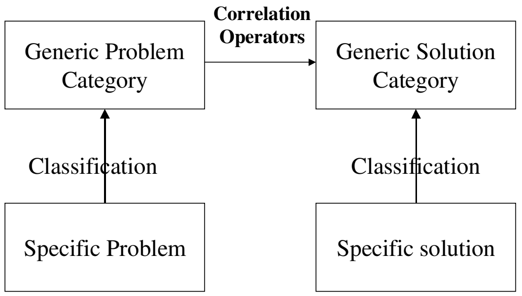


Figure 2: The general case for abstracting a solution system.

This early work convinced Altshuller that there was potential to structure the inventive process around trade-off contradictions and it led to several developments, only two of which are introduced here. In each case empirical data has been used to develop correlation operators using the principle of abstraction. Figure 2, illustrates this process of classifying the problems and solutions to seek out a correlation that enables a set of generic problem solving operators or principles to be identified. This basic model will be referred to as we look at two solution systems of classical TRIZ base around contradictions.

After having identified the significance of contradictions Altshuller went on to classify them into 39 parameters and in a similar way he identified 40 common principles that he found had been repeatedly used to resolve them. To display the possible technical contradiction combinations he produced a 39X39 matrix and identified which of the 40 inventive principles were more closely associated with each specific combination.. This matrix is called the Technical Contradiction Matrix. Figure 3 shows the process associated with this first solution system.

For illustration, if we consider Skinner's aircraft trade-off, a typical trade-off might be speed versus adaptability (eg take-off and landing distances). The above TRIZ approach to breaking this

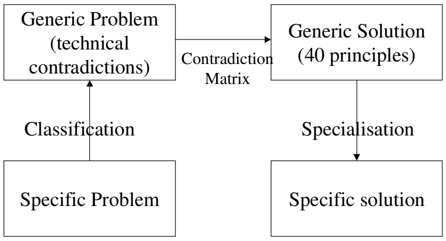


Figure 3: Use of the general case applied to technical contradictions

contradiction would be to relate the trade-off parameters to the 39 standard technical contradiction parameters to find the closest match. In this case there is an exact match Speed (parameter 9) and Adaptability (parameter 35). The contradiction table developed by Altshuller recommends 3 of the 40 principles (principles 15, 10 & 26) for early consideration. Principle 15 is 'dynamicity' which is illustrated with various examples that can be linked to the concept of variable wing geometry as a possible solution. This would have classified as a level 3 solution.

These 40 inventive principles and the contradiction matrix have stood the test of time, however this was only the first of the TRIZ solutions systems.

2.3.1 Physical Contradiction Solution System

Over a period of time Altshuller identified a further level of abstraction from the technical contradictions. He found that in many cases the technical contradiction or trade-off could be presented as two extremes of one feature, which he called a Physical Contradiction. Put more formally: A Physical Contradiction requires mutually exclusive states as they relate to a function, performance or a component. Figure 4 illustrates the higher level of abstraction associated with the Physical Contradiction solution systems.

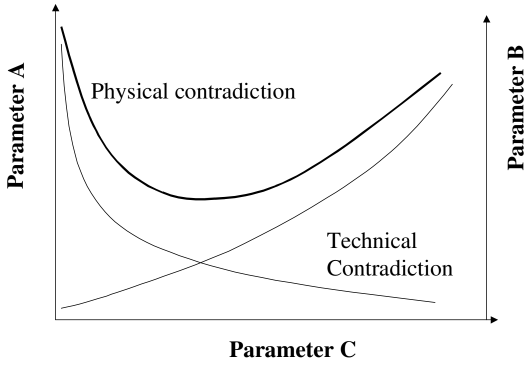


Figure 5: A graphical representation of technical and physical contradictions

Typical physical contradictions include: fast vs. slow; hard vs. soft; solid vs. porous; heavy vs. light; moveable vs. stationary; dark vs. light; hot vs. cold; big vs. small; etc.

The relationship between the Technical and Physical Contradictions can be viewed graphically as illustrated in Figures 5.

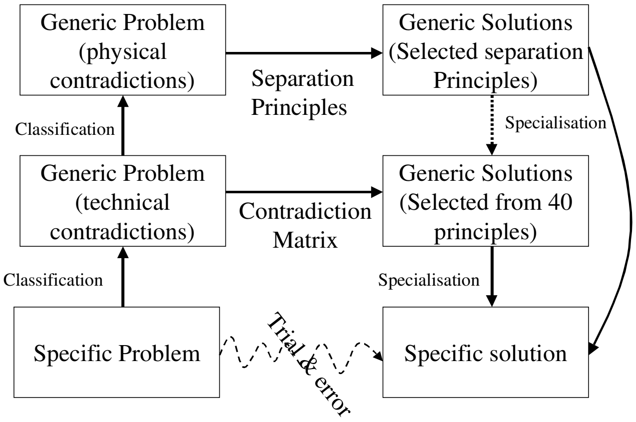


Fig 4 :The second level of abstraction

In the figure a technical contradiction between parameters A & B has been further abstracted to present the contradiction in terms of a common variable parameter C, which represents the physical contradiction. Altshuller found that by defining the contradiction around one parameter with mutually exclusive states the correlation operators used to detect a solution could be more generic and there are just four separation principles used to help resolve this type of contradiction.

These Separation Principles can be summarised as:
Separation of opposite requirements in space;
Separation of opposite requirements in time;
Separation within a whole and its parts;
Separation upon condition.

If we consider the aircraft example again, this development would take the original Technical Contradictions of speed and adaptability and look for another common parameter displaying mutually exclusive states, as displayed in figure 5. Such a parameter in this example might be wing area. For speed a small wing area is required, but for take-off, landing and general manoeuvrability a larger wing area is required. The four Separation Principles would then be considered and in this case 'separation in time' naturally leads to the possible option of variable wing geometry.

2.4 Conclusion

These two solution systems represent the founding work of TRIZ centred on contradictions. For a more comprehensive introduction see [9] or for more depth [10,11]. Having introduced the innovative role of trade-offs in mechanical design let us now look at the related aspects of TOC and distill out some of the common principles with manufacturing examples.

3. TOC

The Theory of Constraints has been developing over 20 years by Dr E Goldratt and from 1986 within the Arhaham Goldratt Institute (AGI), an international partnership. There are also independent user groups actively involved in the work, the most notable of which is the America Production & Inventory Control Society (APICS) Constraint Management Special Interest Group. [12]

TOC as with TRIZ is also focused on developing innovative solutions, but in this case the focus is on managing or breaking constraints within organisations. It originated with the development of Optimised Production Technology (OPT), a revolutionary computerised planning and control system of the 1980s, which is now considered a seminal development in Advanced Planning and Scheduling (APS) systems [13]. Since the mid1980s the principles have been applied to addressing not only physical constraints, but also policy and paradigm constraints within organisations. A recent application of this work to conflicts associated with project management has resulted in the generic solution of Critical Chain Project Management, which is becoming widely acknowledged by industry [14]. In addition to the development of these generic solutions there has been the parallel activity of developing a practical improvement process, to which Goldratt attributes his generic solutions. This process centres on identifying and eliminating policy or paradigm constraints, which are closely associated with trade-off conflicts. There are two basic tools used in this process, one is used to maps cognition through Effect-Cause-Effect (ECE) analysis, and the other is used to expose and break the core conflict or constraint through the Evaporating Clouds (EvC) technique. As with TRIZ, TOC is very much industry led, but the theoretical base is evident in that it has enabled the generic solutions to be developed over the past 15 years [15].

The underlying premises behind TOC :

- All organisations have a purpose or goal they aspire to continually move towards.
- Opportunity for value adding improvement is limited by few constraints.
- Identifying and breaking these constraints can be structured.

3.1 *All organisations have a purpose or goal they aspire to continually move towards.*

As TRIZ focuses on improving the functionality with minimum waste, TOC focuses on improving the value adding performance of the organisation rather than reducing cost. Where the organisation is for-profit the term Throughput (T) is used to identify the financial value added component and Operating Expense (OE) is used to cover all other expenses.

Throughput (T) = Sales -Direct materials and directly varialble costs.

Operating Expense (OE) = all other operating costs.

Therefore
Net profit = T-OE
Or
Value Added Productivity = T/OE

As with the Ideality ratio of TRIZ the statement is not original, but the focus with the support tools is. TOC centres on increasing Throughput rather than reducing Operating Expense; arguing that although cost cutting is important it is limited and can be dangerous without a strategic perspective. Focusing on increased Throughput is inevitably strategic in nature requiring a systems view of the business to enable the identity of what limits or constrains current and future Throughput.
The focus on 'goal units' is also widely applied to non-profit making organisations, but the unit of measure is not so convenient in these cases.

3.2 *Opportunity for value-adding improvement is limited by few constraints.*

The TOC defines a constraint as, *'Anything that prevents the organisation from achieving higher performance versus its goal'*. So in the case of a profit making organisation this centres on what limits T. The TOC claim is that there are few constraints to any system preventing it from achieving its goal.
Although TOC originally focused on physical resource constraints the underlying constraints are commonly underlying policy, or deeper paradigm constraints. TOC uses cognitive mapping to verify this assumption where necessary, but there are many other authors who acknowledge the importance of underlying core problems that constrain system improvement. Senge refers to the need to tackle underlying 'mental models' [16] and Argyris refers to the need for double-loop-learning where the deep-seated 'governing variable' [17] are restricting organisational improvement.
As with TRIZ these constraining core problems are exposed as contradicting requirements that otherwise tend to be ignored or accommodated via local sub-optimisation models.

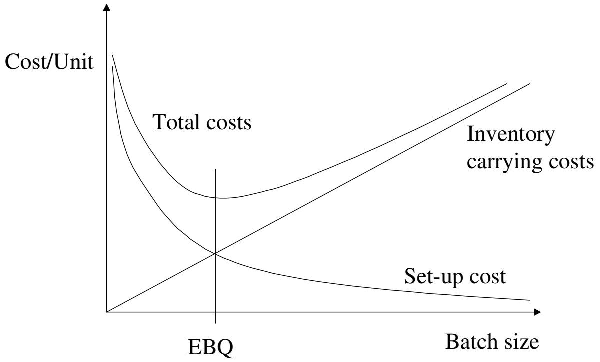


Figure 7 Traditional Batch Size Conflict

A classic example of this is evident in the Economic Batch Quantity (EBQ) formula graphically illustrated in figure 7. As can be seen the traditional batching policy represented by this simple model reflects the conflicting parameters in a similar way to TRIZ Physical Contradictions. This is a classic example of a trade-off compromise viewed very narrowly with many embedded assumptions, which have proved to be increasingly invalid. However, such models represented a paradigm that has had wide implications in manufacturing management and there is a similar model for quality costs. JIT and TQM developments challenged the validity of such models in the 1980s demonstrating how they could be broken, and resulting in a paradigm shift in manufacturing management thinking. It is clearly evident that the TRIZ concept of Physical Contradictions is closely related and this will be illustrated later.

3.3 *Identifying and breaking these constraints can be structured.*

TOC and TRIZ actively seek out such compromises with a view to focusing attention on a critical area of the system and so enabling overall systems improvement. Typically the contradiction, or conflict of major concern would be verified by a form of cause and effect analysis in both TOC and TRIZ [18].

In TOC the contradiction is presented in what is called an Evaporating Cloud (EvC), sometimes known as a Conflict Resolution Diagram. The diagram is a simplified cause and effect diagram used to expose and challenge the underlying logic linking conflicting needs. The cloud depicting the batch size conflict is illustrated in fig. 8.

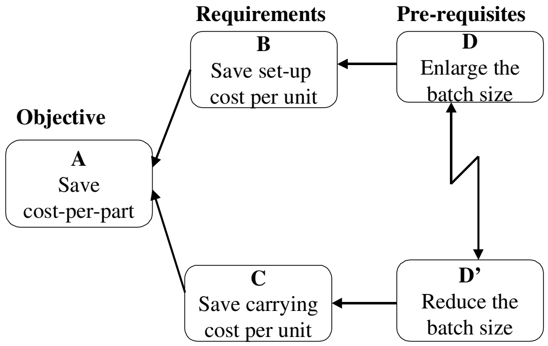


Figure 8 Batch Size Cloud

In the diagram, the requirements B&C are necessary (but not sufficient) to achieve the objective A. Similarly the prerequisites at D and D' are necessary (but not sufficient) to achieve the requirements at B and C respectively. It is normal with the EvC to formulate the problem from the prerequisite conflict and to then work from there, clarifying the thinking behind the causal links along the way, through B, C and finally A. This is however usually an iterative process.

Each of the arrows in the diagram is then scrutinised during a TOC analysis of the problem situation to examine the assumptions contained in the problem definition. In TOC terms, the Cloud is evaporated (i.e. the problem is solved) if one of the assumptions embodied in the arrow can in some way be invalidated.

By way of example, both JIT and TOC have challenge the assumption contained in the arrow B-D, that large batches are a prerequisite for reducing set-up costs. Therefore, if means are found to break the perceived relationship then the problem is solved.

The JIT approach to this problem was to challenge the assumption that set-up times were cast in stone. The wider benefits of low inventory and the opportunity to simply reduce set-up time was a revelation to many industrialists and, in some cases, effectively eliminated the conflict at source with little expense.

The traditional TOC challenge to this arrow relates to the underlying performance measurement systems that assume that increasing the number of set-ups automatically means increased Operating Expense or reduced Throughput. In reality there is often spare capacity that results in neither increased cost nor reduced Throughput. But more importantly the impact on T & OE needs to be clearly distinguished and located if appropriate action is to follow.

This particular cloud has also been broken at the D-D' conflict arrow. The false assumption is that there is only one definition of 'batch', but the two requirements put different interpretations on the word. The conflict can be evaporated, at least in some cases by acknowledging the distinction between a process batch and a transfer batch.

The breaking of the arrow at D-D' is closely related to the breaking of a TRIZ Physical Contradiction using the four separation principles. If we apply the principle of 'separate in time' the opportunity to distinguish between process and transfer batches becomes evident. Earlier work by the authors' [18] has explored these parallels more closely.

3.3.1 The breaking of paradigm constraints

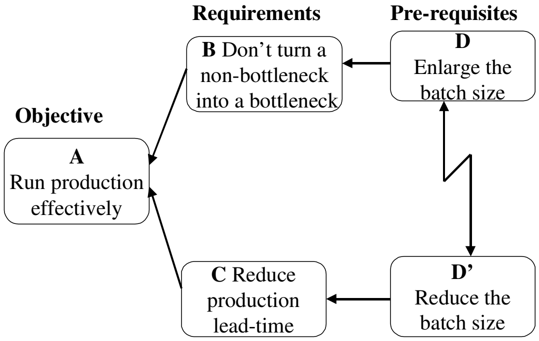


Figure 9 Batch Size Cloud in the Throughput World [20]

The breaking of clouds at arrow B-D or C-D' typically represents the breaking of a policy constraint, but the work of JIT, TQM and TOC went further than this. It can be argued that the batch size cloud is built around a 'costing paradigm' particularly prevalent in the West and graphically illustrated by Skinner in The Productivity Paradox [19]. Here Skinner's case work illustrates how many American companies in the 1980s were focusing on a very narrow and declining perception of productivity, direct labour productivity, and not considering the impact of their direct labour cost focus on the loss of orders through the trade-off with service and quality.

If we consider the concept of evaporating clouds the breaking of a paradigm constraint will tend to be at a more fundamental location such as arrows A-B or A-C. In the case of this cloud the stated objective is also embedded in the costing paradigm, which Goldratt refers to as the 'Cost World' [20].

Figure 9 is the version of the cloud advocated by TOC, which redefines the objective and requirements. Objective C now more clearly reflects the impact on customer service and therefore future Throughput, whilst objective B reflects the need to consider available capacity and therefore the possibility of constraining current Throughput. This redraw of the cloud reflects the paradigm shift associated with TQM, JIT and manufacturing strategy thinking.

The TOC argument is that the important question is, what to change? Arguing there are many possible 'improvements' but very few that will impact on what constrains Throughput. The cloud is used to acknowledge the conflict and seek to find an inventive solution that evaporates the problem. Over the years TOC generic solutions have been developed, such as Drum-Buffer-Rope[21] and more recently the Critical Chain [22] mentioned earlier. But even if these applications are relevant it is argued that the cloud still has its place in focusing attention and involving all relevant functions in agreeing with the conflict analysis and actively participating in exploring solutions

This section has illustrated the EvC approach, but provided limited detail on its practical use. For more detail on this and the TOC thinking process see [23].

4. Common aspects of TOC and TRIZ

- Both subordinate the importance of reducing cost in improving 'Ideality' and 'Value added productivity'.
- Both focus on trade-off situations in the form of conflicts and contradictions as key to purpose centred improvement.
- Both claim the resolving of contradictions and conflicts can be structured.
- In defining the contradiction the TRIZ concept of physical contradictions and the TOC EvC has been shown to have a common basis, where breaking a physical contradiction relates to evaporating the EvC D-D' arrow.
- In finding a solution TRIZ is more knowledge based in that achieving the paradigm shift associated with solutions at levels 3 and 4 often requires knowledge of existing technology external to the field and knowledge of scientific effects.
- In finding a solution TOC is more psychologically based where the thinking underpinning the prerequisite conflict is more often the source of a solution than the conflict arrow D-D'. This distinction possibly just highlights the complexity of human activity systems and the artificial nature of organisations.

5. Manufacturing Strategy

Having explored the deeper relevance of trade-offs through TRIZ and TOC let us consider the broader implication for manufacturing.

5.1 A way of thinking

Manufacturing strategy is often referred to as requiring a different way of thinking, which embodies a cross-functional perspective and a focus on how the manufacturing function can support the business to compete in the market place. In a similar way TRIZ and TOC are concerned with an holistic view of the system and systematic means of focusing on the value adding component of strategic improvement. A new paradigm will involve new thinking, but this needs to be selectively applied to meet the innovation needs of each system.

5.2 Acknowledge conflicting performance criteria

Skinner[24] and subsequently Hill [25] have stressed the need to acknowledge that price is not the only competitive criteria and that satisfying different order winners and qualifiers requires different system designs. This is very evident in skinner's analogy comparing manufacturing systems design to the mechanical design of aircraft. Viewing the system in totality is essential if conflicting sub-optimisation is to identified. Although some levels of innovation are much more significant than others all innovation involves conflicts and most solutions are low level. This is also a fundamental aspect of the TRIZ and TOC concepts.

5.3 Reconciling the conflict

The classic manufacturing strategy conflict centres on different competitive requirements that manifest themselves in a range of different conflicting prerequisites. Possibly this is best summarised by the demand for both long and short production runs as illustrated below in figure 9. The prerequisites have similarities to the earlier batch size clouds, but as you can see the A,B and C have more in common with the 'Throughput world' cloud. This cloud acknowledges the importance of different order winning criteria associated with Engineer to Order (ETO) and Make to Stock (MTS). Consequently different manufacturing tasks, which are shown here to result in the prerequisites of short and long production runs.

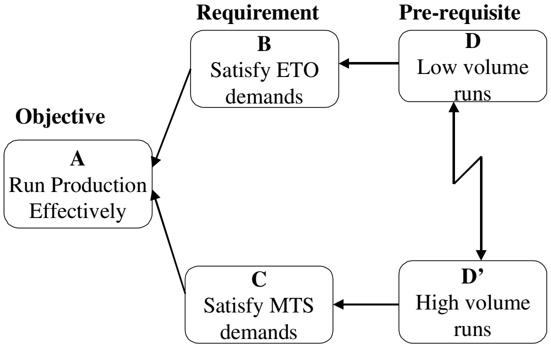


Figure 10 Generic Manufacturing Strategy Cloud
(ETO:Engineer to order. MTS: Make to stock)

It is interesting to note that Skinner's generic solution to the above cloud was to set up separate focused manufacturing units or a Plant Within a Plant (PWP) concept [3]. Similarly the TRIZ approach to resolving Physical Contradictions is to use the four separation principles, the first of which is to 'separate in space', which directly relates to the PWP concept. The common problem with this solution is that it raised another contradiction over the loss of economies of scale, but it has been shown to be a major step forward for many companies as they have acknowledged the consequent increase in T more than compensates for the increase in OE. Lean manufacturing and agile manufacturing arguments would question the C-D' arrow but any solution needs to be viewed in relation to specific applications to ensure the conflict is real and the solution is viable.

5.4 Tailored solutions are required.

The paradigm shift associated with JIT, TQM, Lean Thinking, and TOC applications has undoubtedly had a major impact on the structural and infrastructural design choices of manufacturing systems. However this revolution in thinking does not mean that performance conflicts are no longer relevant. Skinner [5], Hill [25] and others stress the need to tailor solutions to meet the needs of specific product-market combinations. In a similar way there is a need to identify constraining conflicts specific to certain product market combinations. This will enable the focused application of the new thinking in a considered rather than prescriptive manner.

There are many examples of companies adopting panacea solutions without assessing the need first. One such company in the early 1990s produced high specification aluminium extrusions and at that time had an 18 month waiting list. They had a reputation for being ahead of the field in implementing new developments and at this time decided to adopt a policy of minimum inventory and Jidoka line stopping when a problem occurred. In the attempt to prescriptively improve their process they had not considered the detrimental impact on current and future Throughput.

At the day to day operational level both TRIZ and TOC thinking processes reflect a basic skill of focusing attention on adding value adding improvements and seeking win-win solutions. It is not surprising that there is much popular, if less formalised evidence of this thinking in highly effective people [26].

It is suggested that systematic innovation concepts and tools embedded in TRIZ and TOC enhance the traditional manufacturing strategy thinking with tools to challenge and break the on-going trade-offs as well as help focus attention on and manage the strategic choices.

6 Conclusion

A generic term Systematic Innovation has been used to convey the common underlying principles embedded in two very focused industry based approaches to strategic innovation. Both approaches view the identification and the elimination of performance contradictions as key to long term value added improvement of a system and the tools used to break the conflict have been shown to have common features

The trade-off analogy associated with manufacturing strategy is still valid but needs to be developed further to encompass the importance of not only acknowledging trade-offs in managing the inherent conflict but using the conflict as a focus for structured innovation. Although the paradigm shift in management thinking in the 1980s resolved major contradictions originally cited by Skinner this highlights the opportunity to exploit this new thinking in resolving constraints to meet the needs of different applications.

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