Anticipating Failures with Substance-Field Inversion

A TRIZ Methods Case Study

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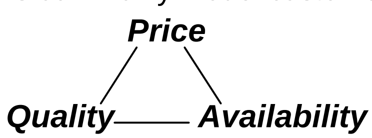
Anticipating failures is a powerful tool for shortening the time required to develop robust products. Inverting Standard Techniques of Substance-Field analysis allows anticipation of failures caused by a useful function not being performed.

Value Definition and Product Trade-offs

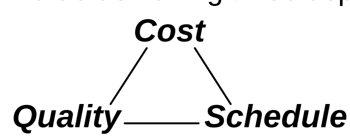
> *"Value can only be defined by the ultimate customer. And it's only meaningful when expressed in terms of a specific product . . . which meets the customer's needs at the right time at the right price. Value is created by producers – from the customer standpoint, this is why producers exist."*[1]

In this age of global competition and Internet marketplaces, the only certainty for producers is that customers define – and rapidly redefine – value. The producer with the product that best meets the customer needs *first* has market advantage.

Producers commonly model customer and producer value as having three aspects:



Customer Value Model



Producer Value Model

It is common to treat the producer model as having three conflicting goals, producing a trio of "Tyranny of the OR" problems:[2]

"You can have lower cost *or* shorter schedules."
"You can have shorter schedules *or* higher quality."
"You can have higher quality *or* lower cost."

Using this model, producers work to drive product costs down while, at the same time, they shorten schedules to reduce development costs. The result is often unsatisfactory because of uncertainty how trade-offs of goals affect customer perception of value.

This uncertainty isn't necessary. In the 1950's, Lawrence Miles laid the groundwork for customer perception of value as the relationship of benefits to costs.[3]

$$Value \equiv \frac{\sum UtilityFunctions + EsteemFunctions}{\sum \Pr ice + Harms}$$

Applying this view to the Cost-Quality-Schedule triangle would define producer value in a way that clarifies the relationships, offering options beyond "Tyranny of the OR":

$$Value \equiv \frac{\sum Quality}{\sum Cost + Schedule} \equiv \frac{\sum Functions}{\sum DevlopmentCosts + TimetoMarket}$$

This model supports the producer habit of reducing costs and shortening schedules. Further, it clarifies that increasing function improves producer – and customer – value.

Defect Discovery and Time to Market

Producers increase function, either by new or revised design, through a product development process. A critical part of the product development process is proving the reliability of the design.

Traditional development processes rely on completing passes through Design-Prototype-Test-Analyze (DPTA) process cycles to discover and correct defects (Figure 1). The effectiveness of this empirical method is in direct proportion to how many times the cycle is completed. However, the time available to complete trips through the cycle is limited by ordinary delays and pressure to shorten the schedule. The limitation is worse if the process cycle relies on testing of the complete system. Because the time for each subsystem to reach stability depends on its complexity, the first few turns around the test cycle at the system level are often disabled by failures in just one subsystem. This inherently random defect discovery process makes time-to-market unpredictable.

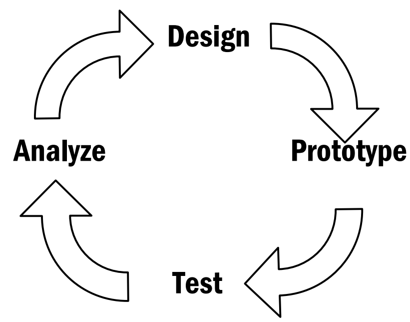


Figure 1. Defect Discovery Cycle

Reducing Time to Market by Anticipating Defects

An effective way to improve functional quality *and* shorten schedules is to anticipate failures during the design process (Figure 2). By inserting failure anticipation cycles, the number of full DPTA process cycles required to achieve functional goals is reduced.

Many Risk Analysis tools exist, for example Failure Modes and Effects (FMEA), Fault Tree (FT) and Event Tree (ET) and Hazard and Operations (HAZOP) Analyses. Each of these, by predicting and relating initiating events, mid-states and end states, attempts to produce a severity-ranked listing of all the undesirable phenomena possible for a system. For example, FMEA assumes failure modes of the individual system components as initiating events, and then attempts to create the mid- and end-state consequences. It is, like most Risk Analysis tools, answering the question "Given a known state or event, what can go wrong?"

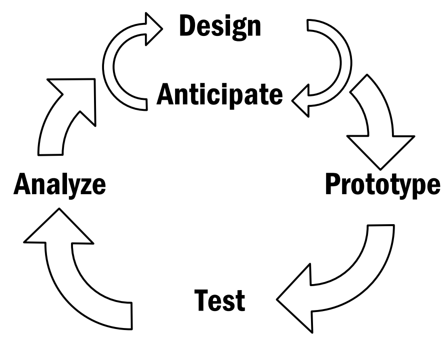


Figure 2. Defect Anticipation Cycle

Failure anticipation based on the Theory of Inventive Problem Solving (TRIZ) takes a fundamentally different approach. TRIZ failure anticipation seeks to answer the question, "Given the system, how can I most effectively *invent* failures?" From the original application for failure determination by V.V. Mitrofanov, it has been extended to Subversion Analysis by Boris Zlotin, and to Anticipatory Failure Determination by Zlotin, et. al.[4]

Basic Function, Substance-Field Analysis and Failures

Dr. Taguchi elegantly illustrates that the basic function of an engineered system is to transform input energy to an output function in the “P-model” diagram (Figure 3).

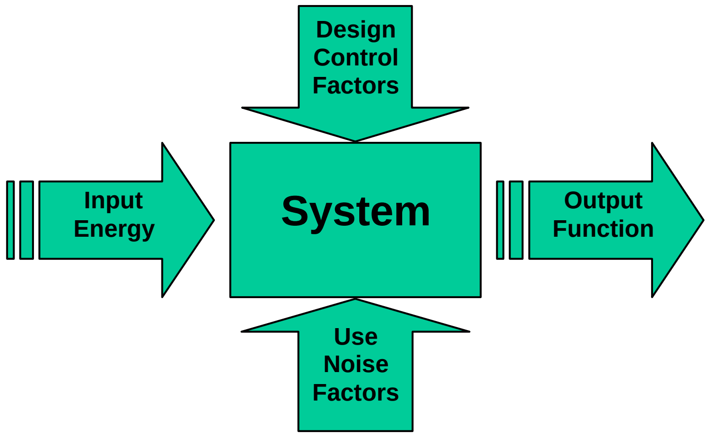


Figure 3. Robust Design System Model

For a system to perform its basic function, the transfer of input energy to output function must be completed within useful limits of magnitude and duration. Conversely, if a useful function is not completed, then a failure may occur.

G.S. Altshuller originated the concept of Substance-Field Analysis for systems.[5]   The basic Substance-Field model is a function pair (Figure 4).

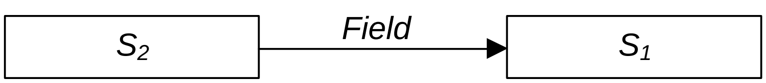


Figure 4. Substance-Field Model

In this model, S_2 is the tool, component or substance transferring an action to an object S_1.   The field represents the energy transfer between the substances, components or systems. Example field types are mechanical, electromagnetic, gravitational, thermal and strong nuclear.   Again, if the energy transfer is completed within useful limits of magnitude and duration, the useful function is performed.

By creating situations in which the useful function is *not* performed, Substance-Field Analysis may be used as a failure prediction tool.

TRIZ Tools – Standard Solutions and Standard Techniques

The TRIZ toolkit for problem solution includes Altshuller's 76 Standard Solutions for Inventive Problems.[6] The Standard Techniques are a further development of the Standard Solutions.[7] One group of these contains six techniques for directly eliminating the effect of a harmful action (Table 1) [8].

Eliminate a Harmful Action – Direct Ways		
Problem There is a harmful action on object S_1	*Solution* Eliminate the harmful action	*Description*
$S_2 \xrightarrow{F} S_1 \Rightarrow$	$S_2 \xrightarrow{F} \vert_{S_x} \quad S_1 \quad S_x=?$	Insulate S_1 from the harmful action by substance-insulator S_x
$S_2 \xrightarrow{F} S_1 \Rightarrow$	$S_2 \xrightarrow[F_x]{F} S_1 \quad F_x=?$	Counteract the harmful action with the opposing field F_x
$S_2 \xrightarrow{F} S_1 \Rightarrow$	$S_2 \xrightarrow{F} S_x \quad S_1 \quad S_x=?$	Protect S_1 from the harmful action by a safety substance S_x that attracts the action to itself
$S_2 \xrightarrow{F} S_1 \Rightarrow$	$S`_2 \quad F \quad S_1 \quad S`_2=?$	Modify the source S_2 of the action to turn off the harmful action
$S_2 \xrightarrow{F} S_1 \Rightarrow$	$S_2 \xrightarrow{F} S`_1 \quad S`_1=?$	Modify S_1 to be insensitive to the harmful action
$S_2 \xrightarrow{F} S_1 \Rightarrow$	$S_2 \xrightarrow{\cancel{F}} S`_1$	Alter amount of the zone of action, its duration or both to decrease or completely eliminate the harmful action.

Table 1. Standard Techniques to Eliminate a Harmful Action *

Each of these techniques presents a Substance-Field solution model for one case of harmful energy transfer producing a harmful function. The standard knowledge bases, databases and solution tools of TRIZ may be used to creatively generate solution concepts

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Substance-Field Inverse Analysis

As stated previously, it is common in TRIZ to use the “other way around” principle to invert problem statements and solution techniques for failure anticipation. One way is simply to invert the objective. That is, a harmful function is treated as useful. The objective then is to magnify that harmful function, its effects and to invent new harmful functions.

Another method is to invert one or more of the TRIZ tools. The method used here inverts a set of Standard Techniques by replacing harmful effects with useful effects (Table 2).

	Eliminate a Useful Action – Direct Ways	
	Problem: There is a useful action on object S_1: $S_2 \xrightarrow{F} S_1$	
	Solution	*Meaning*
1	$S_2 \xrightarrow{F} \vert \quad S_1$ S_x	Insulate S_1 from the useful action by substance-insulator S_x
2	$S_2 \xrightarrow{F} S_1$ F_x	Counteract the useful action with the opposing field F_x
3	F $S_2 \searrow S_x \quad S_1$	Protect S_1 from the useful action by a safety substance S_x that attracts the action to itself
4	F $S`_2 \quad S_1$	Modify the source S_2 of the action to turn off the useful action
5	$S_2 \xrightarrow{F} S`_1$	Modify S_1 to be insensitive to the useful action
6	$\cancel{F}$ $S_2 \quad S`_1$	Alter the amount of the zone of the action, its duration or both to decrease or completely eliminate the useful action.

Table 2. Standard Techniques – Inverted to Eliminate a Useful Action[*]

Each of these techniques presents a Substance-Field solution model for a way to impair a useful function. In each, if the function is not completed, then a failure may occur.

Using these inverted models, the problem now is to *create* situations for each case that will impair or eliminate the *useful* action. That is, to *invent* failures, anticipating them so they may be eliminated. Again, the existing knowledge bases, databases and solution tools of TRIZ are all useful, being inherently designed to solve creative problems.

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[*] Based on ***Standard Techniques to Eliminate a Harmful Action,*** Copyright TRIZ Consulting, Inc., used by permission.

An Example of Failure Anticipation by Inverse Analysis

A trial application of this failure anticipation method was conducted on the paper output system of the DeskJet 990C printer (Figure 5).

Figure 5. DeskJet 990C

Customers value real printing speed. The 990C achieved draft black text speed of 17 pages per minute (ppm), a significant jump from the 12ppm of its 970C predecessor. A key enabler of the speed gain was removing the need to perform a full ejection cycle for every page. The required redesign of the media output system could introduce new failure modes. This presented a valuable opportunity to exercise Substance-Field Inverse Analysis.

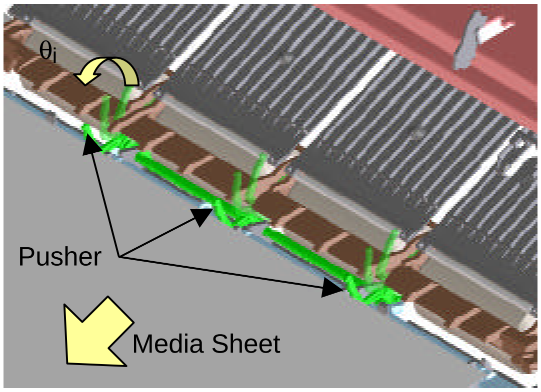

Figure 6. DeskJet 990C Output System

The 990C media output system appears to be quite simple. A trio of fingers on the pusher moves the media into the output tray. So the customer function of the media output system is to move one sheet into position in the output tray for each ejection cycle. This can be represented as changing pusher position θ_i into media position y_o (Figure 6). However, the energy-level engineering definition of the basic function is to convert input drive torque τ_i to output media motion, produced by pusher torque τ_o acting on the media (Figure 7).

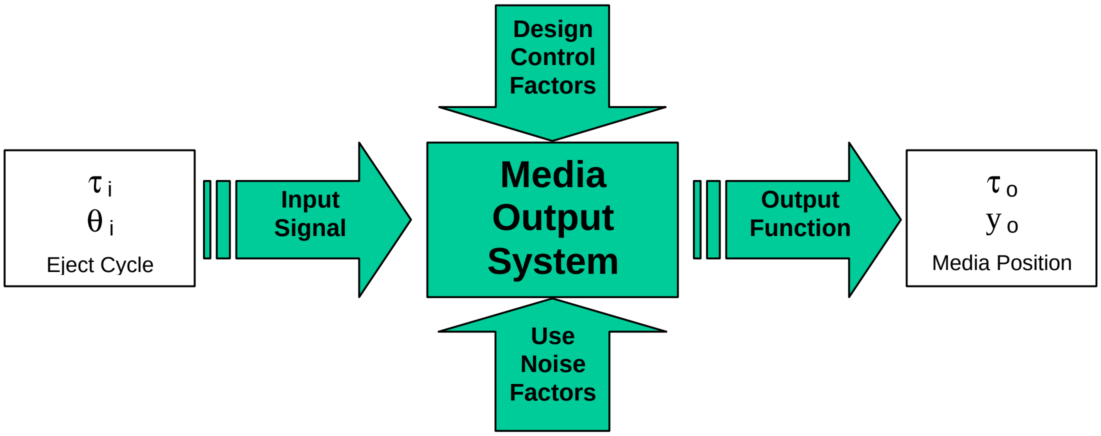

Figure 7. Media Output System Basic Function

Beneath this simple basic function, however, is a complex support and cam drive system to actuate the pushers at only the desired time. To be sure that the failure anticipation would focus on the substance-field pair with the highest likelihood to introduce new failure modes, a functional diagram was constructed (Figure 8), including super-system resources and control system actuation algorithms.[9]

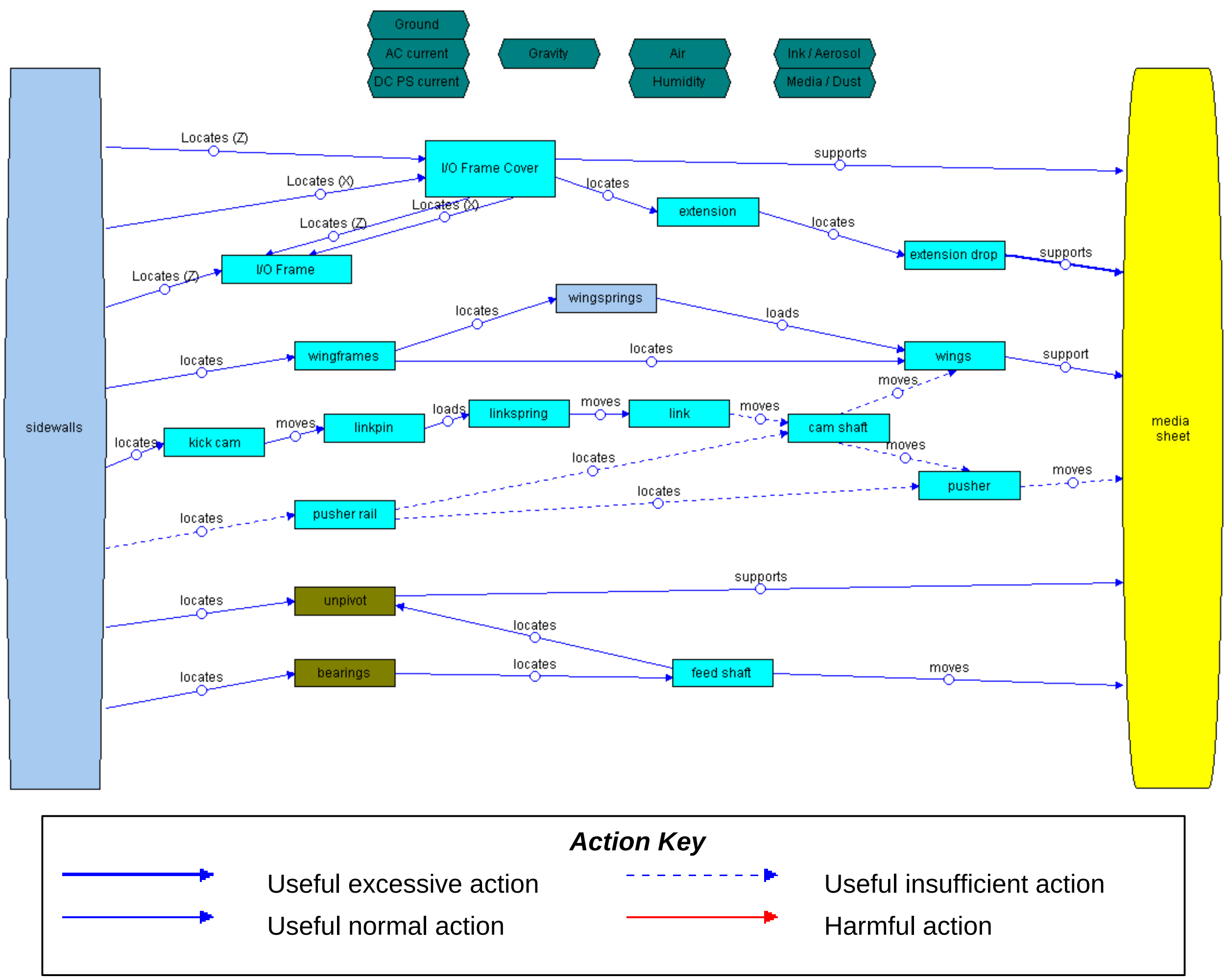

Figure 8. DeskJet 990 Output System Functional Model

The local substance-field action of interest for the 990C media ejection system is "pusher moves media sheet."

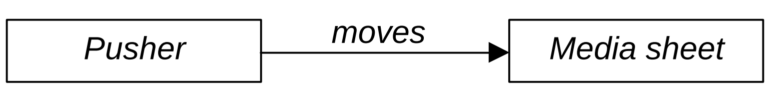

Figure 9. Pusher Substance-Field Pair

With the Substance-Field system of interest selected, the goal is to generate solutions to the inverse model cases. While these may be found by simple system inspection, TRIZ solution resources may identify richer possibilities. Examples of anticipated failure modes for the pusher system are shown in the following tables:[9]

Case 1	F $S_2 \longrightarrow \vert \quad S_1$ S_x	Media is insulated from pusher force
	Concept Source	*Concept Description*
1	System inspection	Pusher hits other components: rail, IO tray parts (photo bin), carriage, inner paper guide, camshaft, UPG, unpivot, etc.
2	System inspection	Pusher hits media output stack in tray
3	System inspection	Pusher hits unexpected media in print zone
…		

Case 2	F $S_2 \longrightarrow S_1$ F_x	Pusher force on media is counteracted
	Concept Source	*Concept Description*
1	Produce force "tribocharging / capacitance"	Media is attracted to (or repelled by) something due to charge: feed rollers, out tray, output media stack, etc.
2	Produce force "Bernoulli effect"	Relative motion of media sheet to out tray or output stack creates low pressure underneath → retarding friction
3	Linked effects to produce force "wedging / deformation"	Pusher drives media into output tray / stack → friction "wedging" media sheet against motion
4	Change force "impact / conservation of momentum"	Ejected media rebounds into print zone
5	Produce force "wedge / inclined plane / friction / gravity"	Pushers trying to move media "uphill" against gravity and friction due to stored output extension
6	Linked effects to change force "adhesion force / lever / deformation"	Changes in adhesion of media to elements in output zone cause resistance. Resources: ink, media coatings, electrostatics, T&H effects, bending stress-induced friction
7	Change force "inertia / impact / conservation of momentum	Pushers bounce off of media
…		

Case 3	F $S_2 \searrow \quad S_1$ S_x	Pusher force is attracted by another object
	Concept Source	*Concept Description*
…	--	No concepts generated

Case 4	F $S^{`}_2$ $\qquad$ S_1	Pushers do not produce force that can act on media
	Concept Source	*Concept Description*
1	Reduce force “friction”	Does pusher cam have friction critical angle problem with camshaft like that seen on the wings?
2	Reduce force “eccentric”	Are we applying forced in a way that could cause eccentric-action binding?
3	Reduce force “elastic deformation”	What’s deforming in current design? Pusher, shaft, link spring, link pin …?
4	Reduce force “reactive force”	Are we moving the pusher rail instead of the linkage?
5	Change force “vibration / resonance”	Will we create vibration or resonance by gear tooth passing frequencies, stick / slip frictions, etc?
6	Change force “thermal expansion”	Do the design clearances allow for this? General cases of expansion and shrinkage (hygroscopic, etc.)?
7	Change force “leverage”	Check leverage increase effects on reaction force and elastic deformations in components
8	Change force “spiral”	Can drafts on components cause twisting / binding / lateral offsets?
9	Change force “eccentric”	Change in effective pusher length through stroke due to media motion results in change in effective pusher force available
…		

Case 5	$S_2 \xrightarrow{F} S^{`}_1$	Media doesn’t respond to pusher force
	Concept Source	*Concept Description*
1	Force change “elastic deformation”	Media deforms instead of moves in response to pusher force.
2	Produce force “tribocharging / capacitance”	Media is attracted to (or repelled by) something due to charge: feed rollers, out tray, output media stack, etc.
…		

Case 6	$\cancel{F}$ S_2 $\qquad$ $S^{`}_1$	Pusher force has incorrect magnitude, duration or zone of action to act on media
	Concept Source	*Concept Description*
1	Change synonym “deflect”	Force is applied in wrong direction
2	Change synonym “reflect” and force change “lever”	Opposing force of media on pushers changes input force by leverage ratios (media higher/lower on pushers at various positions of cycle)
3	Change synonym “scatter”	Twist in pusher shaft or cam shaft makes forces on media asymmetric
4	Force change “elastic deformation”	Components or media “absorb” force in deformation (→ unpredictable energy release)
…		

Table 2. Generated Failure Concepts

Trial Conclusions

The new failure mode predicted by the concepts in Case 5 was demonstrated in testing. The output media encountered resistance from the other media already in the output tray. The pusher force then created a force couple resulting in media buckling, rather than moving forward into the tray. Several solution concepts were generated, with final modifications reducing the occurrence of these failures to a negligible level.

Thus, the case study demonstrates how inverting one group of Standard Techniques allows the use of standard TRIZ creative tools to anticipate failures.

Future Method Extensions

The techniques presented only address those cases where the failure is caused by non-completion of the useful action. Application of inversion to other groups of Standard Techniques would expand the scope of failures anticipated.

Also, no energy transfer is perfectly efficient. Some energy is wasted, perhaps in a harmful form (Figure 10).[10] For example, torque is lost in a bearing interface, dissipated as heat that may damage the bearing or its lubricant. Further, if the noise includes a source of energy, or if a feedback loop is present, the magnitude of the output function can exceed useful levels, itself becoming harmful. The Tacoma Narrows bridge failure is an infamous example of this type of failure.

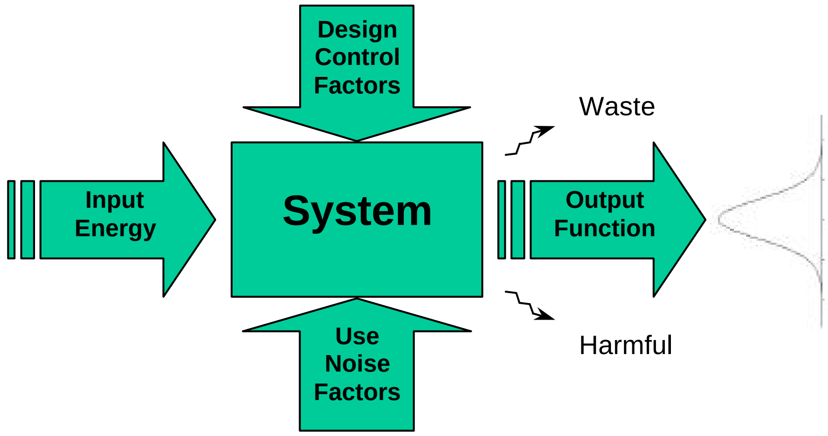

Figure 10. Imperfect System Energy Transfer Model

To mature the capability of Inverse Analysis methods, models that address these energy situations should be developed and tested.

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