The ‘Catastrophe’ of Aerospace Design

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The design of modern aerospace systems is commonly an exercise in creating and working with complex systems. This complexity stems from a combination of the complexity of the system itself, the interaction with environment that it operates in and often the organization which is creating the system. Historically, this complexity has been seen as a source of risk and uncertainty, especially with respect to future the future performance and utility of the system. Consequently actions were taken to minimize the downside risk, and especially eliminate what were considered significant failure modes. This risk minimization encompasses both technical and programmatic aspects. As a response the behavior of the program becomes inherently ‘stiff’ and is less likely to evolve to meet changes in the environment. Consequently it may actually be more likely that the program will fail suddenly and late in its development. One possible theory that helps to describe these behaviors and may unlock some of this information is Catastrophe Theory. When combined with a utility approach, specifically a Value-Driven approach this has the option to help organize the concept exploration and decision making phases of design.

Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tr>
<td>CT</td>
<td>Catastrophe Theory</td>
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<tr>
<td>CV</td>
<td>Control Variable</td>
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<tr>
<td>NPVCF</td>
<td>Net Present Value of Cash Flow</td>
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<tr>
<td>SV</td>
<td>State Variable</td>
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<td>sv</td>
<td>Surplus Value</td>
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I. Introduction

Engineering design in general and aerospace design in particular is a highly complex discipline. People argue over whether design is a problem solving, a creative, or a decision-making undertaking. Even the most stalwart advocates of one approach or the other would not say that it is problem solving only to the exclusion of creativity and decision making, but many people tend to think that it is more one type of undertaking that the others. In reality a good design process is all three of the above. Engineering products must solve some real or perceived problem, e.g. transport me from Manchester to London. Creating a new product, especially one that addresses an unforeseen problem requires significant creativity on the part of the engineer. Finally, no matter what level of problem solving and creativity is involved it is necessary to make decisions that is irrrevocably allocate resources to a product. 1, 2 For each approaches the proponents have offered a range of methods and approaches to help stimulate problem solving, creativity, or decision making.

The debate between methods that focus on stimulating new designs and those that look for the truth in decision making is somewhat bane and not necessarily productive. In reality no concept is ever truly eliminated and any concept that is identified later has always existed. What does change is the ability to determine the estimate expected utility and the uncertainty underlying that utility. However, it is this utility function, especially when combined with the technical ‘cost’ and performance of each solution concept that produces significantly interesting behavior. One of the facets of this behavior is that it exhibits the properties of a ‘catastrophe’ as described by Thom in his description of Catastrophe Theory.

II. Background

Design processes have long focused on eliciting a set of desired functions and translating them into a set of functional and physical requirements. This has commonly been done by eliciting the preferences of customers and stakeholders and using a series of well described techniques to map them onto a series of extensive and even intensive physical and conceptual attributes. Historically, these mappings have included the assignment of specific settings of requirements. However, that is changing, at least in some circles, as the recognition that it is
useful to understand the systems behavior around the ‘requirements’ if not counterproductive to set them in the first place.

A. Requirements, Extensive Attributes, and Inaccessibility

Any complex system can be defined by a conglomeration of component, subsystem, and system attributes that produces behavior that is not directly proscribed by the simple summation of those attributes. The set of all of these attributes functionally defines a specific system. This is as true of aerospace systems as it is for any other complex system. Experience teaches us that it is possible to loosely determine the system type with far fewer variables than those necessary to determine the final vehicle. For example, by choosing to build a commercial jet transport, the designer or manufacturer has already eliminated most system types. This reduction in “design freedom” is consistent with the ideas shown in Figure 1.

Further, because requirements may change over the course of a program, both during development and the remainder of the system's life-cycle, a lack of thorough understanding of the effect of the requirements can easily produce systems that perform poorly. This was cited by Mavris and DeLaurentis amongst others.

Mavris and DeLaurentis summed it up thusly:

The process of system engineering has always emphasized the definition of requirements as the first step toward product development. Typically, however, these requirements were examined in isolation from the potential systems and technologies they would likely impact. Further, requirements during design were treated deterministically, which sometimes led to non-robust and poor performing actual systems which encountered different requirements. Thus, there is a need to examine requirements early on and in a new way....

Given the issues with setting specific requirements, as indicated by Collopy and Collopy and Hollingsworth, i.e. that the setting of requirements tends to create deadweight losses in the systems that are created it is advisable to step back from the usage of requirements and focus on the extensible attributes that the requirements are meant to address. In this case, for example, instead of proscribing a specific goal of a maximum payload-range at 3200 nm, instead look at the maximum payload-range attribute in itself. If instead of setting requirements on specific extensive attributes the engineer places a utility function that is maximized at the previous requirements the same global outcome can be achieved.

However, while removing the specific setting of a requirement has a number of benefits to the full design program it does not move away from the issues that were recognized with moving requirements. That is over the course of a long development program or the operational life of an engineered system the underlying needs, environment and applications will evolve. In the extensive attribute optimization view of the world instead of moving a constraint, it would be utility function with regard to that attribute that is viewed as stochastic.

Another feature of engineering design is that there are physical and technological limits to what can be achieved in each extensive attribute. This is something that would not be disputed by any practicing engineer. While true physical limits will remain in place for any given system, e.g. the maximum adiabatic efficiency of any heat-engine is less than one, it is reasonable to expect that technological limits will also evolve as time progresses. What this means is that any engineering system, whether it is one that is purely conceptual or fully realized has limits for each extensive attribute. That is as time progresses systems may no longer be able to provide the functionality requested. In the most basic sense this means that the system is being asked to do something that is infeasible. Conversely could be said that the portion of the extensive attribute space in questions would be considered inaccessible to the solution system. This is one of the key aspects of a portion of complexity science and mathematics known as Catastrophe Theory (CT).

B. Catastrophe Theory

Historically complex systems design has been approached as a fully deterministic system. However, a large amount of empirical evidence suggested that this was not the most correct approach. Further, the actual values of these requirements may not be fully known at the time of program initiation. This nondeterministic behavior
only serves to make the entire problem even more complex. Furthermore, most systems are nonlinear in nature. Nonlinear systems with no deterministic initial and boundary conditions, commonly exhibit instabilities and non-smoothness with rapid changes in behavior for a change in one or more of the system parameters. This behavior is known as a bifurcation, specifically defined as:

Definition 1. A rapid change in the type of system dynamics when parameters in the system are varied is known as a bifurcation.

Bifurcations are well known in aerospace engineering, one of the most common examples being the Hopf Bifurcation, which describes the transition from a stable system to a limit cycle. Aeroelastic divergence and flutter also occur at a bifurcation point. Each of these bifurcations are members of a specific class of bifurcations, those for which both the state and behavior change at the bifurcation point. Of course, the recognized prevalence of bifurcations in systems does not inherently lend any more insight to our understanding of the system behavior, especially since most of the “simplified” models used are designed to avoid the presence of bifurcations. However, the application of a subset of bifurcation and singularity theory, known as Catastrophe Theory, shows significant promise in increasing our knowledge of complex systems design behavior with respect to the design requirements.

Catastrophe Theory, first promulgated by René Thom Stabilité Structurelle et Morphogenèse, deals specifically with the classification of certain types of critical points of smooth functions. The behavior of these critical points result in the bifurcations that Thom calls “elementary catastrophes.” In the most rigorous form the “elementary” catastrophes are solved analytically. These catastrophes are derived from polynomial “potential” functions that consist of two types of variables, the Control Variables (CV) and the State Variables (SV). They are defined as:

Definition 2. A variable, which when changed alters the behavior of a functional system is called a control variable.

Definition 3. A variable that functionally determines the state, i.e. the response, of a system is called state variable.

One of the inherent problems with using analytical catastrophe theory is that the dimensionality of the problem is limited. However, all of the catastrophes possess a series of properties called flags, these flags allow for numeric solutions of problems with nonanalytical solutions and problems of higher dimensions.

C. Mathematics and Properties of Catastrophes

The purpose of this paper is to provide a basic understanding of Catastrophe Theory, and the properties of catastrophes. As such it is necessary to give an overview of the high-level mathematics of CT. A more in-depth review can be found in Appendix A of the author’s PhD dissertation. The functional relationship described by Eq. 1 has a single critical point at x=0. When classified it becomes evident that $Df(0)=0$ and $D^2f(0)=0$ meaning that the critical point is isolated and degenerate. Further, the universal unfolding for Eq. 1 is shown both in Eq. 2 and Table 1. This unfolding adds exactly one CV dimension to the single SV dimension in the original germ. This indicates that the unfolding has a codimension and corank of 1 and 1 respectively. Further the nature and location of the critical point changes. For the trivial case where $c=0$, the critical point remains identical to that in the germ. However, for conditions where $c \leq 0$ & $c \geq 0$ the behavior changes dramatically. To further investigate this behavior, one needs to look at the behavior of the first derivative of $F$, given in Eq. 3.

$$F = x^3$$

$$F = x^3 + cx$$

$$\frac{\partial F(x,c)}{\partial x} = 3x^2 + c$$

Here we see why $c$ is called a control variable, to determine the critical points of $F$ the value of $x$ is determined or “controlled” by the value of $c$. Setting Eq. 3=0 and solving for $x$ we obtain Eq. 4:

$$x = \pm \sqrt{-\frac{c}{3}}$$

This produces an interesting phenomenon. The critical point exists on the real axis if and only if $c \leq 0$. For $c > 0$ the critical points exist away from the real axis, in the complex plane. For the trivial case of $c=0$ there is only one critical point. However for $c < 0$ there exist two isolated, non-degenerate critical points, one minimum and one maximum, located at the points given by Eq. 4. The set of all of the critical points of all partial
functions $F_c(x)$ of $F(x,c)$ is called the **catastrophe surface**. In the case of Eq. 2, this is the parabola given in Eq. 5.

$$M_F = \{ (x,c) : 3x^2 + c = 0 \}$$  \hspace{1cm} (5)

This surface is shown in Figure 2.

![Figure 2. Cubic Germ Catastrophe Surface $M_F$. Adapted from 9](image)

Three different representations of $F_c$ are given in Figure 3.

![Figure 3. Partial Functions $F_c$ of $F$. Adapted from 9](image)

The behavior of the critical points of $x^3$ is the most basic of the elementary catastrophes, the **fold** catastrophe. Each of the unfoldings given in Table 1 has an associated catastrophe. These catastrophes are shown in Table 1.

### Table 1. The Elementary Catastrophes

<table>
<thead>
<tr>
<th>Germ</th>
<th>Codimension</th>
<th>Unfolding</th>
<th>Catastrophe</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[x^3]$</td>
<td>1</td>
<td>$[x^3 + cx]$</td>
<td>Fold</td>
</tr>
<tr>
<td>$\pm [x^3]$</td>
<td>2</td>
<td>$\pm [x^3 - cx^2 + c2x]$</td>
<td>Cusp</td>
</tr>
<tr>
<td>$[x^5]$</td>
<td>3</td>
<td>$[x^5 + cx^4 + c3x^3 + c4x]$</td>
<td>Swallowtail</td>
</tr>
<tr>
<td>$\pm [x^5]$</td>
<td>4</td>
<td>$\pm [x^5 + c0x^4 + c2x^3 + c4x]$</td>
<td>Butterfly</td>
</tr>
<tr>
<td>$[x^2 - xy]^2$</td>
<td>3</td>
<td>$[x^2 - xy + c2(2x^2 + x^2 - c2y)]$</td>
<td>Elliptic Umbilic</td>
</tr>
<tr>
<td>$[x^2 + y^2]$</td>
<td>3</td>
<td>$[x^2 + y^2 + c1x^2 - c2y] + c3y$</td>
<td>Hyperbolic Umbilic</td>
</tr>
<tr>
<td>$\pm [x^2y + y^4]$</td>
<td>4</td>
<td>$\pm [x^2y + y^4 + c1x^2 - c3y - c2y]$</td>
<td>Parabolic Umbilic</td>
</tr>
</tbody>
</table>

As the order and codimensionality of the problem increases the behavior of the “elementary” catastrophes becomes more interesting. The universal unfolding of $x^4$ produces the **cusp** catastrophe, shown in Figure 3. It is in the cusp catastrophe that all of the common properties of an “elementary” catastrophe are present.

These include:

- **Bimodality:** The system can exist in two or more distinct equilibrium states.
- **Inaccessibility:** The system has unstable equilibrium states.
- **Sudden jumps:** A small change in a control parameter produces a large change in the system state, i.e. a catastrophe.
- **Hysteresis:** Transition between states occurs at different values of the control variables. The system is not fully reversible.
- **Divergence** A small change in a control parameter leads to a large change in the final state; however no sudden jumps occur (not present for the fold).
These properties are also known as *catastrophe flags*. The existence and discovery of these flags is important in the cases where a proper analytical model may not be available.

**D. Utility Theory and Value-Driven Design**

In the author’s PhD dissertation, it was proposed that the requirements, or in this context the extensive attributes, be considered at the *control variables*. It is still reasonable to view systems in such a manner, especially when conceiving of different concepts, i.e. the creative portion of design. However, in that document the author specifically shied away from making a decision and allocating resources. This was not because of a lack of recognition of the need to make decisions in the design process, but more so because the author recognized that much of the literature on design, e.g. Frey and Hazelrigg, tended to get bogged down in disputes on ‘truth’ and the benefits of exploring the design space. The being said, regardless of how solution concepts are arrived at it is necessary, at some point, select from amongst them. In this case Hazelrigg is correct, one has to use a method that satisfies both *Arrow’s Theorem* and the *von Neumann-Morgenstern Axioms*. As shown by von Neumann and Morgenstern, this would be expected utility.

The nice thing about expected utility is it only relies on the decision maker’s view of the world. There is no direct need to incorporate the needs and desires of the customers or the stakeholders. In one way of reasoning, Hazelrigg says seems to indicate that the desires of these two groups should be explicitly ignored. Of course, if one truly understands the implication of Hazelrigg’s contention this is not the case, it is just that the needs and desires of the customer and other stakeholders will be contained implicitly in any utility that a rational decision maker derives. In other words to account for them explicitly actually gives greater than intended weight to their needs and ensures that the decision methods will fail to satisfy Arrow’s theorem.

Of course, once it is settled that expected utility is the measure by which decisions need to be made, the difficult problem is in determining this utility. There are a range of different means of creating the measure of expected utility, von Neumann and Morgenstern had theirs, others have been proposed by Abbas, Matheson and Abbas and Abbas and Howard amongst other. Hazelrigg suggests that *net present value of cashflow (NPVCF)* is a good measure. This brings up the idea of using a single, monetized value for utility, which is basically the concept of *Value-Driven Design (VDD)*.

The history of VDD is multi-faceted. However, the basic premise is that it is possible to use a single, consistent, and ‘true’ measure of design goodness across all stages of design. Collopy demonstrates that at least one measure of VDD should provide this. Collopy suggests using *surplus value (sv)* as the measure for most engineering systems. Surplus value is the discounted difference between the end benefits derived from a system and the cost incurred to provide those benefits. In the case of a commercial aircraft that would be the revenues minus the operating and capital costs. This is illustrated in Figure 5.

The benefit of using surplus value is that it provides are relatively simple, monotonic transformation from the systems extensible attributes to an overall utility. Furthermore, it removes any assumptions of price-cost markup and the like. It assumes that both the engineering firm and the customer are relatively rational, at least within the domain of interest. As such any increase in the overall surplus value for a system do to design improvements should lead to, at minimum, no change in profit for the manufacturer, i.e. the overall utility to the firm follows Eq. 6.
Additionally, surplus value only considers future and not past costs. This is one of the requirements that Hazelrigg lists for any decision making aid. The reason for this is that sunk costs are just that, sunk. While they may affect variables like the forward looking cost of capital, and implicitly the rank order of different decision options, if would be both inappropriate and foolish to ‘double count’ them by including them explicitly. Since surplus value, at least within the typical engineering design domain, meets the definition of an expected utility function, and it is a relatively simple transformation from individual monetized values, it makes and ideal measure of ‘goodness’ when comparing different engineering solution options. It is a single scalar value, both monotonic and lacking a theoretical maximum. This means that when married with the technological response it should be possible to determine both which systems are most appropriate, but also what changes in the underlying dynamics of the surplus value run up against the technological and physical limitations of the system.

III. Implications of Catastrophe Theory

Marrying concept explorations, i.e. the creative aspect of design, decision making using VDD and surplus value, and catastrophe theory has the potential to provide significant benefit to the design and design program management process. The basics of the design and decision making process indicated that a closed design is arrived at when the iso-value curves of gross utility and cost are tangential. This is intuitive as if the iso-value curves are not tangential, then an improvement in either cost or utility could be achieved without changing the other. Each of these tangential points has a corresponding surplus value. The curve that traces these points is the surplus value response to the engineering design.

Expanding the surplus value approach to include all possible candidate systems or decision options it is possible to conceive of a multitude of loci creating not a single surplus value curve, but actually a surface in the option space, with each point representing a single, closed engineering solution. Again this can be projected into a single curve of surplus value against a single composite variable \( x \), that is the combination of all system organization and design options/variables.

\[
sv = f(x)
\]

Furthermore, the functional form of \( sv \) is such that it often behaves in such a way that you could represent it, at least in a local domain, as a higher order polynomial, e.g. \( sv=x^n+... \), where \( n \geq 3 \) and \( x \) is the dominating design variable or set of design variables for all of the solution systems. To take a simple example, consider the basic Bruget range equation for an ideal jet aircraft operation in cruise climb. The equation takes the basic form shown in Eq. 8.

\[
R = f(x) = \frac{a}{c_T g} M \left( \frac{L}{D} \right) \ln(z)
\]

where \( R \) is the range, \( M \) is the cruise mach number, \((L/D) \) is the lift to drag ratio, \( c_T \) is the thrust specific fuel consumption and \( z \) is the cruise segment weight fraction, representing the combination of vehicle physical and operation functional design variables. Solving for \( z \) it is possible to understand the design behavior of weight to range and internal design variables. This is given in Eq. 9.

\[
z = \exp \left[ \frac{R c_T g}{a M (L/D)} \right]
\]

The implication is that the cruise weight fraction if basically a function of the physical and functional design variables, \( c_T, M, (L/D), \) and \( R \) that can be remapped as a single variable \( x \). Using the principle of a Taylor series expansion about each design point, over an appropriate design domain \( z \) can be represented by a higher order representation of \( x \). Assume for a minute that the domain chosen allows us to represent \( z \) in the form:

\[
z = ax^4+bx^3+cx^2+dx+e+\epsilon
\]

The constant/intercept can be dropped without consequence as the purpose of catastrophe theory is to describe the behavior of the system and not the absolute value of the response. Further, because the behavior of the original equation is an exponential it is reasonable to view the behavior as dominated by the \( x^4 \) term. As such the lower order terms can be grouped with the higher order terms in the \( \epsilon \). The resulting form,

\[
z = ax^4+\epsilon
\]

is one of the fundamental catastrophe germs, shown in Table 1. If the mapping to surplus value is purely linear then \( sv \) can be represented as the unfolding.
\[ Sv = Sv(z, x) = ax^4 - c_1 x^2 + c_2 x \]  \hspace{1cm} (12)

where \( c_1 \) and \( c_2 \) are \( Sv \) variables such development cost and discount rates.

This is a different approach than what the author suggested in his PhD dissertation\(^{11} \), where the existence of the solution was the response was the germ and the unfolding was the response in relation to the external requirements. The benefit in using the previous approach is that response is directly in terms of things that engineers understand, requirements. Conversely, the approach shown in this paper produces a simple easy to understand output that relies on \( CVs \) that may or may not be intuitive to the engineer. Regardless, the design variables are the \( SVs \). This means that the allowable equilibrium designs are essentially a function of the external factors, be they requirements, or financial and operational parameters.

A. Analytical Solutions

In the ideal world it would be nice to be able to create analytical forms of the catastrophe germs that represent the design of new engineering systems. The approach taken by the author previously\(^{11} \), indicated that in most cases it would not be possible to create an analytical solution. However, when viewing it from the aspect of surplus value, for a reasonably limited set of options over a reasonably limited design range an analytical solution might be feasible if difficult to produce. Regardless of whether or not it is feasible to produce and analytical solution, previous work indicates that it is possible to computationally determine the behavior\(^{11} \). In either case, analytical or computational, it is the behavior described by the catastrophe flags that is important.

B. Catastrophe Flags

The catastrophe flags, described in Section II.C, are what is critically important to understanding the behavior of current and future design decisions. These flags: bimodality, inaccessibility, sudden jumps, hysteresis and divergence. In previous work\(^{11} \) the author indicated that in view of requirements or the systems extensible attributes that these flags commonly exist. An example of this is shown in Figure 6. In Figure 6, if you trace the across the extensible attributes each of the flags, except inaccessibility, can be seen to exist. A more concrete example was shown by analyzing the conceptual/preliminary design options for the US Army’s LHX program.\(^{26} \) In this case four different basic configurations were investigated. The standard single main rotor helicopter, a coaxial rotor helicopter, a tandem helicopter, a compound helicopter and a tiltrotor.\(^{27} \) The results for an LHX like design using technology limits similar to those that would have existed in 1983 is shown in Figure 8. The same for a system that would use 2004 era technology limits is shown in Figure 9.

In the 1983 era case you can see that if the original design was anything other than a tiltrotor, and the firm decided that the only reason they would switch designs is if the basic concept was no longer capable of fulfilling the desired mission, there would be no case where the tiltrotor would be selected. This is a perfect example of an inaccessible portion of the solution space. However, the previous work did not address which systems were ‘better’ at meeting any of the systems requirements. If this was the measure used, then it is quite possible that the tiltrotor concept would become accessible. Whether or not the tiltrotor example is accessible depends on the setting of what is known as the delay convention.

C. Delay Conventions and Inertia

If a system or design exists in one equilibrium point, initially globally optimal, and overtime other equilibrium points appear, due to changes in the \( CVs \), what is the likelihood that the system will move to one of those new points when it becomes globally optimal? If it does move, at what difference in optimality will that occur? The behavior that answers these two questions is what is defined as the delay convention. The two extremes of delay convention are what is known as the perfect convention and the Maxwell convention\(^{12} \). In the case of the perfect convention the system will not switch from its current equilibrium to the globally optimal equilibrium until the current equilibrium disappears. This is illustrated in Figure 7.

![Figure 6: Example of Multiple Systems Across a Dual, Extensive Attribute Space\(^{11} \)](image)
The consequence of the delay convention, when viewed from an expected utility point of view, is that by not switching, i.e. have a more perfect delay, value and utility are being left on the table. That is a deadweight loss is occurring. This is if we had infinite flexibility in our designs they would always be able to optimally meet the needs of the decision maker. In reality there is no way that this can be achieved. In the natural sense each engineering organization cannot modify its designs all of the time. This creates a delay. Furthermore as designs progress from concept to realization the delay, or inertia naturally increases. In fact it is reasonable to assume that even at the initiation of a new design project each organization and each design concept within an organization has a different inherent level of inertia, producing a different delay convention. However, as part of our desire to minimize or eliminate downside risk associated with programs, in a sense control them and remove some of the complexity organizations act to further increase the delay convention. It is common for an organization to setup decision points or ‘toll gates’ in plan for a program. It is at these points that key reviews are held and decisions are made. In the most simplistic representation these might be at the junction of conceptual, preliminary, and detailed design.

The issue is that, as Hazelrigg has indicated, not only are there an infinite number of options there are also an infinite number of decision points. What changes overtime are the gross benefits and costs of each option. Escalating costs of changing direct compared to remaining on the current path can be directly translated into surplus value, e.g. represented as a portion of the control variables. For an organization with no specific expertise it is the pure properties of each concept that will determine its surplus value, if the market changes or technology evolves externally the rank order of different options will change and the firm may easily change its concept. However, most engineering firms have an area of expertise Boeing and Airbus know how to make commercial airliners but might struggle with automobiles, while Ford and Toyota would struggle to develop their first modern commercial airliner. This creates both a lower development cost and risks for those concepts that are more familiar and also increases the cost of switching away from those options in the future.

Unfortunately, because of the way that most decision methods treat risk, specifically the significant aversion to downside risks it is conceivable that the inertia and resulting delay convention are much higher than necessary. This would be similar to the situation that Collopy described with relation to risk aversion methods and discount rates. Collopy suggests that for most engineering projects for the majority of firms the projects should be treated in a risk neutral manner. Mind that by treating projects in a risk neutral manner it is more likely that a given project will fail, but also more likely that the total value summed over all of the successful and failed projects will be greater than for the risk-averse approach. That being said there are many cases where risk adverse behavior may be desired, e.g. cases where the burden of failure is highly disproportionate and there is little opportunity for Coase transactions or Pigovian taxes to be effective. While the details of this loss are beyond the scope of this paper, it is the recognition of the catastrophic properties of design and value that can be useful in determining the potential losses.
I. Conclusion

Aerospace design requires both creativity and decision making all with the goal of solving problems. However, it is not that simple. Most engineering problems are complicated and many are essentially complex. Furthermore, there is an inherent complexity that is added through the organizations that produce engineering artifacts. The consequence of this is that the inherent complexity can describe a significant portion of the behavior of the design process and the design, both expected and unexpected. Historically, engineers have attempted to reduce or control this complexity. The consequence has been that in many cases additionally complexity has been added into the organizational design process and desired performance has been ‘left on the table.’ This may have arisen from purposefully and justifiably risk adverse behavior or may be an artifact of previous attempts and ignorance.

Going forward, recognizing the complexity helps the engineer to understand the real ‘value’ in a design. Further, it needs to be recognized that both the existence of a particular solution concept and the utility or value of all concepts is complex enough to exhibit what is known as catastrophic behavior. Unfortunately analytically solving for the catastrophes is often difficult if not impossible. A saving grace is that it is possible to recognize the behavior that is associated with catastrophes, known as flags, and use those to facilitate a computational solution. Another benefit of recognizing catastrophic behavior is the fact that the way designs switch from one closed equilibrium to another is governed by the catastrophic behavior and the resulting delay convention. Every organization and every design program will exhibit its own delay behavior and that behavior will change over the course of the design. However, in many cases the delay convention is not governed by the parameters and behavior of the design in question nor the utility of the decision maker, but instead by organizational structures that are designed to minimize downside risk without accounting for the system in question. In these cases it is reasonable to assume that global utility, both for the organization and its decision maker, and for society as a whole may suffer from a deadweight loss. If that is the case the methods currently employed, while effectively guaranteeing a successful projects does not actually guarantee a net benefit to those developing the projects. It is suggested that a further investigation of this type of behavior be undertaken.

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