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THE IMPACT OF INSTABILITY ON COMPLEX SOCIAL AND TECHNICAL SYSTEMS

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The Impact of Instability on Complex Social and Technical Systems

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Introduction

Instability is a pervasive phenomenon that has deep implications for virtually all complex social and technical systems.

In engineering, the identification and mitigation of various types of technical instabilities is a well developed practice. This is a key focus, for example, of engineers concerned about the prevention of potentially destabilizing vibration in the frame of an aircraft or the mitigation of sources of technical instability in the operation of a nuclear reactor. However, the nature of instability in complex social and technical systems is relatively unstudied and not well understood. This is unfortunate because instability can have profound effects on the performance of those systems as well as their ability to improve their performance over time.

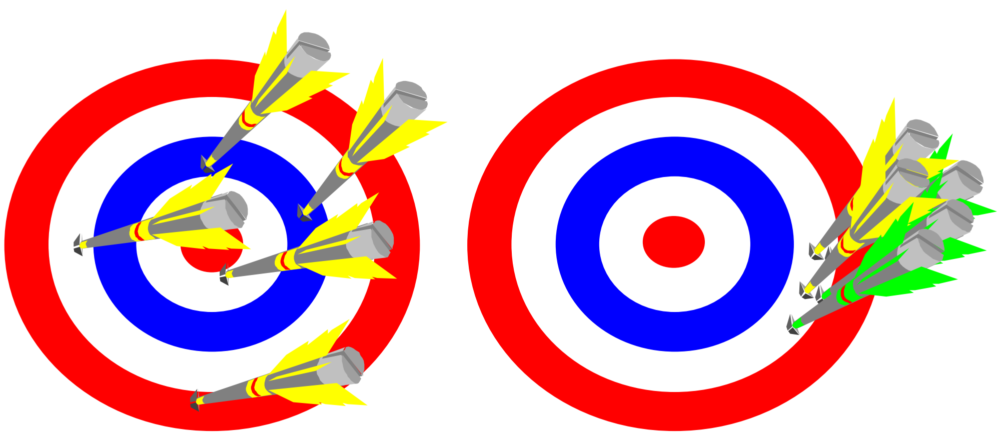
In this paper, we present a conceptual framework for understanding instability in socio-technical systems. To illustrate what we mean by instability in the context of complex engineering systems, we will draw on data from the aerospace industry. In particular, we use two data sets, to trace the impacts of various sources of instability. One data set centers on instability and its impact on aerospace programs, while the other centers on instability and its impact on aerospace production and design facilities.

Consider the case of the F-22 program, which certainly is a complex engineering design and production system. It has also suffered significantly from instability over the course of its lifecycle to date. We will focus in on three specific sources of instability to illustrate this: technological, organizational and economic instability. Economic instability is reflected in several successive budget cuts – some small and some substantial – that have taken place since the inception of the program. This has forced the development of more than 20 program master plans, with far-ranging ripple effects on the prime contractors, employees, suppliers, communities and other stakeholders. Technological instability is particularly evident in the avionics, which were first designed at a time when the fastest available computer chip was a 386 micro-processor. Each major advance in computer technology has forced complex sets of choices around what to re-design and what to functionality to leave unchanged, using the older technologies. Organizational instability is reflected in the merger of Lockheed, Martin Marietta, and the General Dynamics aeronautical sector into Lockheed Martin, as well as countless organizational initiatives, restructurings, partnerships, acquisitions, and leadership transitions. Despite these significant instabilities, the requirement to develop and deliver a complex, advanced aircraft system never wavered.[2]

Traditionally, designers of complex engineering systems have addressed instability as an exogenous factor and concentrated on building buffers to cushion its impact. More recently, the focus has shifted to build flexibility so that systems might be robust in the face of instability. More rarely, though perhaps most effectively, designers have renegotiated the scope or boundaries of systems in order to address the forces or factors driving the instability.[3] Ultimately, organizations have to do more than develop and deliver complex systems while confronting the challenges of instability, though. They must also achieve continuous improvement in aspects of their operations, which typically occurs through initiatives such as Lean, Six-Sigma, and others.

In this context, a key statistical process control (SPC) principle revolves around the importance of stability (or at least reduced variability) as a pre-condition for improvement efforts.[4] Figure 1, for example, is a common illustration of the importance of stability – showing two dart games with a more stable but off center player on the right facing fewer uncertainties in the path to improvement than the less stable but higher scoring player on the left. Most lean implementation frameworks build on this concept and urge the establishment of stability prior to the implementation of systems for "flow" and "pull." A deeper understanding of the nature of instability promises useful insights into the extent to which stability in complex systems can be achieved, and into how complex system performance can be improved in cases where instability is unavoidable.

Figure 1. Illustration of the Importance of Stability Prior to Improvement



Defining Instability

We define instability as a dynamic pattern of stimulus and response in which events become successively less predictable or controllable.

Classically, instability in physical systems is defined as a perturbation that is amplified by feedback in a divergent process – resulting in increased variability. In the context of many complex social and technical systems, there may be many perturbations, many related and unrelated responses and great difficulty distinguishing superficial symptoms from underlying sources of instability. Stability does not necessarily mean the absence of perturbations or new stimulus. It is just a state where responses to perturbations do not induce unpredictable or uncontrollable outcomes.

As part of this definition of instability, it is important to note that instability is not the same as variability. Instability involves both a degree of unpredictability and an increasing lack of control. In this sense, instability can be understood as representing a particular kind of uncertainty in a complex engineered system – one that is particularly challenging for the architects, leaders and others in these systems.

Empirical Background

To illustrate some of the dynamics associated with instability in socio-technical systems, we present findings from two separate lines of research – one focusing on instability at what can be termed the program level and one on what can be termed the facility level. Both studies are focused on the U.S. aerospace industry. At the outset a few cautions are needed. First, the focus on aerospace means that the findings may or may not be fully generalizable to other sectors of the economy. Second, each of the studies involves cross-sectional survey research, combined with some longitudinal case study research – which will only partly capture important longitudinal aspects of instability. Third, the analysis of these data is not complete. In these respects, the research should be treated as illustrative rather than confirmatory.

In the program level research, Some 500 surveys were distributed to the senior program officers in government program management offices in 1996, with 154 providing usable data, yielding a response rate of nearly 31%. Some 300 surveys were distributed to US aerospace industry program managers. 102 surveys provided usable data, yielding a response rate of 34%.

The surveys were part of a study that addressed instability in a comprehensive manner for the first time. As such, it included a variety of questions covering the extent to which a program was affected by instability, what the sources of that instability were, and the strategies the program managers found most effective in avoiding or mitigating the instability. The program-level research identified three primary types of instability faced by aerospace programs: budget or funding instability, instability due to changes in technology, and requirements instability.

In the facility level research, 2123 surveys were distributed in 1999 to the senior facility managers in a stratified random sample of facilities in the airframe, engine, avionics and other key sectors taken from the International Aerospace Directory. Over 100 surveys were returned as bad addresses or facilities that were no longer in the aerospace business (both of which are, at least in part, reflections of instability). Additional follow-up phone calls suggesting that at least 15 percent of the sample should be excluded as not a valid part of the sample. As a result, the 196 usable surveys that were returned probably represent an 11 percent response rate. This research on facilities also focused on three different types of instability: Budget or funding instability, technology instability, instability due to organizational changes such as mergers/acquisitions and other restructuring, and instability in the supply chain.

Although the two projects were conducted independently, there is an important relationship between the two levels of research. The research as the facility level can be seen as operating at a lower, nested level in relation to the research on aerospace programs – which spans many facilities. In this sense, the two projects examine what can be thought of as sub-systems within larger systems. While aerospace may be unique in many respects, both studies indicate that instability is a central characteristic of the socio-technical systems found in this industry – manifest at both levels studies here.

Costs of Instability

Both studies point to substantial costs associated with instability. The program-level study found that, on average, programs experienced 7-8 percent *annual* cost growth (that is, cumulative cost growth of 7-8 percent each year beyond the program plan) from a variety of sources. Program managers then attributed that cost growth to various sources, including budget changes, requirements changes, and technical problems (with the breakdown among types of instability listed in Table 1.) Follow-up interviews with senior program officers confirmed the overall levels of cost growth and their sources, but raised some questions about whether that cost growth could be segregated so cleanly into discrete categories. The point they raised is that interdependencies between funding, requirements, and technical challenges mean that a change in one is likely to affect the others as they are in turn adjusted to return the program to an equilibrium state. Given this uncertainty, it may be reasonable to say that not all program cost-growth is instability-related, but it is realistic to say that a non-trivial component is. This dilemma illustrates very well the interdependencies and stimulus and response nature of instability in complex systems.

Table 1. Average Annual Program Cost Growth and Its Sources.

Source of Program Cost Growth	Government Sample Average Annual Cost Growth (N=101)	Contractor Sample Average Annual Cost Growth (N=80)
Budget or Funding Instability	2.3%	1.8%
Technical Difficulties	2.4%	2.7%
Requirements Changes	2.5%	2.7%
Other	0.1%	0.8%
Total	7.3%	8.0%

The same programs experienced 21-24 percent overall schedule slippage as a result of instability (with Table 2 breaking out the impact across different types of instability). The same caveats apply to parsing this schedule slip into discrete categories as they did to parsing cost growth. The program-level research also documented other costs of instability, including rework associated with creating new plans and contracts, reduction in quantities delivered to meet requirements, and impact on the industrial base through reduction in profits and other factors. A notable finding was that suppliers of critical parts had a much greater risk of deciding to exit the aerospace industry in programs that had high levels of instability than those that did not.

Table 2. Sources of Program Schedule Slip.

Source of Program Schedule Slip	Government Sample Average Schedule Slip (N=76)	Contractor Sample Average Schedule Slip (N=66)
Budget or Funding Instability	8.2%	7.8%
Technical Difficulties	6.3%	5.8%
Requirements Changes	5.0%	3.4%
Other	4.2%	4.0%
Total	23.7%	21.0%
Mean Baseline (months)	85	70

The costs of instability are also evident at the facility level. Among programs experiencing higher levels of instability (for any of the four types of instability examined), Table 3 indicates that approximately 43-56 percent reported an increased loss of people with critical skills. By contrast, only 25-26 percent of the facilities experiencing lower levels of instability reported the same loss of people with critical skills. Note that this finding directly corresponds to the reported loss of suppliers in the program-level research. In each case, a key factor input is at risk as a result of the instability dynamics.

Table 3. Instability and Reported Loss of People with Critical Skills

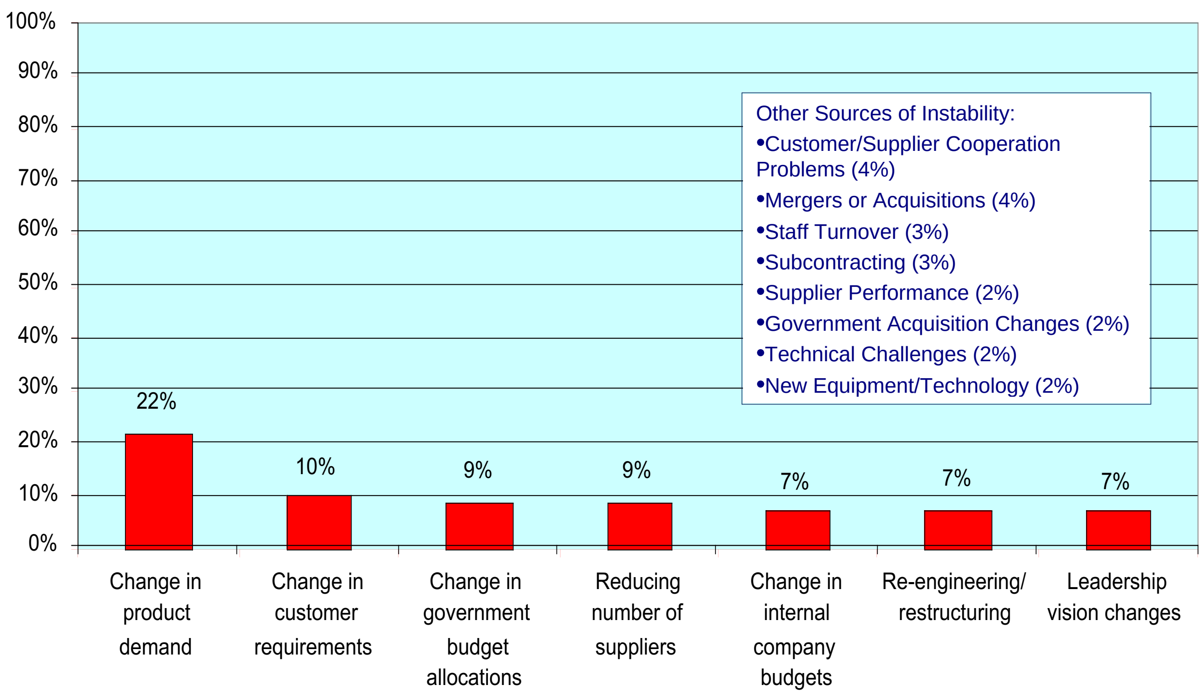
Type of Instability at Facility	Percent of Organizations Reporting a Loss of People with Critical Skills	
	Organizations Reporting Low Levels of Instability	Organizations Reporting High Levels of Instability
Budget or Funding Instability	25%	43%
Instability Associated with New Technology	26%	48%
Organizational Instability	25%	52%
Supply Chain Instability	25%	56%

In summary, program instability represents a significant challenge to the creation and realization of complex systems within the assumptions that prevailed at their commencement. Significant cost growth and schedule slippage may represent mortal threats to programs. The insidious burdens levied by instability also threaten the underlying productive capability required to produce complex systems, whether it involves key factor inputs such as capital or labor or in the technology and supply bases.

Sources of Instability

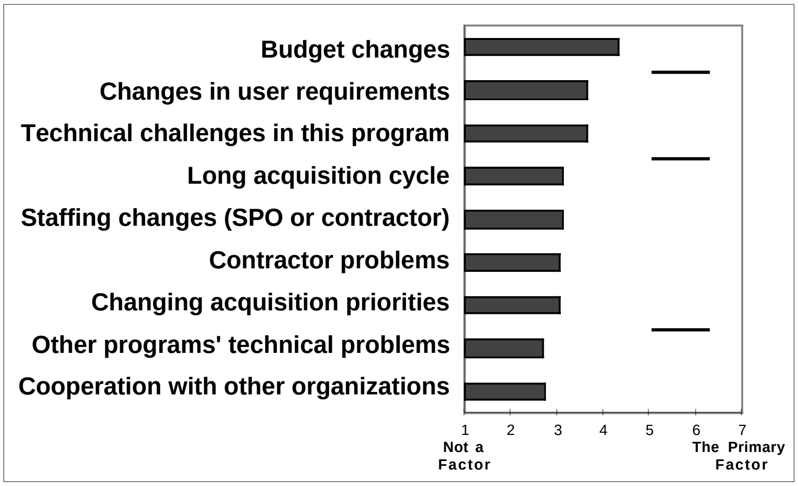
Given the cost of instability in complex systems, it important to try to better understand its sources in hope of ultimately devising effective remedies. Up to this point, we have largely addressed manifestations of instability. In this section we review the data that describes its sources. There was no single dominant source of instability that stood out in the facility level research, as is illustrated in Figure 3. The most common sources of instability facing facilities included: changes in product demand, changes in customer requirements, and changes in government budget allocations, reductions in the number of suppliers (impacting facilities who are suppliers), and changes in company budgets. The first, changes in product demand was cited by 22% of the facilities and the rest were all cited by 9% or fewer of the facilities. This diversity of sources of instability suggests that there will not be any single point solution to this challenge.

Figure 3: Most Significant Sources of Instability at the Facility Level



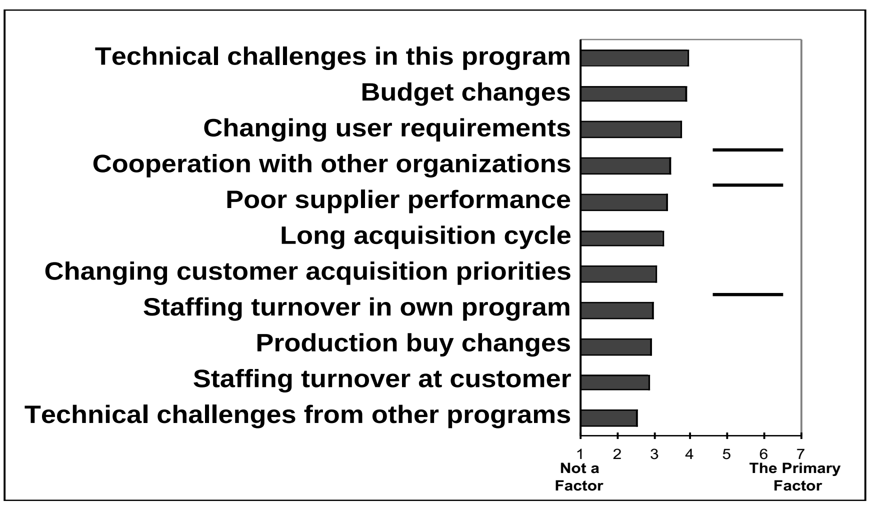
At the program level, the factors causing the greatest instability were similar to those seen at the facility level, including changes in budgets, changes in user requirements and technical challenges associated with the program. This was true for the government program offices and for the contractor organizations. The full set of responses on various sources of program instability is listed in Figures 4 and 5. Similar to the facility survey, there are multiple perceived sources of instability, albeit with lower perceived levels of impact on the program.

Figure 4. Rated Sources of Program Instability (Government).



N= 146. The horizontal lines indicate breakpoints where statistically significant differences in the responses occur (determined using the Wilcoxon non-parametric test at the p=0.05 level of significance).

Figure 5. Rated Sources of Program Instability (Contractor).



N= 98. The horizontal lines indicate breakpoints where statistically significant differences in the responses occur (determined using the Wilcoxon non-parametric test at the p=0.05 level of significance).

A number of factors relating to the acquisition environment and program strategy were examined to determine their impact on perceived instability in a program. While the many program attributes did not explain a significant amount of variance in the perceived effect of instability on a program, there were three attributes that did. They were the total program budget, the program length from start to the planned initial operational capability (IOC) of the system, and the degree to which revolutionary or incremental process technology was required. In other words, the impact of instability is felt most with larger programs, longer running programs, and programs that involve revolutionary process innovations. Among contractors, the level of advance in product technologies, in addition to the others indicated by the government program responses, were associated with higher levels of instability.

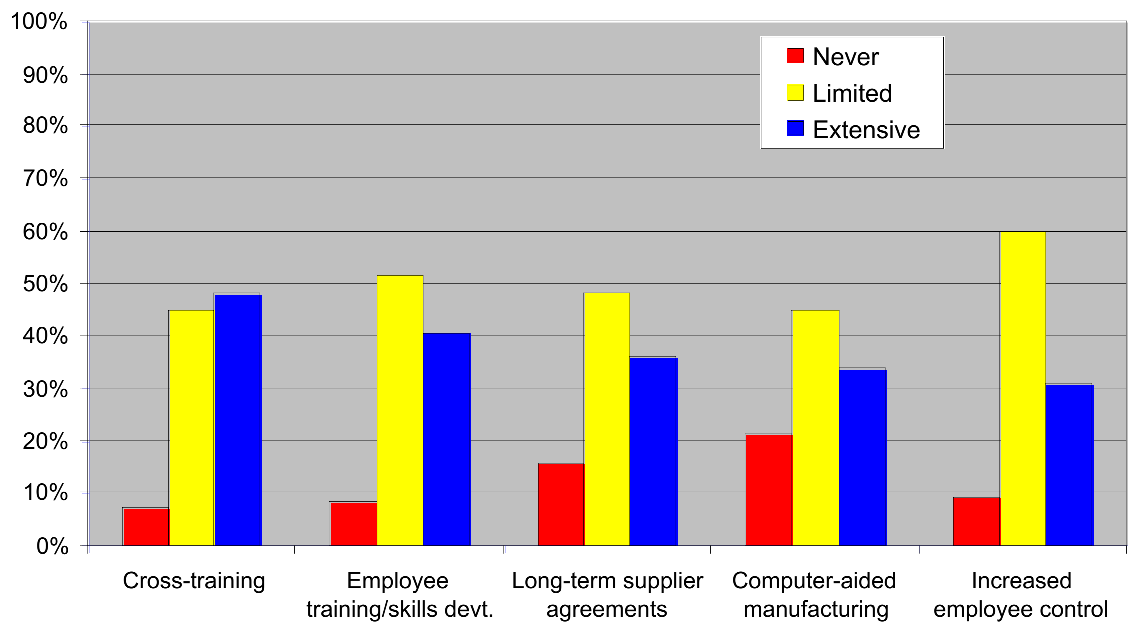
Surprisingly, many of the factors that were anticipated to affect a program's stability were found not to have done so. Specifically, the following attributes of a program were not found to explain any statistically significant variance in perceived program instability: the degree of design uncertainty (including the phase of the program in the system's life-cycle), programmatic complexity (including programs with joint contractors, programs with foreign military sales or international partners, and multiple independent funding sources), perceived priority of the program, or the government service or agency involved. These findings suggest that instability is a larger system phenomenon, with that system being defined beyond the boundaries of the immediate program.

Addressing Instability

As was suggested at the outset of the paper, a traditional response to instability is to build buffers so as to insulate the system or to increase flexibility. At the facility level, such approaches were quite common. The senior facility managers responding to the survey were asked how extensively they utilized each item on a list of 26 management practices, labor strategies or technology tools that might be in use in response to the effects of instability. As

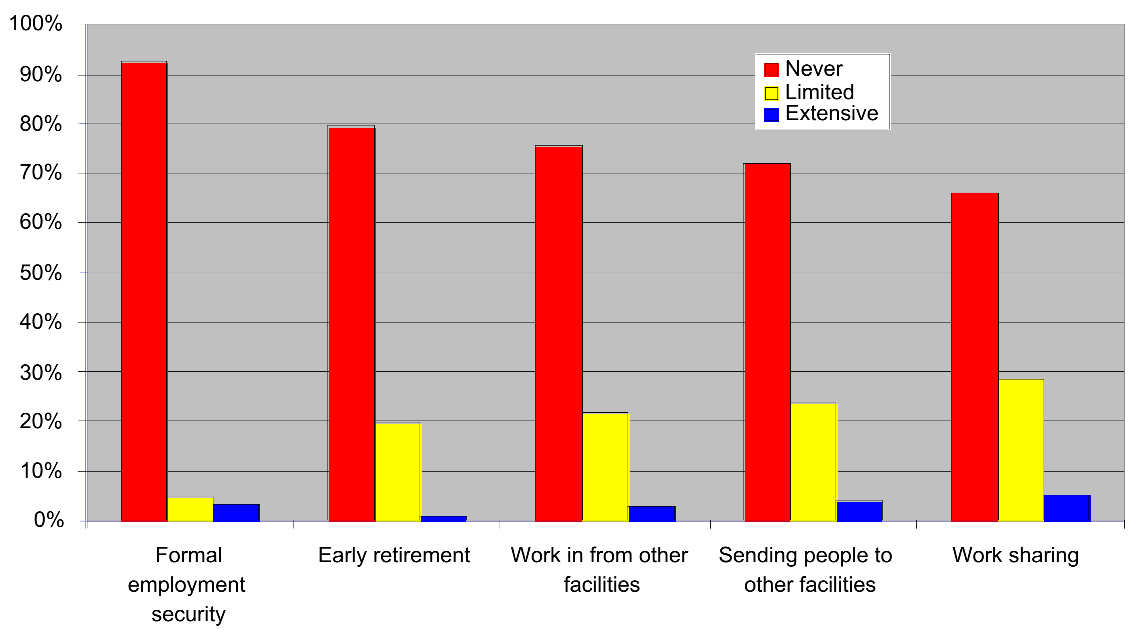
Figure 6 illustrates, the common responses centered on cross training, skills development, flexible technology and employee empowerment. One of the items – long-term supplier agreements – can be understood as renegotiating the boundaries of the system (albeit firmly within the domain of control of the customer facility), but this is the only response that has this quality.

Figure 6. Most Common Facility Responses to Instability



In contrast, the least common responses include a number of items that would require a substantial renegotiation of system boundaries, as is illustrated by Figure 7. These include the movement of work and people across multiple facilities. While the balancing of work and staff across multiple facilities might significantly mitigate the effects of instability, it would require new institutional arrangements among management, labor and communities. Such arrangements do exist in other industries – such as the use of hiring halls in the construction industry or networking organizations in the Silicon Valley – but they are examples of loosely-coupled systems that rely on market mechanisms for coordination and control. These data point to the lack of such mechanisms in aerospace, where system coordination and control mechanisms must necessarily be more tightly coupled. Note too that the respondents were not even asked about mechanisms such as the restructuring of government acquisition policies or other forms of renegotiation that would be far beyond the focus of any given aerospace facility.

Figure 7. Least Common Facility Responses to Instability



The program-level study also examined mechanisms to address instability. In this case, respondents were asked to indicate the effectiveness of strategies to avoid program instability, as well as mitigate its negative impact on their programs. Overall effectiveness was gauged by averages of the ratings for all of the strategies explored. Additionally, the responses of the top quartile of programs (based on program cost performance, in this case those programs that either met or were below their planned program cost) were compared with the rest of the sample to assess whether these higher-performing programs had a different understanding of the effectiveness of program instability responses. Two points are worth noting before reviewing the data.

First, the distinction between instability avoidance and mitigation is subtle but important to understanding the perceived effectiveness of responses. Instability avoidance is a renegotiation strategy aimed at preventing instability in the first place, typically by addressing the program's exogenous environment. Mitigation strategies, in contrast, largely focus on buffers and flexibility in order to take corrective action once instability (in this case considered an exogenous factor) has struck.

Second, what is considered an effective strategy depends on the type of work being done and who is doing it. It is important to bear in mind the differences in concerns and stakeholders for both the government and the contractor when reviewing their responses to instability response strategies. The primary job of government program managers is to coordinate between multiple organizations to define, contract for, and ensure that a system is delivered that conforms with the expectations of all parties. In essence, the government program manager delivers a program (i.e., a product, at a specified cost, delivered on a specified schedule) that conforms as closely as possible to the agreed-to plan. The contractor, on the other hand, is responsible for delivering the system, and is concerned with all the details of realizing that system, from working with suppliers to managing labor relations to developing an appropriate design.

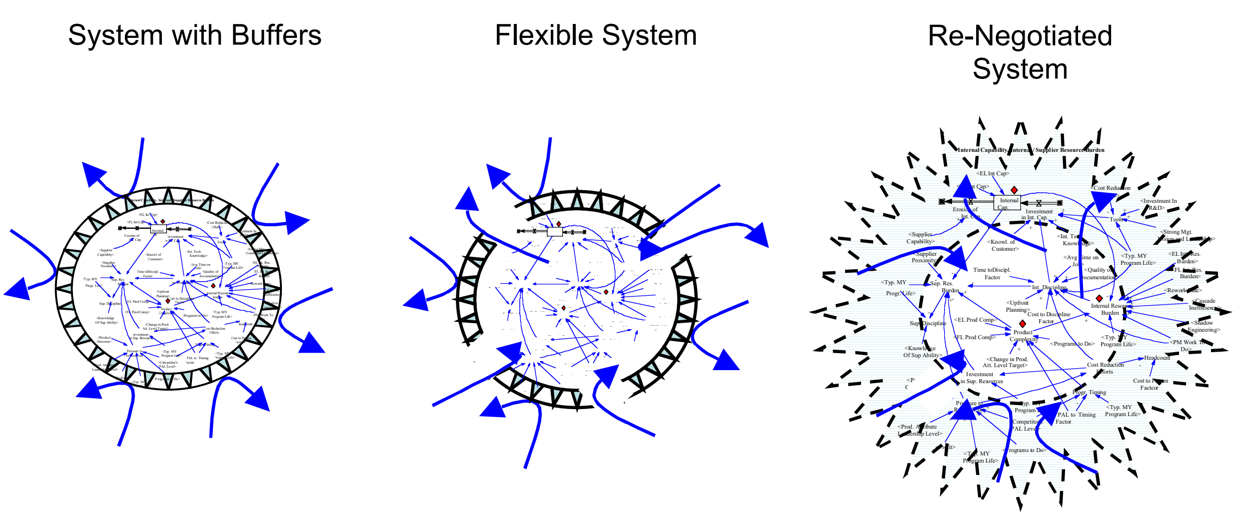
The top-rated program-level instability avoidance for government program managers was having the system's user involved in developing the system's requirements. Also rated high in effectiveness (all equally rated for effectiveness) were aggressive advocacy to generate support for the program, involving the contractor in developing the system's requirements, and involving the contractor in developing schedule. The contractor's response was similar; the top response was open, frequent communication with customer, followed by aggressive advocacy to generate support for the program, involving the contractor in developing the system's requirements, and involving the system's user in developing the system's requirements. Note that in the case of instability avoidance, the strategies considered most effective by contractor and government program managers alike involved reaching out across organization boundaries to involve key stakeholders. Interestingly, the lowest-rated strategies for instability avoidance in general involve what might be considered endogenous program management tools—primarily risk reduction by taking incremental steps in technology or program management hedges.

Top-rated instability mitigation strategies common to both contractors and government program managers include the use of integrated product teams (IPTs) and management reserve. In the mitigation response we begin to see differences between government and contractor priorities. Government program managers also rated as most effective managing all major subsystems within one program office and involving users in program decision-making. This conforms to the primary government role of coordinating inputs from multiple stakeholders. In contrast, contractors rated more highly the use of computer-aided tools for scheduling, modeling, and design. These all represent means to respond flexibly to exogenously-imposed changes while still delivering a product. These same strategies were not valued as highly effective by government program managers for mitigating the effects of program instability.

Interestingly, when one examines the responses of those programs that were in the top quartile for cost performance, a consensus begins to emerge between government and contractor program managers on the top-rated instability mitigation strategies. The highest-performing programs place more emphasis on the ability to flexibly respond to changes (e.g., the use of computer-aided tools for scheduling, modeling, and design) and risk management (e.g., shortening the pace of technological advance, validating designs during system development). The convergence of opinion among these top-performing programs in both government and contractor sites suggests a correlation with the top instability avoidance strategies—developing a shared view of the system and how to respond to perturbations.

Altogether, the three different strategies for addressing instability are summarized in Figure 8. The first is the more traditional approach of building in buffers, where the system is insulated from sources of instability. The second is a flexible approach, where some aspects of instability enter the system and drive adjustment or adaptation. The third is one where the system boundary is expanded so that the sources of instability are incorporated within the definition of the system.

Figure 8. Three Approaches to Instability in Complex Social and Technical Systems



Conclusion

This has been a preliminary exploration of the concept of instability. In complex social and technical systems, instability is both all pervasive and highly problematic. Instability is not the same as variation – it also involves a degree of unpredictability and increasing lack of control.

The survey results suggest that it is difficult, but feasible to highlight factors that act as sources of instability for aerospace facilities and programs. Further, it is possible to identify significant costs that can be attributed, at least in part, to these sources of instability. Finally, an analysis of the reported mechanisms for addressing instability highlights strategies that range from buffers to designed flexibility to the very renegotiation of the system boundaries.

At the heart of this paper is a suggested shift in the engineering mindset when it comes to instability – a shift from seeing instability as a contextual circumstance or a description of system behavior to seeing instability as an appropriate domain for attention and action. Much of traditional engineering systems teaching and practice involves what can be thought of as a "buffering" strategy for addressing instability. This includes incorporating contingency options in program planning, emphasizing "robust" design that essentially consists of adding technical margin, establishing inventory capacity in material flow systems, and other approaches that are focused on a relatively narrow span of control on the part of the system designers. All of these responses are designed to insulate a system from the impact of instability. At the root of this approach is a key underlying assumption in much of systems engineering, which involves establishing system boundaries, optimizing operations within those boundaries, and buffering interactions across the boundaries. In fact, the most common responses to instability at the facility level involved these buffering strategies.

Increasingly, attention to “lean” and “agile” approaches to operations represents movement from a buffer strategy to more of a flexibility strategy. In these cases, for example, a focus on small batches, cycle time improvement and value stream flow all represent ways to minimize the lag between stimulus and response. In this respect, these approaches open up the boundaries on many engineered systems to encompass supply chains, market shifts, and other factors previously treated as exogenous to the system.

Ultimately, the logic of attending to instability involves a focus that goes beyond buffers or even flexible responses. It involves system design that incorporates capability to address the root causes of instability. This involves re-negotiating the very boundaries and definition of the system. We do find evidence of such strategies at the program level, which represents a broader scope than the facility level, though much remains to be learned about the dynamics of such strategies over time.

Anticipating longitudinal research on this topic, there are a number of propositions that we offer as topics for further research on the concept of instability. First, we would suggest that narrowly focused responses to instability can actually increase, rather than mitigate the problem. This is because buffers and flexible responses designed to minimize the impact of instability can hamper the ability to see and understand of root causes.

Complex systems are driven by multiple factors with many interdependent relationships. As such, research on instability should focus on the multiple interdependencies that exist in socio-technical systems. For example, we would predict that attempts to mitigate instabilities by focusing on one variable may actually induce more instability – a dynamic worthy of further research. Efforts to mitigate instability at a "sub-system" level will have limited impact when the source(s) of instability are at the level of the larger system. As well, the impact of instability varies across stakeholders, requiring multiple stakeholder involvement in the mitigation response.

Instability is a longitudinal dynamic phenomenon in which mitigation efforts must consider what can be termed the frequencies and harmonics of the underlying forcing functions, as well as the damping functions if they are to be successful. The research presented here has been based on cross-sectional surveys and targeted case study analysis, which again points to the need for further research attentive to the longitudinal dynamics.

The implications of this paper for Engineering Systems are multifold. MIT has deep expertise in the many buffering strategies and a growing commitment to building expertise in the flexible strategies. There are, however, only beginning areas of exploration around what it take to renegotiate the definition of an engineering system. We highlight this as an essential area for research and education – with deep implications for policy and practice. Ultimately, a deeper appreciation of instability reveals the degree to which stability is never a steady state. As such, continuous improvement in social and technical systems depends on the mastery of strategies for addressing instability.

Partial Endnotes

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[1] We would like to thank MIT's Lean Aerospace Initiative and MIT's Labor Aerospace Research Agenda – both projects supported the survey research presented in this paper.

[2] Murman, et. al., *Lean Enterprise Value: Insights from MIT's Lean Aerospace Initiative.* New York: Palgrave, 2002.

[3] Walton, Richard, Joel Cutcher-Gershenfeld, Robert McKersie, *Strategic Negotiations: A Theory of Change in Labor-Management Relations.* Boston: Harvard Business School Press, 1994.

[4] Deming, W. Edwards. *Out of the Crisis.* Cambridge: MIT CAES, 1986.