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Introduction

Accuracy is a measure of how a cost estimate will differ from the final actual outcome. Empirical estimate accuracy data has been researched for over 50 years. However, as published by the author in 2012, the level of industry understanding of the reality of accuracy and our ability to predict this reality is very poor. [15] That article pointed out that using AACE recommended practices to quantify systemic risks (i.e., parametric methods) supported better forecasting. However, none of the AACE Recommended Practices (RPs) are able to predict the reality that 10 percent of large projects overrun their budgets by 70 percent or more. Overruns of that scale for a mega project can cause significant financial damage to a company, project financed or not. [11]

Falling back on the Rumsfeldian “unknown-unknowns” construct to excuse our predictive failure (i.e., ignore the reality we see.) is a cop-out; it does not help us make better project decisions or improve practices. The author has learned from benchmarking and post-mortem analysis experience that project cost disasters generally result from a stew of systemic weaknesses, risk events and poor practices of all kinds. This mix of mundane risks, in the presence of complexity and stress, can push a project’s behavior over the edge of chaos; i.e., the tipping point. Chaotic project behavior is unpredictable except to say that the cost outcome will likely be a disaster. What we can predict is the approaching edge of chaos and we can do things to avoid it.

This paper summarizes the author’s learnings from industry regarding chaos and complex systems theory in respect to project cost behavior. It then presents a set of practical risk quantification methods, building on AACE RPs in place, that allow us to warn management of pending chaos and how to head it off.

Project Cost Behavior

This paper concentrates on engineering and construction projects in the process (e.g., oil, gas, chemical, mining, metals, utility, etc.) and infrastructure (often associated with process projects) industries. They are characterized by complexity, unique work scopes, design change and sometimes new technology. For these industries, cost behavior, expressed in terms of estimate accuracy (i.e., actual outcome/funding estimate), is well documented and rather grim. Figure 1 from a paper by the author shows the heavily skewed actual distribution of accuracy versus the much less skewed distributions that that we are forecasting for funding estimates. [15]

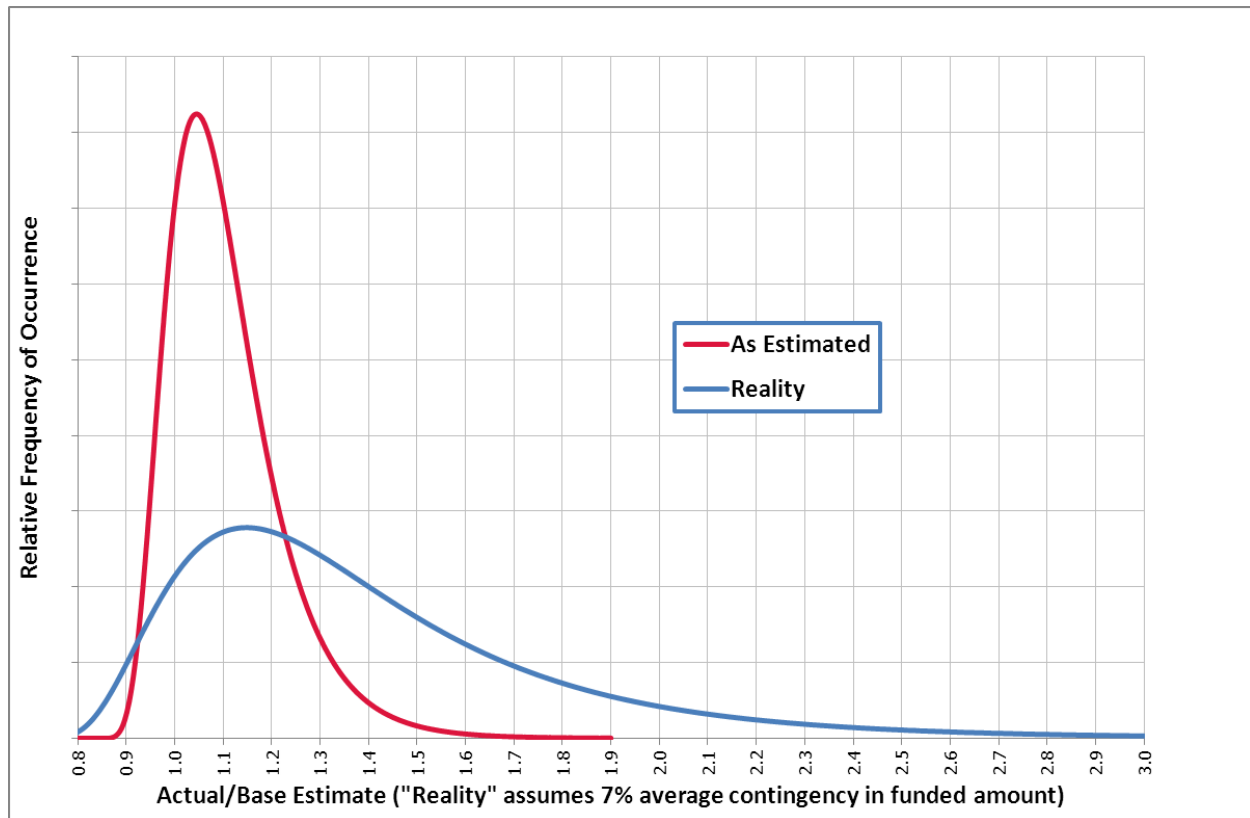


Figure 1 – As Estimated and Target Accuracy Vs. Empirical Accuracy at Funding

A parallel AACE paper by Ogilvie et al. based on the more robust and statistically solid data from benchmarking firm IPA, Inc., adds insight into the actual distribution of accuracy for estimates at different project scope development phases as represented in Figure 2. [26] For the respective Estimate Class (industry tends to authorize projects based on estimates closer to Class 4 than Class 3) these empirically-based sources agree; there is no question as to the reality of the very long tail.

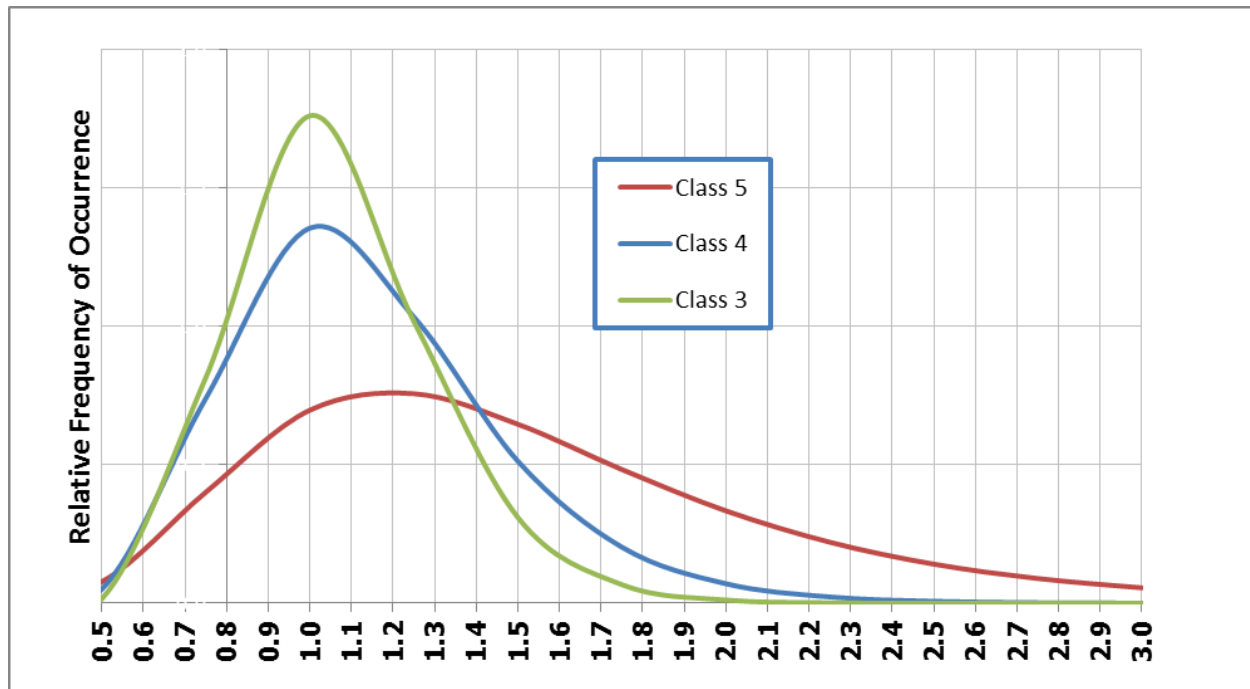


Figure 2 – Accuracy for Estimates at Different Phases of Scope Development

The long tails in Figures 1 and 2 have been smoothed by curve fitting by the author (log-normal distributions are a good fit.) However, the actual data distributions are not smooth (i.e., not orderly.) As Mr. Edward Merrow, the founder and CEO of IPA, Inc. said in a recent podcast on mega-projects: “the distribution of success or failure is highly bimodal.” [24] This bi-modality is evident in the IPA histograms in Figure 3. [26] The author’s hypothesis, is that the mode on the high end is dominated by projects that crossed the edge of chaos; an alternate, but not uncommon, project reality. Another hypothesis, as suggested by Dr. Bent Flyvbjerg, is that these projects were intentionally underestimated. [12] However, my experience agrees with Mr. Merrow who stated that “...no Machiavellian explanation is required” to explain these dismal outcomes. [23]

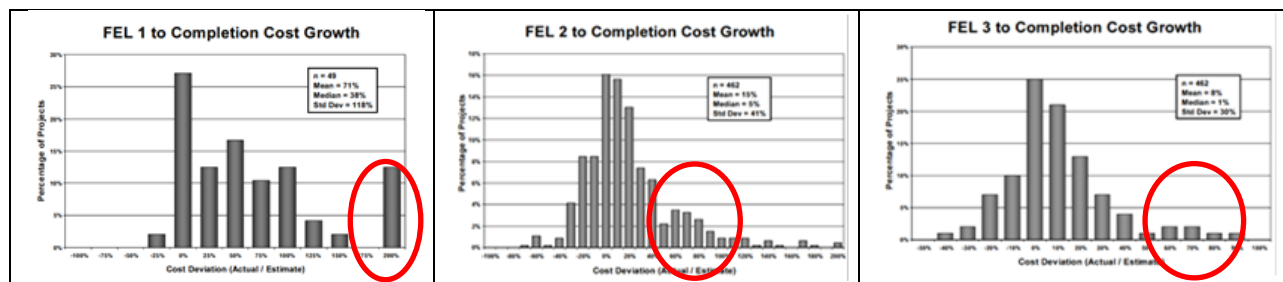


Figure 3 – Bimodal Tendency in Estimate Accuracy Data (used with permission [26])

The projects in or near chaos defy our current risk quantification methods, but they are too prevalent to ignore and write off as unknowable. If we can understand where the edge of chaos is; i.e., *the tipping point* in terms of combinations of complexity and risks, we can at least warn management of impending disaster, and, at best, provide recommend actions to pull the

project back from the precipice. As it is, every industry risk analysis I see today is presented to management as if the project were a well behaved, orderly system (albeit skewed), even for projects with extreme risks; this is not the whole story. The story is one of chaos and complexity as discussed in the next section; this will set the stage for presenting a tipping point warning indicator.

Systems, Chaos and Complexity

In searching for practical methods to address the true distribution of project cost uncertainty, my learning path went from system dynamics, through chaos theory to complex system theory. It is a logical progression of thought and I hope the following summary in layman's terms will adequately explain the basis of the methods I arrived at.

First, I have learned to look at projects as *systems* (something with parts that interact to form an integrated functioning whole). This view has been around a long time; e.g., an author in a 1971 AACE publication said "Cost Engineering must be viewed as an integral part of *systems engineering*" [31]. It does not take much experience for one to see that project systems are also dynamic; they change over time. These realizations lead one to *systems dynamics* (SD) which studies how *complex* systems behave over time. SD has evolved fascinating models using feedback loops (e.g., rework). Unlike Critical Path Method (CPM) based risk models that do not address rework, SD models demonstrate *nonlinear* behavior which looks more like reality than traditional risk analyses. Work by Cooper and many others since the 1970s has demonstrated SD application on projects, particularly in claims analysis. [10] Unfortunately, current SD models are too difficult for everyday use and they are based on the premise of complex but orderly (i.e., reductionist) systems when disorder is the observed reality of most of our bimodal projects.

The search for non-linear/disorderly models leads one to *chaos theory*. The work of Lorenz in the 1960s on weather forecasting (and the advent of powerful computers) kicked off this field. [20] In simple terms, researcher Sven Bertelsen tells us that "chaos may be defined as a state of the project system where the future development of the system is not predictable or only poorly predictable." [8] Chaos is a disordered and unpredictable state; one that is out of control. Chaotic systems are also non-linear which for projects means that progress is not proportional to the work effort; i.e., the project seemingly goes in all directions, racking up huge bills and delays and getting nowhere. John Hackney, a founder of AACE, gave us an excellent case description of such a project in the "Chaos" chapter of his seminal book on capital project management. [14] The "edge of chaos" then is where a project teeters between order and chaos. If we could know the key attributes of projects at and over the edge of chaos, we might have the start of a risk analysis method. That key attribute in systems dynamics and chaos theory is system *complexity*.

This takes one to *complex systems theory*. Rigorous study of complexity is fairly new; the definition of complexity is still being debated. [6] It is generally agreed that complexity is more

than complication. Complication implies lots of parts or size (e.g., a complicated WBS) while complexity implies lots of interrelationship and interaction of the parts. Complicated, non-complex systems are likely to be orderly, linear and responsive to traditional control while complex systems are more likely to be disorderly, non-linear and at worst, chaotic. Aggravating the complexity are stresses put on a system by management, the market or environment (e.g., pushing for accelerated schedules). Bertelsen does a good job summarizing the relationship between complexity (*dynamics* in his terms), stress and the edge of chaos. [8] Figure 4 borrows from his concept; the person losing their balance represents a project on a system playing field with the cliff representing the edge of chaos towards which complexity and stress are pushing the project.

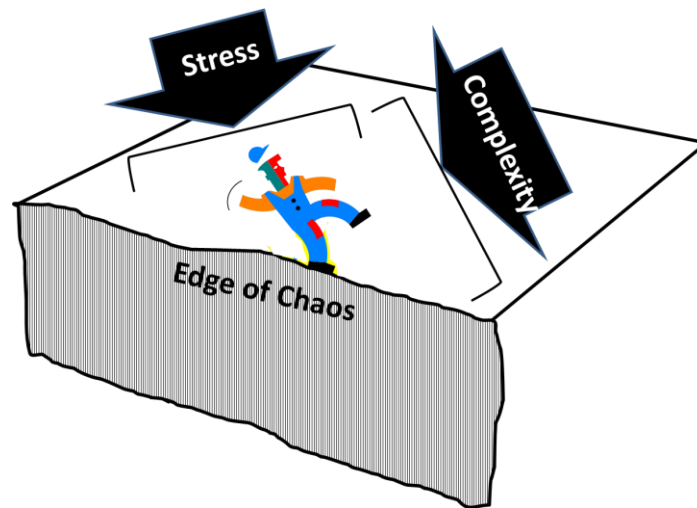


Figure 4 – Complexity and Stress Can Drive a Project Over the Edge of Chaos

Stress (or pressures) can be positive. The power of stakeholders, owners and management to take mitigating action and make changes can be a positive force (Bertelsen called this “decision power.” [8]) However, reactive decisions often add more negative stress. For example, accelerating a lagging, disordered project can be deadly; as Merrow put it: “speed kills.” [24] Lastly, risk events or unexpected conditions can compound negative stress, add to complexity (e.g., added risk treatment scope) and confound change efforts. Figure 5 illustrates the added stressors.

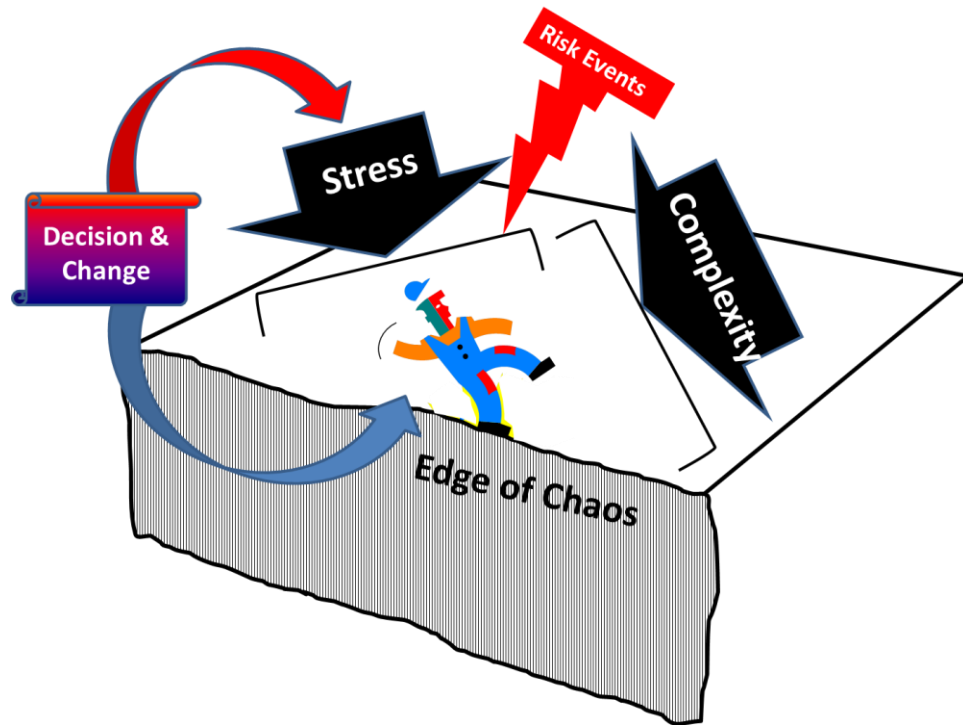


Figure 5 – Adding Stressors at the Edge of Chaos

A final element of complexity is uncertainty. An analogy for general uncertainty is a fog obfuscating or confusing the system. If we can measure these stresses (positive and negative), the complexity (or dynamics) and their interaction with risk events, allowing for uncertainty, we may have a way of measuring how close our project is to the edge of chaos. The next step is then to identify the attributes of complexity and stress and how to measure them; when are they too much?

But before we leave this topic, it is important to note that in theory and in my experience, traditional “control” cannot restore order to a chaotic project. Diabolically, “change” is required to restore order. [29] This is a problem because change during the project execution phase is anathema to most project management systems. In theory, *complex adaptive systems* can address how ongoing project organizations living on the edge of chaos can change to restore order, but adaptation requires more time than a lone project usually has. Control versus change will be revisited in later discussion about risk treatment.

Measuring Complexity and Stress

As mentioned, the definitions of complexity are still maturing. An early paper by Baccarini that reviews complexity definitions is often referenced. [7] A more recent paper by Gul and Khan pulled together a complexity model referencing many other researchers that with a few changes fit my purposes for a risk analysis tool. [13] Figure 6, based conceptually on the Gul

model, shows the elements of *complexity* with their typical attributes (some attributes apply to multiple elements).

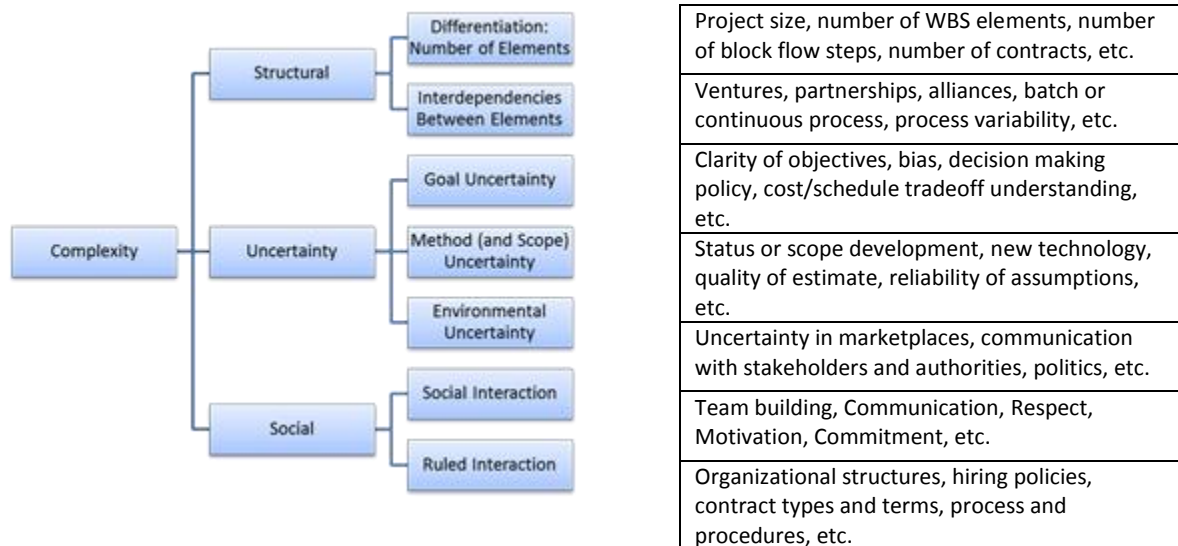


Figure 6 – Breakdown Model of the Elements of Project Complexity

Figure 7 illustrates the components of *stress* on a project. Arguably, these are just more elements of system complexity, but these reflect elements that tend to act on a system once it is in place. This is conceptually based in part on Bertelsen's construct of stress and decision power with the author's addition of risk events. [8]

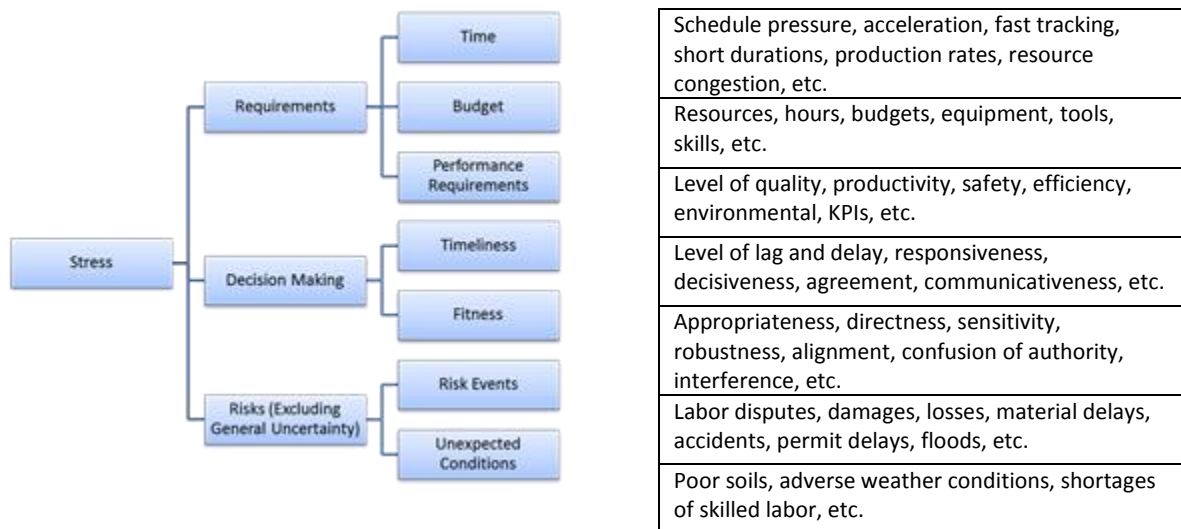


Figure 7 – Breakdown Model of the Elements of Project Stressors

Given these elements of complexity and stress, how do we measure them? Fortunately, we already have the fundamentals in hand in AACE Recommended Practices (RPs) for risk quantification and the research they are based on. One can leverage the AACE RPs in a tipping point warning model.

AACE Recommended Practices and Tipping Point Measures

Starting in 2007, the AACE Decision and Risk Management committee developed a robust set of risk quantification RPs based on agreed principles. [16, 17] One principle was that risks differ in how they impact project costs and therefore methods will vary in how to quantify these risks. AACE defines this methodological risk breakdown as:

- Systemic Risk: artifacts or inherent attributes of the project and enterprise system
- Project-Specific Risk: risk events and conditions affecting the specific project and plan
- Escalation Risk: driven by the general economy

Analogies for these risk types suggested by others include: strategic (enterprise), operational (project), and contextual (global) risks respectively. [28]

The AACE RPs for methods for quantifying these risk types include:

1. Systemic: RPs 42R-08 and 43R-08 cover Parametric methods [3 and 4]
 - Note: These RPs are based in large part on research by RAND Institute [25]. Since the RAND research, IPA, Inc. has added a “Team Development Index (TDI)” factor as a major systemic risk driver. [22]
2. Project-Specific: RP 65R-11 covers Expected Value with Monte Carlo Simulation (MCS). [2]
3. Escalation: RP 68R-11 covers Escalation methods using indices and MCS. [1]

Figure 8 below takes the complexity and stress indicators based on theory and match them up with the risks identified in the AACE RPs and underlying research. In each case the complexity/stress factors are addressed in existing methods, albeit linearly. All that has not been dealt with is the non-linear interaction of these risks at the edge of chaos.

Complexity Model Elements	Complexity Element Description	Addressed in AACE RPs
	Project size, # of WBS elements, # of block flow steps, number of contracts, etc.	Systemic: 42/43R-08
	Ventures, partnerships, alliances, batch or continuous process, process variability, etc.	Systemic: 42/43R-08
	Clarity of objectives, biases, decision policy, cost/schedule tradeoff clarity, etc.	Systemic: 42/43R-08 (with TDI)
	Scope development, quality of estimate, reliability of plan assumptions, etc.	Systemic: 42/43R-08
	Uncertainty in marketplaces, regulatory biases and policies, politics, etc.	Systemic: 42/43R-08 Escalation: 68R-11
	Team building, Communication, Respect, Motivation, Commitment, Conflict, etc.	Systemic: 42/43R-08 (with TDI)
	Organizational structure, HR policies, contract terms, procedures, regulation, etc.	
	Aggressive schedules, acceleration, fast tracking, production rates, resource congestion, etc.	Systemic: 42/43R-08 (with TDI)
	Reduced resources, hours, costs, equipment, tools, etc.	
	Challenging level of quality, productivity, safety, efficiency, environmental, KPIs, etc.	
	Lag and delay, unresponsiveness, indecisiveness, disagreement, uncommunicative, etc.	
	Appropriateness, directness, sensitivity, robustness, alignment, etc.	
	Labor disputes, damages, losses, material delays, accidents, permit delays, floods, etc.	Project-Specific: 65R-11 Escalation: 68R-11
	Poor soils, adverse weather conditions, shortages of skilled labor, etc.	

Figure 8 – Complexity/Stress Elements and AACE RPs That Address Them

Addressing Nonlinearity

The parametric and expected value methods in the AACE RPs use linear approaches which only apply to projects in an ordered mode. They do not predict the long tail, let alone bimodality. Complex systems theory and observation suggests that these risks can interact in a non-linear way (i.e., the output is not proportional to the inputs). In other words, the impact of two risks is not the sum of the impacts but something like a power function of them. As stated by Ackermann, “the impact of the whole is greater than the sum of its parts.” [5] A way to look at this mathematically is that the risk impacts are x and y ; then the total impact as one approaches the edge of chaos is not $(x+y)$ but $(x+y)^e$ where e is greater than 1. We have all seen this proverbial effect as “the straw that broke the camel’s back” (an analogy that fits the swaybacked bimodal distributions in Figure 3.)

So, what in our complexity measurement roster is e ? My hypothesis is that the drivers of non-linearity and disorder are the stress factors. A complex project, even with uncertainties, will tend to stay in the realm of linearity and order if the net stress (as e) is near 1; the more that the net stress exceeds 1, the closer the project will be to chaos. One can summarize the stress factors in Figure 7 as follows:

- aggressiveness of requirements
- team/stakeholder management
- quality of decision making (recognizing authority and responsibility)
- risk events and conditions that occur (focus on critical risks)

Each stress can be a positive or negative influence on e depending on whether it is aggravating the complexity and uncertainty (e.g., pushing for a faster schedule or hitting rock in the soil) or mitigating it (responsive decision making or experiencing perfect weather). The first three factors may be attributes of a defined project system and organization and it is tempting to equate a “well-defined” system as an inherently positive actor. However, as discussed by Taleb, legacy systems nurtured in an ordered environment, may be fragile at the edge of chaos [30]. Care must be taken to measure how these stressors behave when faced with disorder.

Putting the Parts Together in the Tipping Point Indicator

Based on the theoretical grounding of complex systems theory, and the practical grounding of AACE RP based risk analysis tools and empirical research findings, I enhanced the risk analysis toolset I use to support my client’s major projects. [16,17,18] My existing toolset is a hybrid method employing three integrated tools:

- Systemic: a parametric model based on RAND and other published empirical research findings (e.g., IPA’s team development and project control findings),
- Project-Specific: an expected-value model with MCS for risk events and conditions (i.e., probability times impact) that integrates with the systemic risk model (i.e., uses the systemic tool outcome as the first project risk), and...
- Escalation: a price index model with indices from economists with MCS applied; it incorporates the probabilistic cost and schedule output distributions from the other tools.

This toolset also produces a “universal” capital cost and schedule risk output distribution. For an ordered regime, it provides the most complete and empirically valid outcome I know how to produce; however, it is not enough. Even though it may tell an owner that their p50 value contingency is say 25% (rather than 10% from traditional methods), 25% does not communicate the risk story; in fact, it may not even raise an eyebrow. In his text on project financing, John Finnerty indicates that financiers would view overruns of 25% as “modest.” [11] What we need is something to clearly warn management that the modest contingency is actually sitting at the

edge of a much larger blow-out. The warning should come with tips for backing away from the edge.

In sum, as shown in Figure 9, I added a simple tipping point warning sign to my integrated toolset. This is in addition to the usual cost and schedule outcome distributions and risk tornado diagrams. Note that the category of “risk events and conditions” flags the presence of critical risks; i.e., those shown to contribute to disorder such as a shortage of skilled labor and/or where the risk response would likely result in major increases in project manpower and/or the control base (e.g., work packages, budgets, schedule logic, etc.).

Aggressiveness of Requirements	●
Team/Stakeholder Management	●
Decision Making	●
Risk Events and Conditions	●
Overall; Threat of Chaotic Outcomes	●

Figure 9 – A Simple Tipping Point Warning Indicator

This indicator is similar to the concept of the systemic “Risk Filter” reported by Ackermann in 2006 [5]. The Risk Filter (a rating based on a systemic risk questionnaire) results in one of three outcomes that in simplified terms are: Cancel/Recycle, Treat, or Go. In 2006, Maidment and Gough reported on a “Project Stability Index” in 2006 which is a ratio of positive over negative stressors (i.e., the product of project system integrity and team effectiveness divided by a measure of risk severity. [21] The Canadian Treasury also presented a “complexity and risk assessment” tool in 2012 that they use to filter proposed projects to higher approval authority levels depending on the sponsor department’s rated capacity to handle projects of a given risk level. [19] For the later tools, one must take care to rate system “integrity” and “capacity” in respect to their robustness in the face of disorder (i.e., fragility). In all these tools, the indicator serves as a kind of filter to assure that the project risks gets the appropriate senior management attention. These stressor risks, other than minor risk events, generally belong to senior management to take action on.

For my tipping point indicator, the general criteria for each tipping point indicator and typical risk treatment advice for management are shown below in Table 1:

Stress Factor	Criteria	Typical Risk Treatment
Aggressiveness of Requirements	Based on quantitative estimate and schedule validation/benchmarking which shows if the plans are more or less aggressive than industry norms. Green is > norm.	Ease off cost and/or schedule “savings” not resulting from real value improvements or scope changes, etc.
Team and Stakeholder Management	Based on systemic ratings of the team resourcing, alignment, competency, etc. Green is best practice.	Add resources, provide training, perform team building, improve communication, etc.
Decision Making	Based on systemic ratings of clarity of goals, engagement, responsiveness, buy-in, etc. Green is best practice.	Clarify and communicate goals, expedite, lead, minimize gaming, clarify authority, etc.
Risk Events and Conditions	Based on project-specific and escalation tool risk outcomes compared to industry norms. Green is < norm.	Increase focus on the risk treatments identified in risk management. Make changes as needed.

Table 1 – Tipping Point Indicator Criteria and Risk Treatment

Behind the green/yellow/blue stress factor indicators are quantitative ratings of the expected norm for each factor as well as the project being reviewed.

Applying the Tipping Point Indicator in Quantitative Risk Analysis

As mentioned, in my consulting practice I use a hybrid parametric and expected value risk analysis toolset consistent with AACE RPs 42R and 65R. It was the most empirically validated toolset I could devise. However, it was unable to generate the 70% cost growth at p90 (for Class 4) and bimodality as seen in Figures 1 to 3. Using the stress factor rating behind the tipping point indicator, I developed a version of my model that could generate bimodal output. This required adding an alternate risk impact distribution that reflected a chaotic regime and incorporating a percentage of iterations in a Monte Carlo simulation crossing over the edge into chaos based on the stress factor (e). A random number generator was used to develop the merged, bimodal distribution. [27] Figure 10 compares the chaos model’s Monte-Carlo simulation output to that of the empirical IPA data from Figure 3; the similarity is remarkable (both reflect Class 4/FEL 2 estimates.)

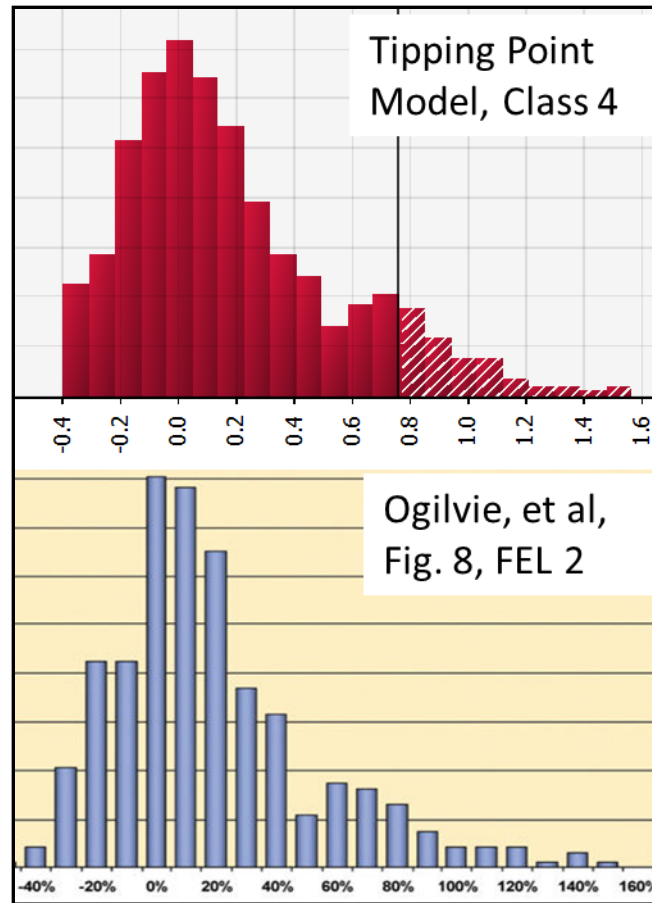


Figure 10 – Tipping Point Model versus Actual Cost Growth Outcomes

The tipping point model outcome in Figure 10 reflects two key input assumptions:

1. The alternate chaos distribution is the same as the base (non-chaos) distribution except shifted to the right by about 5 to 6 times the base contingency set at p50. One might call this factor the “chaos penalty”. For example, if the base contingency was \$100M at p50, then the chaotic regime distribution would be shifted by \$500M (5X) to the right.
2. The impact of the stress factor (e) resulted in 15 percent of the Monte Carlo iterations using the alternate chaos distribution. If this is what is really happening, it means that 1 in every 6 or 7 major projects experience chaos (the hypothesis being that this proportion was highly complex and/or stressed).

I am reluctant to use this model version in practice because it is reductionist; implying that the outcome of chaos is predictable and that my assumptions reflect reality. More empirical research is needed. In any case, Figure 10 does present a dramatic picture and it is useful for illustrating the tipping point concept.

Tipping Point Indicator Application and Risk Treatment

Unfortunately, in weak project systems, the initial tendency is to hide problems; optimism bias and/or fear of punishment prevail. PMs or key members of the team may hide problems or upper management may ignore the PM's demand for change. John Hackney even suggested that an ignored PM might "ride the rapids" into chaos to convince (i.e., scare) upper management of the need to make changes [14]. A subtle tipping point indicator would not help such an organization; what is required is a "risk-aware" organization that has already learned its lessons and is open to early warning signals.

For such an organization, the tipping point indicator tool should be applied at decision gates, but also at key milestones during project execution or whenever problems become apparent. When the "yellow" light comes on during execution, actions that reduce stress such as slowing a schedule or reducing work on overtime may be called for. When the "red light" goes on (or if the warning was not heeded and chaos is already happening), it may call for immediate risk responses that one major chemical company client called "containment". No theoretical understanding was needed by this company; they knew that when a project was "going off the rails" they needed to take action. As John Hackney stated in his book, "action must be swift and decisive." [14] Seasoned veterans know that one large project blowout can destroy the capital effectiveness of a whole company portfolio (and ruin the credit ratings for smaller companies).

A common risk response noted by Hackney and also employed by the company above is to assign a "swat team" of experts who can step in to help beleaguered projects. Rebaselining the control system from scratch is a common response when disorder is prevailing. Replacing the PM, ineffective contractors, and/or vendors may be called for. In any case, business as usual will not suffice. These responses are stressful; but in all cases they are directed towards vigorously restoring order. Theory suggests that reductive control only works in an ordered, linear regime; recovery from chaos requires timely, decisive and appropriate change.

Conclusion

This paper went a long way through theory to arrive at a simple tool; however, decision makers should appreciate the theoretical and empirical research grounding of the method. Complex systems theory is evolving and fairly new to most people and companies. The risk analysis approach described here is a starting point; many variations of dealing with potential chaos are possible and it is hoped that other methods will be developed and reported.

In summary, this paper reviews the studies of actual project cost growth and the bimodal nature of reality. It hypothesizes that the cost outcomes we are seeing are the mixed result of linear/ordered projects and disordered/non-linear/chaotic projects. It points out that reductionist control only applies to the former. The paper then takes a logical walk through the evolving topics of systems dynamics, chaos theory and complex systems theory to explain the disaster projects. I believe that these areas of knowledge are where our next generation of

practical risk analysis tools will come from. The paper also explains that we cannot reliably predict the outcome of chaotic projects; we can only point out when a project is nearing the edge of chaos and disaster.

The paper then presents a method to apply learnings about complexity and chaos into a practical risk analysis tool; a tipping point warning indicator. The good news is that AACE RPs provide many of the building blocks in terms of risk identification and rating (albeit in a linear/ordered way.) The paper hypothesizes that the concept of “stress” on complexity is a main driver of non-linearity; compounding the effects of complexity and pushing towards the edge of chaos. Some similar tools by others are offered for comparison. Finally, the paper suggests advice to management about ways to help them pull the project back from the edge or contain a blowout.

It is hoped by the author that this paper will motivate others to delve into the non-linear world and come up with practical ideas that get the knowledge of SD, chaos and complexity out of its academic purgatory. We need to take our risk analysis practices to the next level (after all, putting theory to work in a practical way is our role as engineers.).

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