Task Group Summary 7

How can we enhance robustness of engineered systems, and how can the methods of engineering analysis be extended to address issues of complexity and management in other fields?

Challenge Summary

The support of policy, industry, or private decisions involving complex, dynamic systems and uncertainty, is a challenge that presents common features across different fields. For example, lifecycle risk management in the automotive, space, and medical device industries involves complex physical systems, organizations, and uncertainties that vary with experience (test results, operational data, etc.). Similarly, the maintenance of the heat shield of the US space shuttle involves the physical characteristics of the tiles as well as human and organizational factors (including errors). The methods of engineering analysis can be extended beyond the realm of engineered systems to address issues of complexity and management in other fields.

For instance, the design and operation of health care systems include both technological and human factors: how can information and incentives best be managed to enable affordable, quality healthcare, given the complex hierarchical domains involved, with levels ranging from clinical practices to the delivery of care and specific organizations? Another example is the management of the Internet, whose structure and interactions with different markets evolve constantly, requiring an understanding of both the network and the complex behaviors of their users.

One common thread is the engineering approach that can be adopted for the design and management of such complex systems, with an emphasis on architecture (structure and functions) and a systematic, coherent treatment of both dynamics and uncertainties. One of the challenges is to build in and preserve robustness and adaptability, accounting for complex interactions among components; for example, to include interfaces and interactions of systems with the medium in which they operate and to anticipate future performance *in situ* (the human body for medical devices, soil/structure interactions, variations of external parameters of space for satellites, etc.). At another level, these interactions include those between the physical system and its operators (pilots, technicians, doctors), and between these operators and the managers who set the incentives and the information base for the people in charge of operations. The goal is to adapt the methods of engineering systems analysis to other types of complex systems (human, climatic, etc.) in order to support policy decisions before full information has been gathered.

Decisions pertaining to the management of design, tests, development and operations can be supported by a combination of systems analysis (static and dynamic), risk analysis and decision analysis. In addition, methods of economic analysis (including for instance, utility theory, principal-agent models and game theory) allow us to evaluate questions such as incentives as well as issues about budget optimization.

Uncertainties are often at the core of the problem. In the context of risk management, one can rely on classical statistics when that information exists and the system is stable enough; but these data are not always available or relevant to all challenges—for instance in the design stage of new devices. Bayesian probabilities are useful to support risk management decisions, in all phases of a device life (design, testing, approval, operation, and retirement). The challenge is to combine the powers of all existing methods to make the best possible use of incomplete information in the management of complex systems, both in industry and in government.

Key Questions

The key question is: how can the methods of engineering analysis of complex systems be extended to other types of systems (human, biological, physical), medical systems (e.g., anesthesia in operating rooms), threats of terrorist attacks, climatic phenomena, etc.? Problems can arise at the interface of engineered systems and the medium in which they operate, or the organizations that manage them. These interactions and the corresponding uncertainties have to be accounted for in a systematic way to support rational decision making. One focus can be the assessment and management of the risks of system failures and/or of reduced levels of performance based on concepts of systems analysis, probability, stochastic processes, and economic analysis.

The challenge to the working group is to come up with engineering strategies to address the fundamental problems of information and decision-making associated with the management of complex systems.

Required Reading

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Suggested Reading

Basole RC, Rouse W. Complexity of service value networks: conceptualization and empirical investigation. *Systems Journal* 2008;47(1):53-70.

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TASK GROUP SUMMARY

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Human beings have long used engineering principles to solve complex problems, but these systems aren't infallible and increasing their robustness is a pressing concern.

With this theme in mind, 11 scientists from different engineering and biological fields met at the 2008 National Academies Keck *Futures Initiative* Conference on Complex Systems to discuss their assigned question: How can we enhance robustness of engineered systems, and how can the methods of engineering analysis be extended to address issues of complexity and management in other fields?

Robustness refers to the ability of a system to preserve itself in response to perturbations. In other words, a robust system is one that can withstand variations with minimal damage or loss of function. Examples are buildings designed to maintain their integrity during an earthquake, power cords with built in surge protectors, and a mammal's ability to maintain a constant internal temperature in different climes.

Specific characteristics generate robustness in a system: redundancy, control systems, distributed robustness, error-correction and hardness. Redundancy is the duplication of critical components that will increase the reliability of a system. Control systems are devices that manage or regulate the system to keep it functioning properly. Distributed robustness means the robustness is spread throughout the system. Any system will fail at its weakest point. Error-correcting systems simply refer to the system's ability to detect and fix errors without perpetuating them. Lastly, hardness means over-designing something to make it stronger. For example, an aircraft that has two engines (with one for back up) is redundant, whereas a bridge designed to remain standing in winds exceeding what engineers expect to see in nature is hardness.

As the Task Group (7) discussed various specific engineering fields and broader aspects of biological systems, an underlying theme arose. Biological systems are inherently robust. Gene flow, genetic drift, natural selection, non-random mating, and mutation (the five mechanisms of evolution) result in the most robust of systems because with living organisms, health and proper function must be the norm.

The group generated questions spanning biology and engineering and clustered them according to common themes. Why are most engineered systems rigid while biologic systems are soft? Which engineering principles for robustness are applicable to human/social systems? And which engineering principles are not found in biologic systems and vice versa?

The group focused on the latter part of the last question, “Which biological systems are not used in engineering?” to address its ultimate question, “What complex biological behaviors or systems can be applied to solve engineering problems and make engineering systems more robust?”

Uncertainty and human error are major problems compromising the robustness of engineering systems. An example would be the maintenance of the heat shield on United States space shuttles, which requires precise engineering as well as human and organizational factors. As we saw in 1993, human error and organizational problems at NASA led to the devastating Challenger explosion. The group began to ponder: Can we engineer a system to adapt and regenerate despite perturbations caused by human error or other uncertainties?

Consider regeneration from a biological perspective. Regeneration, or the replacement of a defective limb, is a terrific example of redundancy in nature. Imagine if engineered systems could adapt to a problem by spontaneously fixing themselves. What if we could engineer a space ship to regenerate broken parts? What if we could somehow manufacture cells that would replace the damaged heat shield in the same way that our skin heals when cut?

Once the group hit on this topic, it began free-associating. Could one apply regeneration to automobiles, robotic space probes (e.g. the Phoenix), and space shuttles? A biologist jumped in: how could we design a house that could repaint itself every other spring or replace the shingles on its roof after storms? Could we design roads and highways that would fill their own potholes?

The Questions Seemed Endless

Having begun the conversation wondering how to apply engineering concepts to biological systems, the group then asked whether understanding of biological systems could enhance the robustness of engineered systems. Engineers have long looked to biology for inspiration. The sleek and efficient body plan of the bottlenose dolphin has been exhaustively studied by submarine designers. Detailed study of the albatross wing aided aircraft manufacturers, and our newest super-computers attempt to incorporate our limited understanding of neural networks to increase processing speed.

Research proposals eluded the group but some felt that the discussions generated enough new ideas for a short perspective that could be published in a scientific journal. The perspective focuses on how engineered systems might learn from biological principles of regeneration to build more complex robust systems. Specifically, they are examining modular components at small scales. For example, using a limited number of building blocks (e.g. 21 amino acids) and using those blocks to build something new (e.g. heat shield on a spacecraft).