

EXTENDING TRIZ TO HELP SOLVE NON-LINEAR PROBLEMS

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ABSTRACT

TRIZ currently contains little to assist problem solvers in the definition and solution of situations containing non-linearities. Solution suggestions take no account of the magnitude, change or rate of change of the applied solution strategy or how the problem situation will respond. The paper highlights the potential dangers of such shortcomings and goes on to suggest and demonstrate effective means by which TRIZ tools may be extended to overcome the problems such shortcomings can and often do cause. The analysis described within the paper is built around the Substance-Field Analysis method and its extension to handle non-linearities using techniques introduced from Taguchi methods. The paper goes on to demonstrate how the non-linear methods have then also been useful in arriving at innovative solutions using pointers to other TRIZ solution concepts like 'use of resources', 'trimming', 'ideal final result (IFR)', and 'knowledge/effects'. A number of real technical problem situation case studies are presented.

1. INTRODUCTION

Non-linearities exist in abundance. By way of example, we examine some of the non-linearities present in the aerodynamic design of aircraft. Non-linearities here include things like angle of incidence of airflow over a wing – where a increasing incidence offers lift performance benefits which suddenly turn into negative lift if the incidence reaches a level where the airfoil stalls; Cross-wind is similarly non-linear beyond a certain extent – again potentially leading to a sudden stall of aerodynamic surfaces; Flow over the surface of a wing undergoes non-linear effects as transition from laminar to turbulent flow takes place during acceleration; similarly drag coefficient versus Reynolds Number correlations also exhibit highly non-linear behaviour; Wake turbulence is a non-linear effect in which one aircraft flies into the wake caused by an earlier aircraft. This is shown in Fig. 1 below. Aircraft landing in very heavy rain have been known to suffer from the highly non-linear effect of engine flame-out if the level of water entering the combustion chamber of an engine exceeds a certain level. This is shown in Fig. 2 below.

Fig 1 : Nonlinear characteristics of Wake Turbulence

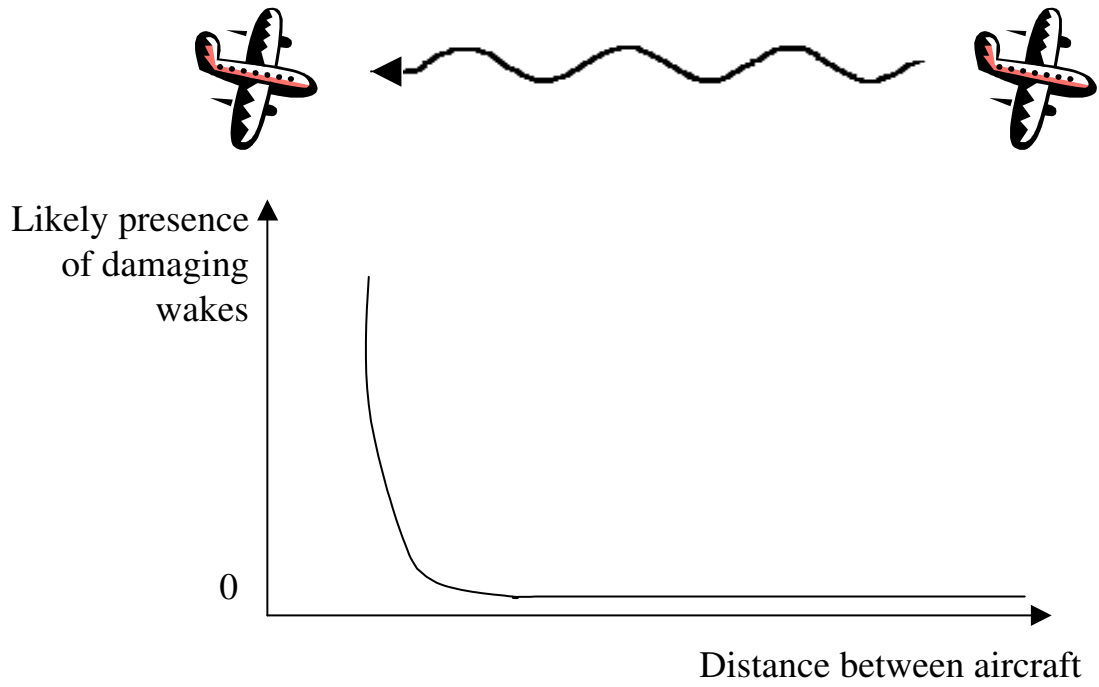
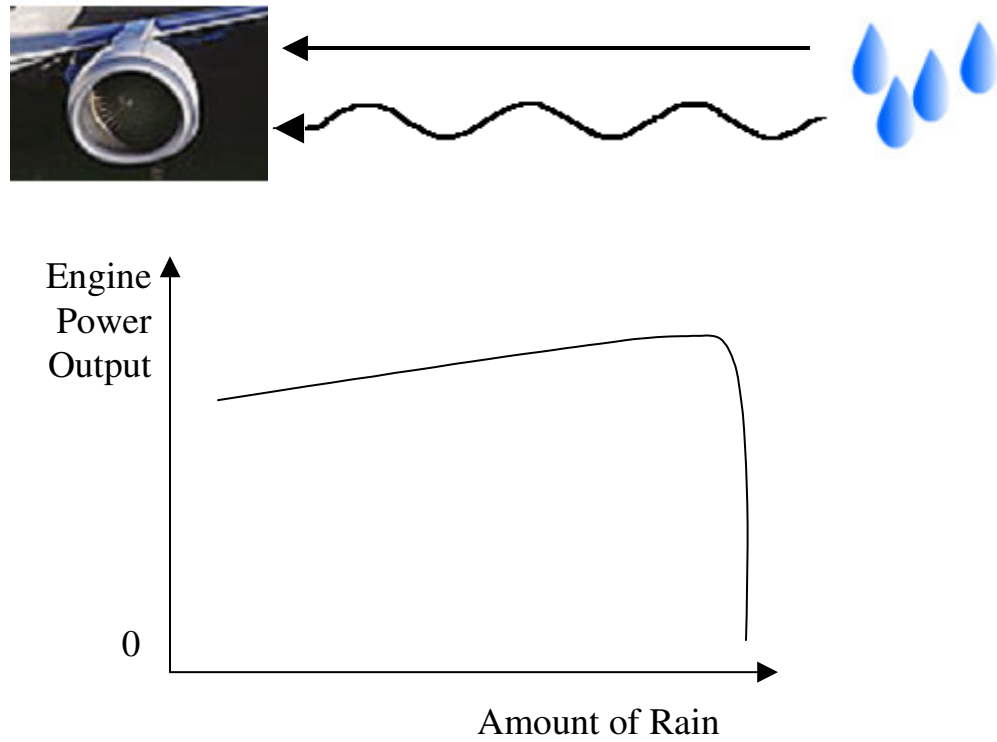


Fig 2 : Nonlinear characteristics of Tropical Rainstorm Idle-Descent Flame-Out



A large part of the job of engineering may be seen to be developing ways and means of handling such non-linearities. The usual means of achieving this process is either to find a way of approximating or averaging the non-linearity into the design (as is the case with the above laminar-turbulent and drag-Reynolds Number instances) or to attempt to restrict operation of a system within the boundaries of predictable behaviour (as is the case for the other described instances).

Neither of these strategies may be said to be ideal, and both in fact are highly compromise based in that we usually find ourselves severely compromising average performance to compensate for the possible emergence of the negative effects of the non-linearities. One of the main philosophical threads of TRIZ, of course, tells us that compromise is a bad thing. On the other hand, TRIZ is not currently very well equipped to help us in the task of tackling non-linear problems – either in terms of modeling or solving. The closest it currently comes is after we have recognized the existence of a cliff-edge type non-linearity (Reference 1) and use it to formulate a physical contradiction (e.g. ‘I want a large distance between aircraft taking off AND I want a small distance’; ‘I want rain AND I don’t want rain’, etc). While often useful, such a capability is some way short of comprehensive. Our main purpose in conducting the work for this paper is to begin the process of constructing a much more robust and effective series of tools and strategies for handling non-linear problems. We used the Substance-Field model as our start-point.

A Substance-Field model represents the smallest building block of a technical system that performs a specific function. The transformations of the S-Field model are primarily aimed at improving the function by (i) elimination of harmful effects, (ii) enhancement of the useful action and (iii) moving forward along the trends of evolution towards a more ideal system.

A conventional S-Field Model is shown in Fig. 3(a). The Field ‘F’ acts on a substance ‘S2’ (called ‘tool’) which develops a useful action as well as a harmful action on another substance ‘S1’ (called ‘object’). Inventive Standards include suggestions to add substances or fields to absorb/ isolate/ attenuate the harmful action between existing substances or fields. The ‘mediating’ action of an added substance ‘S3’, for example, could be thought of as a 3-terminal device having input, control and output terminals in which the harmful action forms the input, the interposed substance ‘S3’ forms the control and the reduced harmful effect forms the output. This is shown schematically in Fig.3(b). A large (wavy) input is shown to diminish in amplitude in the nonlinear function box to a much-reduced (wavy) output. Some property or feature associated with the substance ‘S3’ acts as the control signal that determines how small the (harmful) output that reaches ‘S1’ will be. The control signal could have a monotonous nonlinear effect or a parabolic (bell shaped maxima or valley shaped minima) function. Either way, we show how one can identify conditions when a harmful effect reaching ‘S1’ is minimum.

Fig 3(a) : Add Substance S3 to Eliminate Harmful Effects

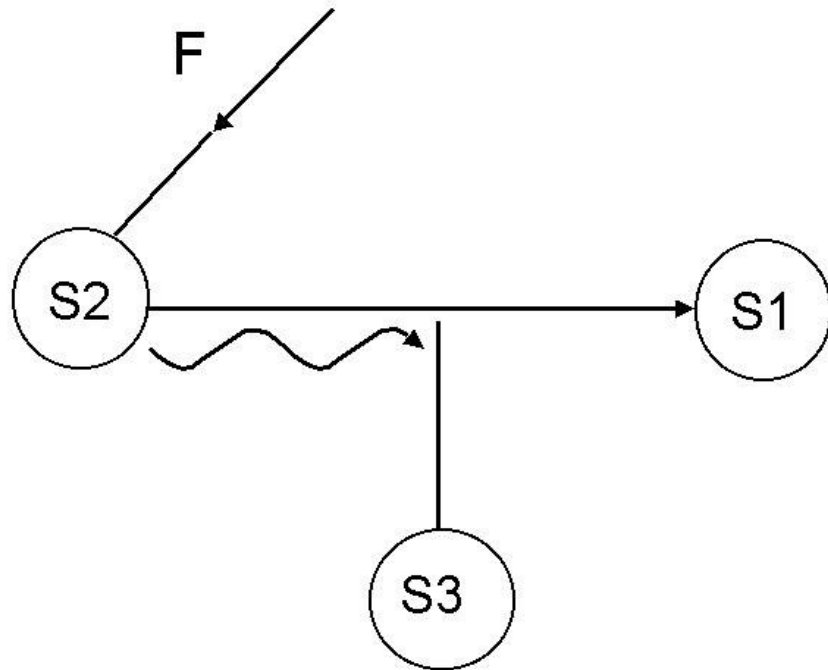
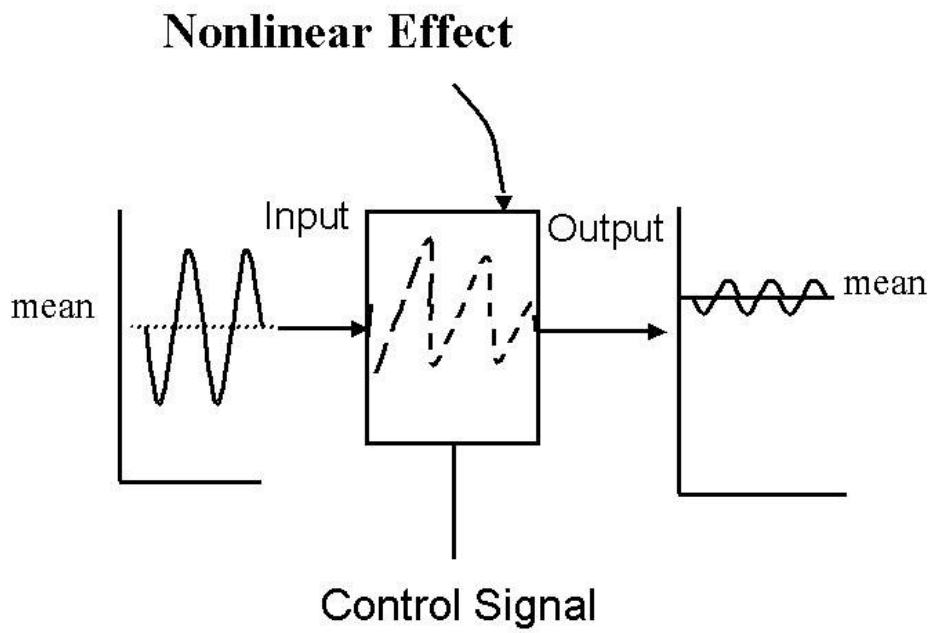


Fig3 (b) A non-linear function to reduce/eliminate Harmful Effects realized by a 3-Terminal control function block



We draw parallels between the “2-step unconstrained optimization” [Reference 2] used by Taguchi method for process improvement to help choose ‘S3’ or any other suggestions recommended by the Inventive Standards in order to handle non-linearities. We further show how substance or field ‘control signals’ can be used to ‘adjust’ desirable output and how this plays an important role in moving along the ‘trend of evolution’ or to the ‘next generation’. Furthermore, we show how when the ‘trimming’ technique [References 3, 4] suggests a drastic action that ‘removes’ ‘S2’ altogether – so there is no ‘harmful action’ to eliminate, but the ‘useful action’ also disappears - the choice of added substances or fields to act as the ‘adjustment factor’ or the ‘control signal’ in the ‘nonlinear SF model’ allows one to realize the useful action without adding harm.

This paper attempts to describe first the nature of the nonlinear S-Field model and the parallels from Taguchi methods that are very useful in arriving at innovative solutions using pointers to TRIZ solution concepts like ‘use of resources’, ‘trimming’, ‘ideal final result (IFR)’, ‘Effects’ and last but not the least “Standard Solutions” [Reference 5].

2. NON-LINEAR S-FIELD MODELLING

A conventional S-Field Model is depicted in Fig. 4(a). The Field ‘F’ acts on a substance ‘S2’ (called ‘tool’) which develops the desired useful function by acting on another substance ‘S1’ (called ‘object’). However, a harmful action/effect may also result due to this action by S2 on S1.

A substance ‘S3’ is interposed to absorb/isolate/attenuate the harmful action between S2 and S1 such that the substance ‘S1’ feels a much-reduced ‘harmful effect’ (see Fig. 4(b) below).

The ‘mediating’ action of the substance ‘S3’ could be schematically depicted by a 3-terminal device having input, control and output terminals as shown in Fig. 4(c) below. The nonlinear function is shown by a large (wavy) input being diminished in amplitude in the function box to a much-reduced (wavy) output. Some property or feature associated with the substance ‘S3’ acts as the control signal that determines how small the (harmful) output that reaches ‘S1’ will be.

Fig. 4(a) A Conventional S-Field Diagram

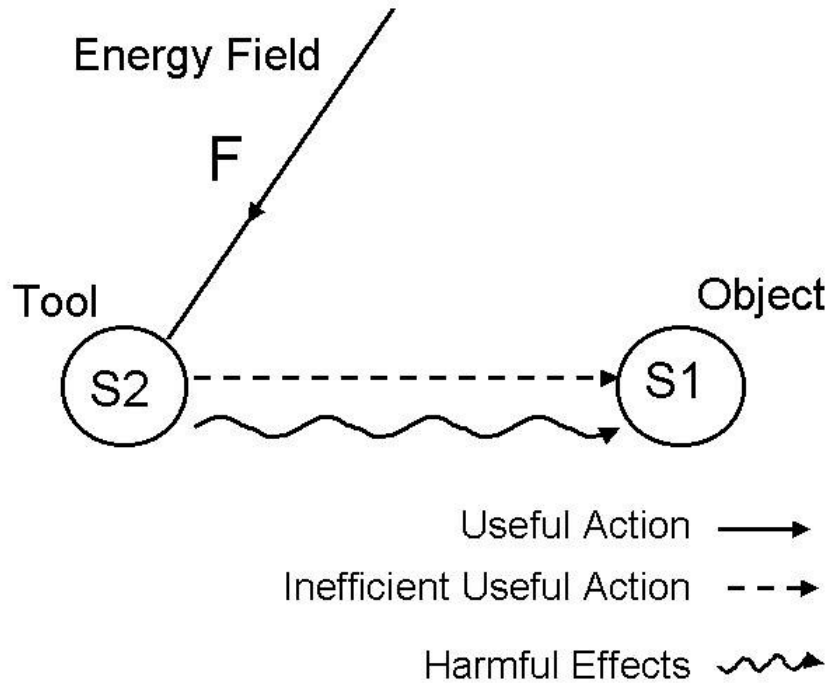


Fig. 4(b) Add a Substance S3 to Eliminate Harmful Effects

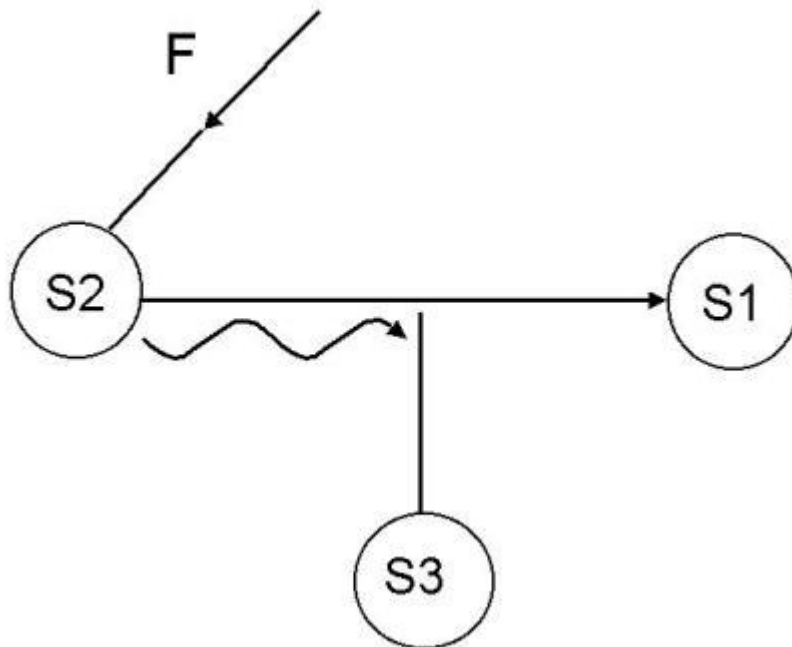
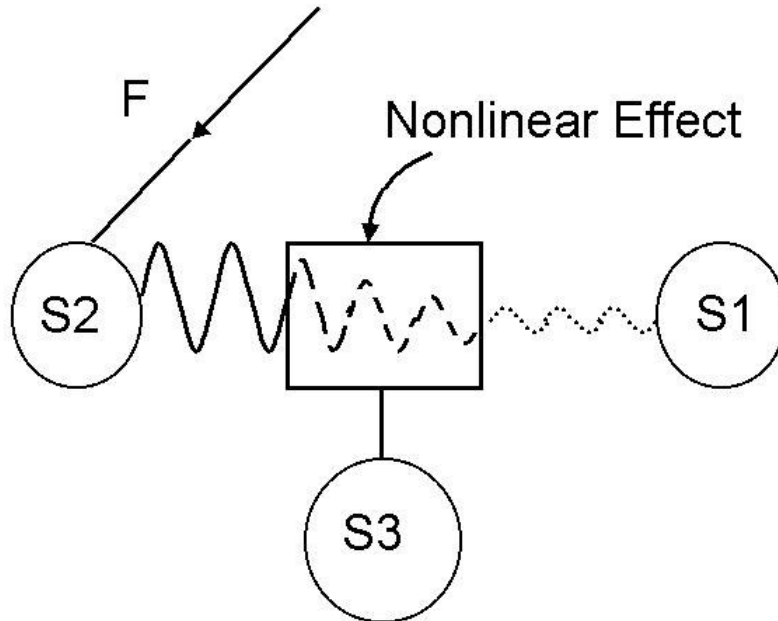


Fig. 4(c) A schematic representation of a non-linear function to Reduce/Eliminate Harmful Effects



A substance 'S4' can be interposed to improve/enhance the Useful Action between S2 and S1 such that the substance 'S1' receives a 'desired' level of Useful Action. (see Fig. 5(a) below). The 'mediating' action of the substance 'S4' could be depicted by a 3-terminal device having input, control and output terminals as shown in Fig. 5(b) below.

Schematically, the nonlinear function is shown by a small input being enhanced in amplitude in the function box to the desired level at the output. Some property or feature associated with the substance 'S4' acts as the control signal that determines how large will be the output level that reaches 'S1'.

Fig. 5(a) Add Substance S4 to Improve/Enhance the Useful Action

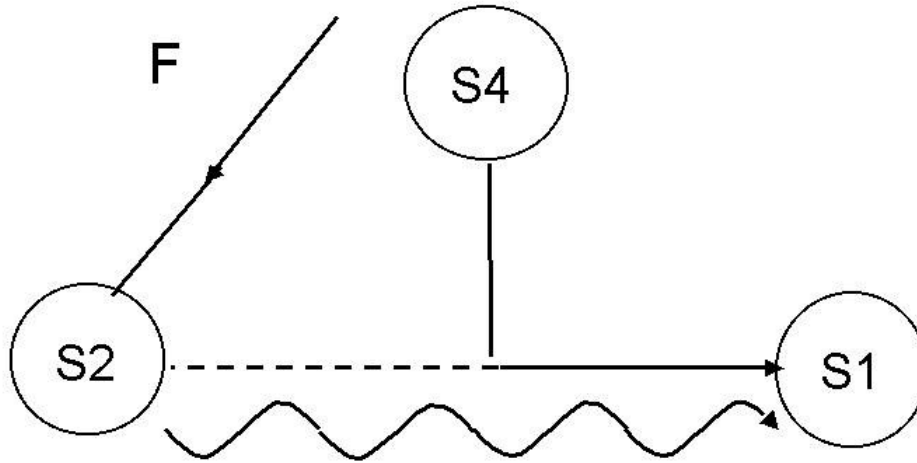
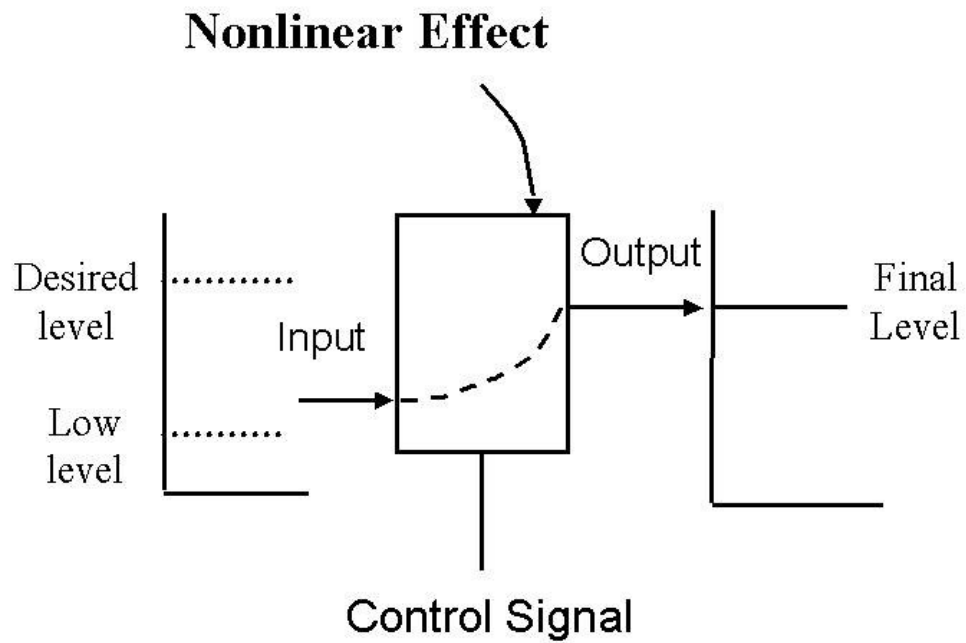


Fig. 5(b) A non-linear function to Enhance Useful Action



A Field 'F1' can be used (instead of a substance 'S3') as the control signal on the nonlinear function box between 'S2' and 'S1' to obtain much reduced (wavy) output. Similarly, a Field 'F2' can be used (instead of a substance 'S4') as the control signal on the nonlinear function box between 'S2' and 'S1' to obtain enhanced useful action at the output. Incorporating the Field 'F1' or Field 'F2' as control in the nonlinear function box is shown in Fig. 6 below.

Fig. 6(a) Add a Field F1 to Eliminate Harmful Effects and/or Add a Field F2 to Enhance Useful Action

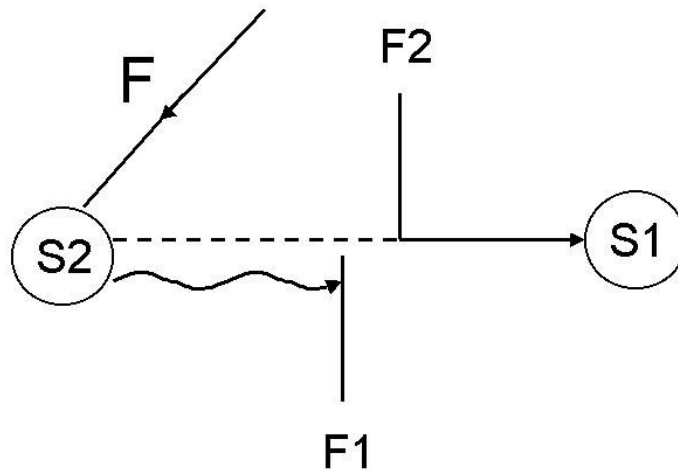
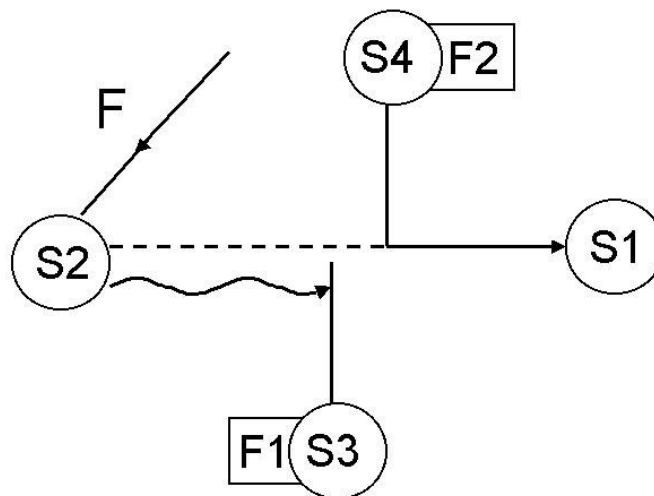


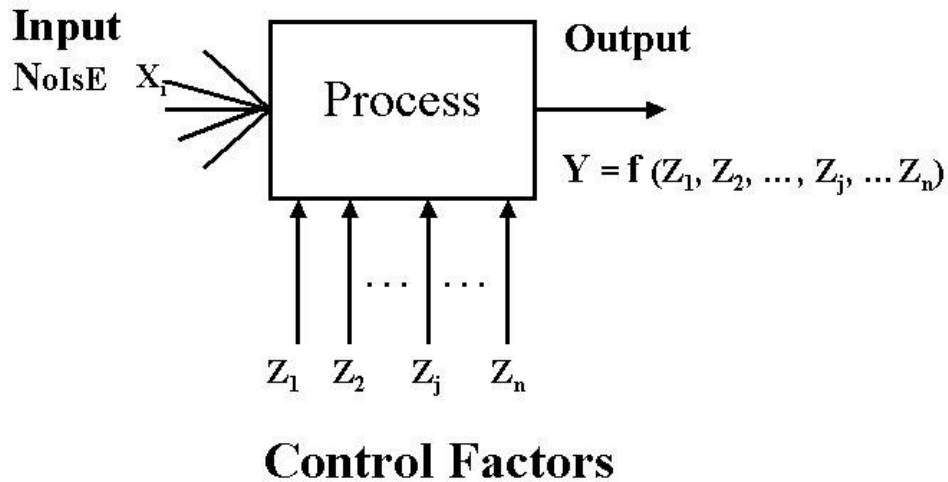
Fig. 6(b) A generic depiction showing "Substance S3 or Field F1" to Eliminate Harmful Effects and/or "Substance S4 or Field F2" to Enhance Useful Action



The control signal, whether coming from SubstanceField 'S3' 'F1' or 'S4' 'F2', could result in the input-output having a monotonous function (slowly increasing, hyperbolically reducing) or a parabolic function (bell shaped maxima or valley shaped minima). Either way, one can identify conditions when harmful effect reaching 'S1' is minimum as well as conditions for obtaining desired level of useful action at 'S1'.

In Taguchi Method, the P-diagram (P stands for Process or Product) shows this simply as a multi-input, single output function box (see Fig. 7)

Fig. 7 Taguchi's P-Diagram shows a process being controlled by control factors and being affected by NoIsE. Minimum noise in the output is obtained at 'optimum' levels of control factors



Referring to Fig. 7, the output Y is a function of control factors and NoIsE factors and is given by,

$$Y = f(X, Z)$$

Where,

$X = (x_1 , x_2 , \dots , x_n)$ noise factors

$Z = (z_1 , z_2 , \dots , z_m)$ control factors

‘variance’ in the output is given by,

$$\sigma_y^2 = \left[\frac{\partial f}{\partial x_1} \right]^2 \sigma_{x_1}^2 + \left[\frac{\partial f}{\partial x_2} \right]^2 \sigma_{x_2}^2 + \dots + \left[\frac{\partial f}{\partial x_n} \right]^2 \sigma_{x_n}^2$$

$$\sigma_y^2 = S_1 \sigma_{x_1}^2 + S_2 \sigma_{x_2}^2 + \dots + S_n \sigma_{x_n}^2$$

The coefficients S_1, S_2, \dots, S_n are called the sensitivity coefficients. These are functions of control Factors Z .

Without loss of generality, we assume that ‘ X_i ’ is the only noise factor, then we would get,

$$\sigma_y^2 = S_i \sigma_{x_i}^2$$

If ‘ Z_j ’ was the only control factor (or it could be a sub-set of $\{Z\}$) that has a strong (nonlinear) correlation with ‘ X_i ’ then ‘ S_i ’ will be a function of ‘ Z_j ’,

$$S_i = \xi (z_j)$$

The optimum value of ‘ Z_j ’ will give lowest ‘ S_i ’ and thus the variance σ^2 will be minimized even in presence of noise variance $\sigma_{x_i}^2$.

Of course, the mean value, Y_{bar} , will be a function of ALL control factor levels,

$$Y_{\text{bar}} = \Psi(Z)$$

Thus, while 'Zj' can be adjusted to get minimum output variation, it will also affect the 'mean' output – it could either 'degrade or improve' the mean!! The mean output is usually defined as the 'useful action' (or as the 'desirable action') and hence the substance 'S3' or field 'F1' (that is interposed between 'S2' and 'S1', to reduce the harmful effect at 'S1') will also affect the 'useful action' – either degrade or improve it.

Some features of the substances 'S3', 'S4' etc and fields 'F1', 'F2' etc essentially constitute the control factors, of which one is effective in 'eliminating harm' and another could be effective in 'adjusting' the useful action levels reaching the substance 'S1'.

The nonlinear S-F model can now be constructed such that a substance 'S3' or a Field 'F1' is primarily introduced to eliminate or reduce the 'harmful effect'. Fig. 8 shows 'S3' or 'F1' giving the IDEAL result, (i) eliminate/reduce the harmful effect', and (ii) improve/enhance the useful action.

Fig. 8 shows 'S3' or 'F1' giving the **IDEAL** result,
 (i) eliminate/reduce the harmful effect',
 and
 (ii) improve/enhance the useful action

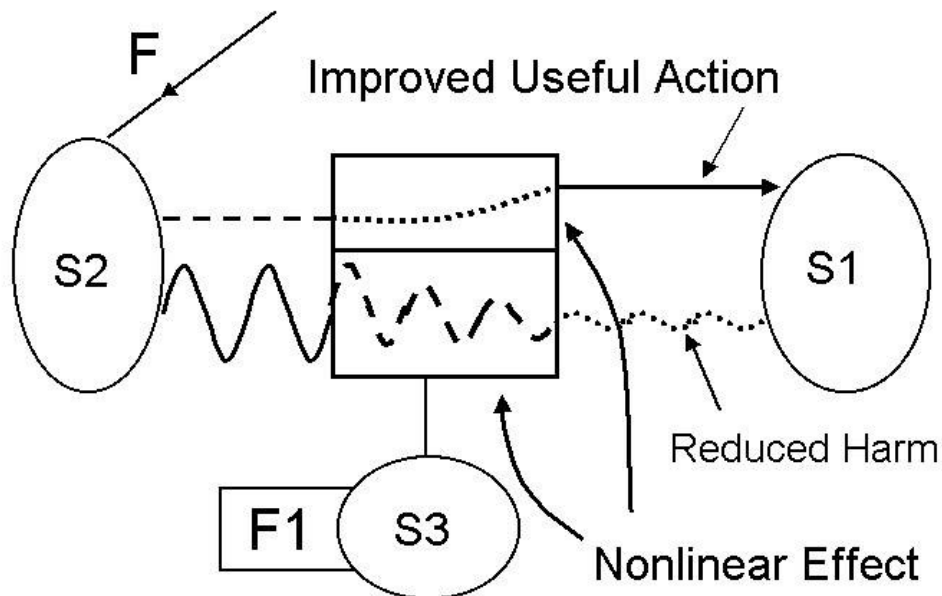
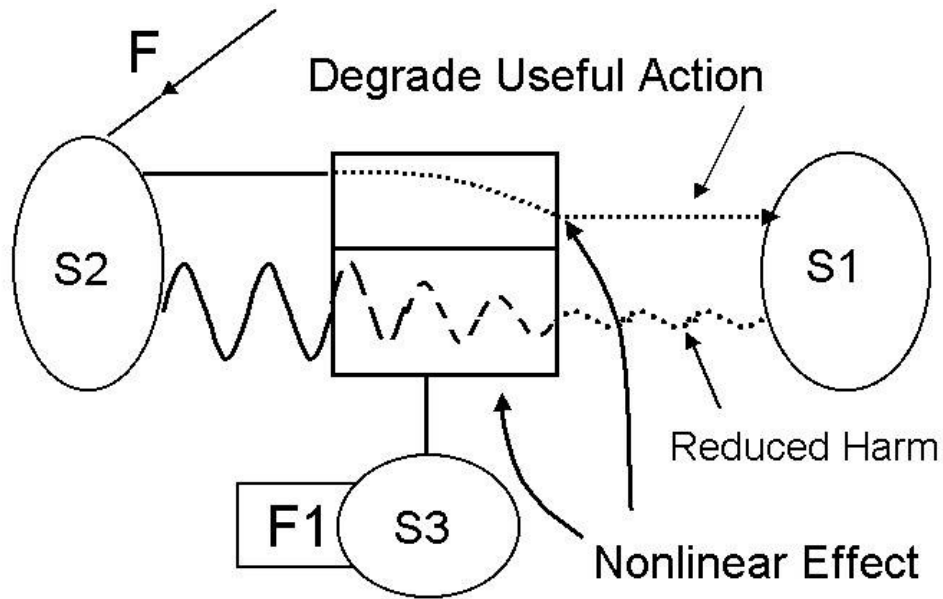


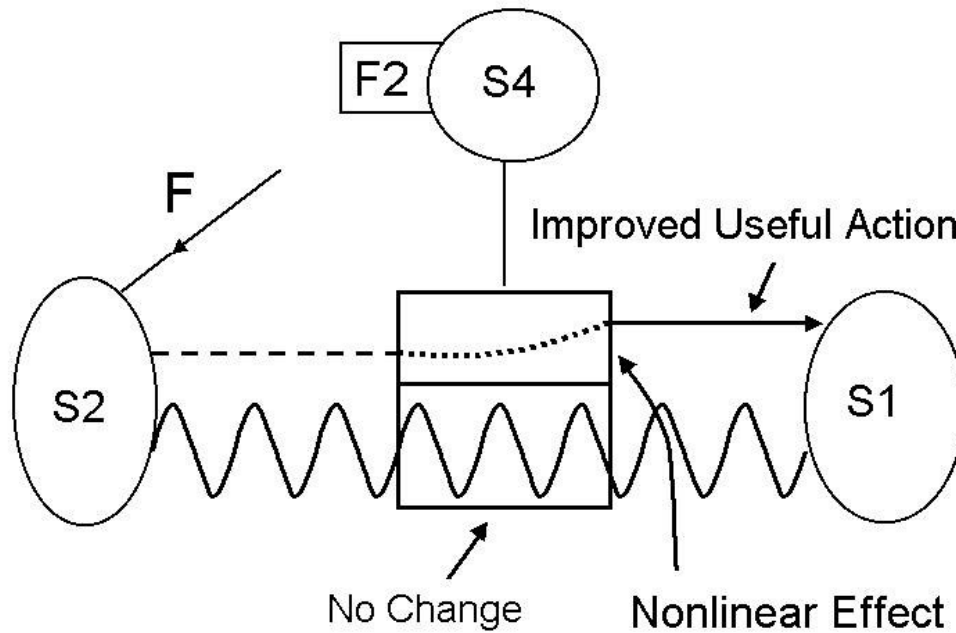
Fig. 9 shows 'S3' or 'F1' giving the 'good' result by (i) eliminating/reducing the harmful effect', but also a 'poor' result by (ii) degrading the useful action.

Fig. 9 shows 'S3' or 'F1' giving the 'good' result by
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 but also a 'poor' result by
 (ii) degrading the useful action



There is another nonlinear S-F model that can be constructed such that a substance 'S4' or a Field 'F2' is primarily introduced to 'improve' useful action. (so far we had only considered introducing substance 'S3' or field 'F1' to eliminate 'harmful effect'). This is shown in Fig. 10 below,

Fig 10 Substance 'S4' or a Field 'F2' primarily introduced to 'improve' useful action (and may have no effect on harmful action)



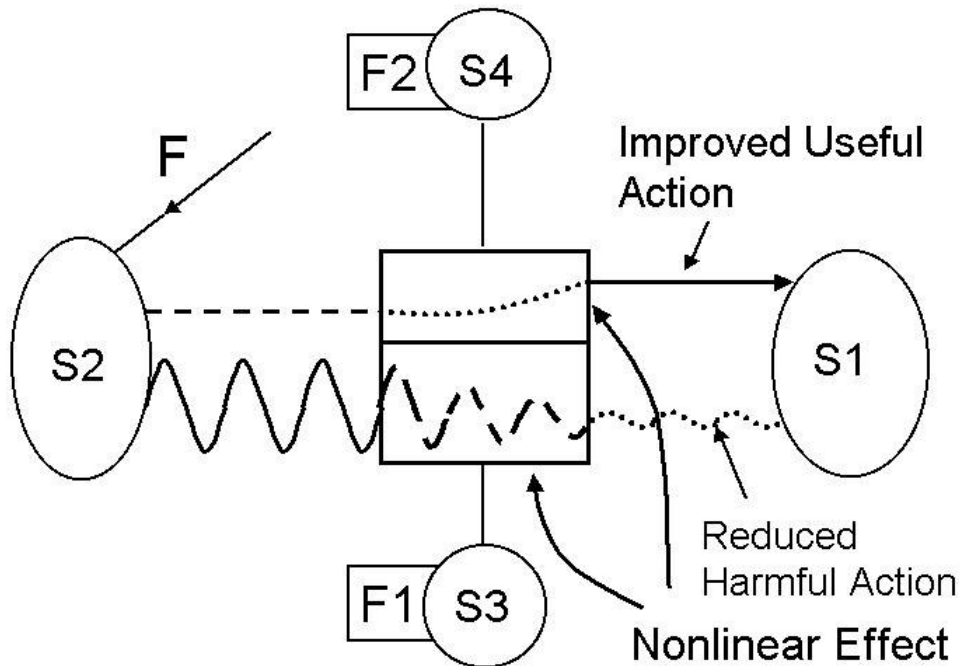
Ideally, a substance 'S3' or field 'F1' should simultaneously 'reduce harmful effect' at 'S1' and 'improve useful action' between 'S2' and 'S1'. Such an ideal solution has already been depicted in Fig. 8 earlier.

However, a substance 'S3' or field 'F1' might 'reduce harmful effect' at 'S1' but also cause 'degradation of useful action' between 'S2' and 'S1'. Such an 'partially good' solution has also been depicted in Fig. 9 earlier.

A substance 'S4' or field 'F2' could be so chosen that it will 'enhance Useful Action' at 'S1' but will have no effect on the harmful effect originating at 'S2' i.e. it will reach 'S1' without any change. Such an 'improvement of useful action' solution has also been depicted in Fig.10 above.

We need to use a substance 'S4' or Field 'F2' to 'overcompensate / correct' the degradation in useful action caused by 'S3' | 'F1' (as was shown in Fig. 9). Thus one controls the harmful effects and the other controls the useful action (as shown in Fig. 11 below),

Fig. 11 Nonlinear SF model showing **IDEAL** transformation to result in
 (i) Reduction in Harmful effect due to 'S3'/'F1'
 (ii) Improved Useful Action due to 'S4'/'F2'

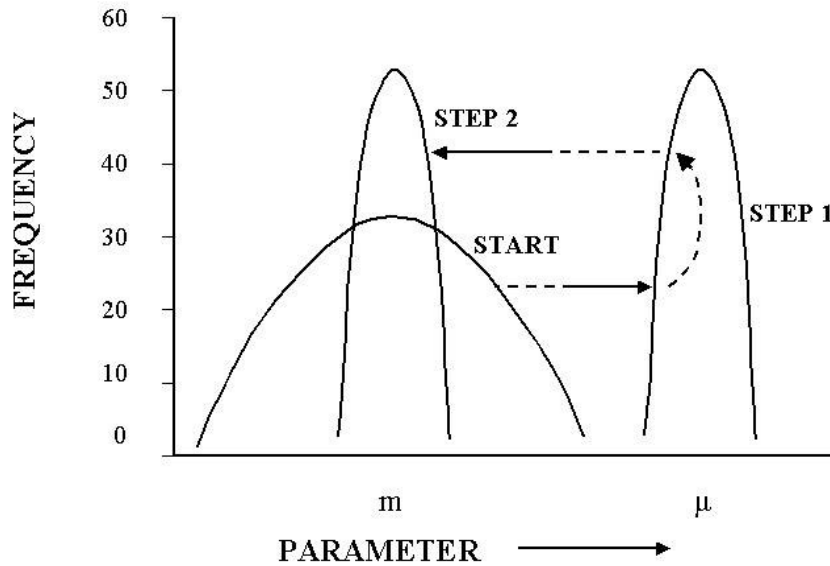


In practice, substance 'S3' or 'S4' and/or field 'F1' or 'F2', may **NOT** be an 'available resource' or may not be easily recognized or identified or known to give ideal results – reduce harmful effects and improve useful action. The correct order for selecting 'S3'/'F1' or 'S4'/'F2' is pointed out in Taguchi's "2-step unconstrained optimization procedure" (Reference 2). The Fig. 12 shows the two steps for reducing 'variance' and 'putting mean on target,

- STEP #1 : Obtain reduced 'variance' (irrespective of mean)
- STEP #2 : Put the mean-on-target (while keeping reduced 'variance')

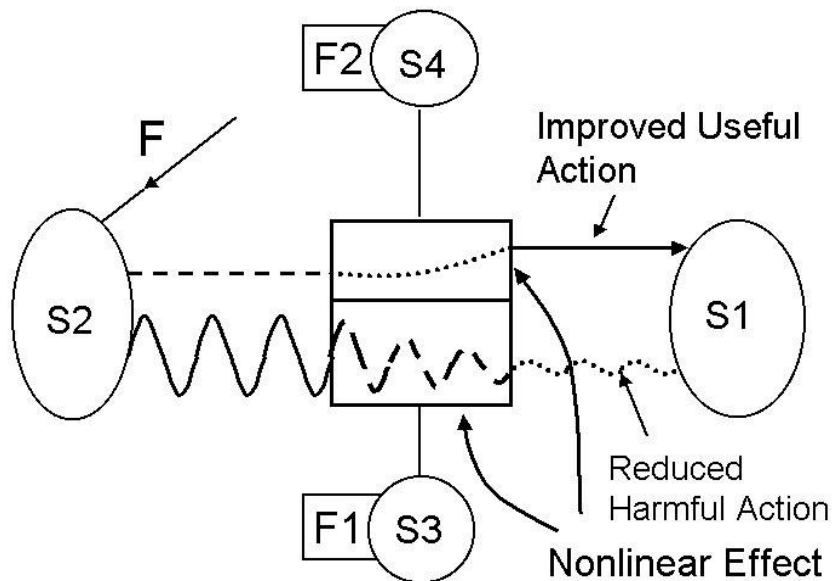
Fig. 12 Taguchi's 2-Step Optimization

2-STEP OPTIMIZATION



Thus, identify substance 'S3' or field 'F1', that will reduce 'variance' (read – harm), also identify substance 'S4' or field 'F2', that has no effect on harmful action, but has (-hyperbolic) effect on 'useful action'. This is shown in Fig. 13 below.

Fig. 13 Use substance 'S3' or field 'F1' to reduce 'variance' (read – harm), and use substance 'S4' or field 'F2' that has no effect on harmful action, but improves 'useful action'

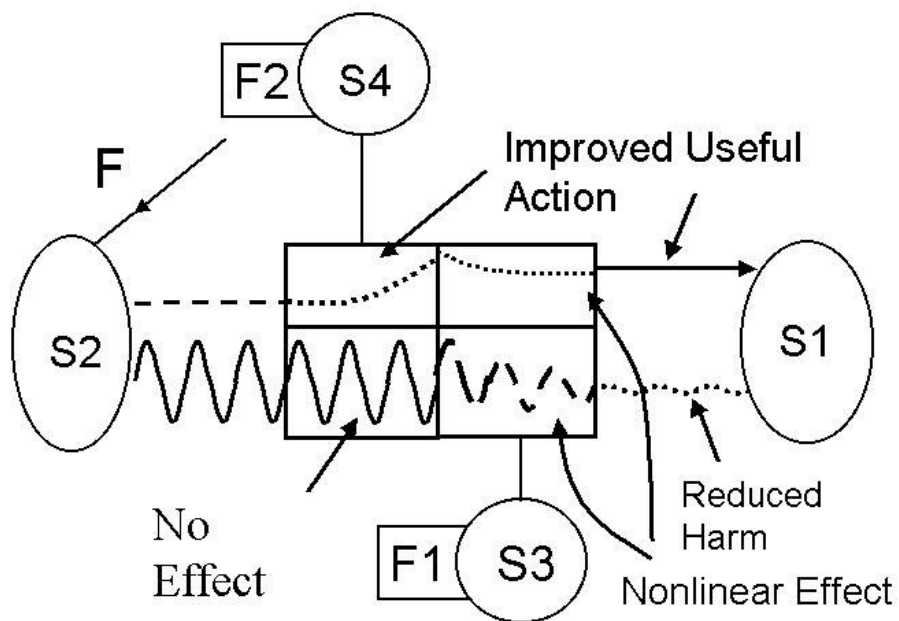


Thus, 'S4' or 'F2' can be used for improving the 'useful action' in a controlled/continuous way, while maintaining the low 'harmful effect' resulting from 'S3' or 'F1'. The substance 'S4' or field 'F2' can act as 'control signals' that can 'adjust' desirable output – this 'adjustment factor' plays an important role in moving along the 'trend of evolution' or to the 'next generation'. [These are in the Class 3 of the Standards].

Substance/Field (S3,F1) and (S4,F2) are acting in tandem or series and their effects get 'multiplied' (rather than in parallel as shown in Fig. 13 as well as all earlier figures – the parallel signifies 'addition' of effects). Taguchi's S/N ratios, which are log forms of objective function, and the additivity model, help us to rationalize this aspect – the 'additions of log terms' imply 'multiplication' in real life.

Fig. 14 shows the 'S3,F1' controlled function and (S4,F2) controlled function in series or tandem. The (S4,F2) control has no effect on harmful effects i.e. transfer function is 'unity'. But the effect of (S4,F2) on 'useful action' must be sufficiently LARGE to 'overtake' the 'degradation' caused by (S3,F1) in the 'useful action'!! This is depicted in Fig. 14, the net 'improvement' in 'useful action' is the product of effects of (S4,F2) and (S3,F1). The 'reduction in harmful effect' is primarily achieved by (S3,F1). The same 'net' result appeared in the Fig. 13, which depicts the effects of (S3,F1) and (S4,F2) in parallel.

Fig. 14 : 'S3,F1' controlled function and (S4,F2) controlled function act in tandem. Net 'improvement' in 'useful action' is the product of effects of (S4,F2) and (S3,F1)



3. NONLINEAR S-F MODEL and TRIMMING

We are now in a position to analyze the process normally adopted for ‘trimming’ (References 3, 4)

The Fig. 14, showing (S3,F1) and (S4,F2) in tandem, brings out following important points,

Point #1: First, find (S3,F1) that will substantially ‘reduce’ (or even eliminate) the ‘harmful effects’

Point #2: Once (S3,F1) is determined to ‘reduce harmful effects’, observe what it does to the ‘useful action’ –

- (i) it is ‘improved’ → very good !!! No need to find (S4,F2) !!
- (ii) it is ‘degraded’ → the go ahead and identify (S4,F2) as in next step

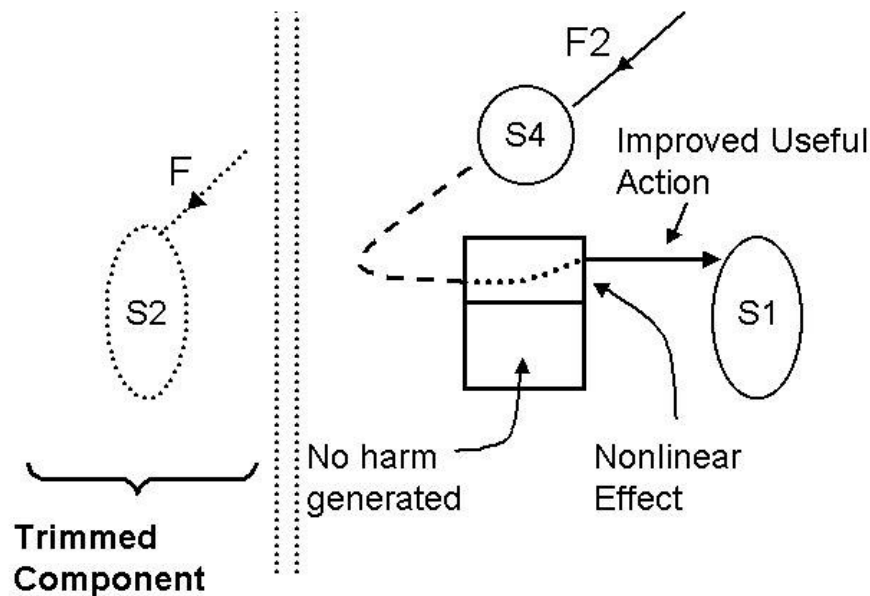
Point #3: Identify (S4,F2) that has a LARGE influence on the ‘useful action’ (increasing, hyperbolic or bell shaped), **but** no influence on ‘harmful effect’ on ‘S1’

(This is the ‘adjustment factor’).

Adjust the ‘strength’ of (S4, F2) such that it ‘overcompensates’ the ‘degradation’ caused to ‘useful action’ by (S3,F1).

“Trimming” suggests drastic action (unlike point #1 and #2) that ‘removes’ ‘S2’ altogether – so no ‘harmful action’ to care of !!! However, the ‘useful action’ also disappears!! We have to look for (S4,F2) from the ‘available resources’ that will perform the ‘useful action’, without ‘creating’ any ‘harmful effect’ (like the one we eliminated by trimming ‘S2’ or any other ‘new’ harm). The ‘trimming’ principles are easily depicted using the nonlinear S-F model as shown in Fig. 15.

Fig 15: Look for (S4,F2) from the 'available resources' that will perform the 'useful action' directly on S1 without 'creating' any 'harmful effect'.
(The substance S2 is thus 'trimmed')



4. CONCLUSIONS

In the S-Field transformations used in TRIZ, substances are added to reduce or eliminate harm. We have suggested that these are strong nonlinear functions and can be depicted as 3-terminal boxes in the S-Field model. We have used 2 directions from Taguchi method : The first direction is from the 2-step optimization strategy that recommends **first** adding substance to reduce harm and **then** adding another substance to realize improvement in useful action. The second directions is derived from the P-diagram of Taguchi method that helps identifying the properties associated with the added substances that have a no or little correlation with the causes of harm. Once the property is identified, it can be used as the control terminal of the nonlinear function and thus **'adjust'** the level of useful action. We have demonstrated that the search for a substance that can 'adjust' the level of useful action without affecting/creating harm can lead to trimming of the 'tool'.

The nonlinear S-F model enables TRIZ practitioners not only to look for the nonlinearities but also to exploit them. The authors feel strongly that innovation really lies in exploiting these nonlinearities.

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