

ENGINEERING SYSTEMS MONOGRAPH

FOUNDATIONAL ISSUES IN ENGINEERING SYSTEMS:
A FRAMING PAPER

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INTRODUCTION

In this paper, we discuss foundational issues associated with large-scale, complex engineering systems, such as architecture, uncertainty, flexibility, safety, and sustainability. These issues are discussed in greater detail in the following five papers in this monograph. The goal of this paper is to frame this set of issues. We believe that these issues and related ones merit a new field of study that we call Engineering Systems. We distinguish Engineering Systems from traditional engineering disciplines, such as Mechanical or Electrical Engineering. The latter have flourished since World War II largely by becoming engineering–science disciplines. We also distinguish Engineering Systems from other multi-disciplinary approaches to engineering, such as Operations Research and Systems Engineering.

What pervades Engineering Systems is a mode of thought or a way of thinking about large-scale engineering systems. Examples of large-scale engineering systems are a family of airplanes or a telecommunications system. A key emphasis in the field is on managing change. Large-scale engineering systems tend to change a great deal, especially when we consider long time frames, such as the entire lifetime of the system. Engineering Systems takes a relatively optimistic view of ways of dealing with change. One way of managing change is to consider those aspects of the system that will remain relatively stable. For example, while the overall function of the system may change dramatically over time, its macro-scale architecture may be relatively stable. We believe that this macro-scale architecture can have a large influence on the detailed design and behavior of the engineering system. Thus we would choose architectures that lead to desirable properties in the resulting system, even as it is changing.

There are several other ways of managing change in engineering systems. For one, we may be able to design processes internal to a system that can handle certain changes. A robust temperature control system is an example of such a process that relies on feedback. Some changes are too difficult to be handled in this internal manner, and will require outside intervention by an engineer, for example, often at a point after the system has begun operation. While the future is uncertain, we might nonetheless make it relatively easy to implement responses to many classes of changes. We call engineering systems flexible if they possess built-in options that may be used later when changes in the system's environment force changes in its implementation. Spreadsheet systems that are designed to be customized with relative ease by the end-user are highly flexible in this view.

A particular feature in the Engineering Systems mode of thought is holism. That is, emphasizing the behavior or structure of the whole in contrast to its parts. From a foundational perspective of Engineering Systems, holism lends itself to thinking about appropriate abstractions for describing and analyzing engineering systems as a whole.

A life-cycle perspective pervades the Engineering Systems mode of thought. One usually optimizes the function, performance, and cost of a system for its intended initial use. In Engineering Systems, one is also concerned with these issues over the lifetime of the system, and over the lifetime of the family of related systems.

Much attention is paid in the Engineering Systems mode of thought to certain feedback processes. For example, the organization of an enterprise can influence the architecture of the

systems it designs. Similarly, the architecture of a system can influence the organization of the enterprise. Feedback processes also play a key role in certain important properties of engineering systems, such as safety.

Engineering traditionally involves the design of technical products or systems that satisfy well-defined specifications. Along with the emphasis on managing change, Engineering Systems tends not to have sharp boundaries between the technical system and its environment. While deeply technical issues in components may not be a particular concern of Engineering Systems, Engineering Systems is concerned with the design, manufacturing, and operation of large-scale, complex engineering systems. In addition, the management of the enterprises that perform such design, manufacturing and operational processes is a significant concern in the field. Furthermore, the economic, social and political context in which the engineering systems operate is a significant concern. Sustainability, for example, is particularly important in Engineering Systems and deals with such contextual issues. Engineering Systems practitioners need to be able to understand and appreciate interrelationships in all these spheres, namely the technical, managerial and societal.

This paper is based in part on an earlier overview paper by the Engineering Systems Division Symposium Committee (2002). The remaining papers in this monograph, except for the paper on system safety, are the product of committee deliberations within the Engineering Systems Division over the past eighteen months. These papers are:

Whitney et al., "The Influence of Architecture in Engineering Systems" (2004)

De Neufville et al., "Uncertainty Management for Engineering Systems Planning and Design" (2004)

Allen et al., "Engineering Systems: An Enterprise Perspective" (2004)

Cutcher-Gershenfeld et al., "Sustainability as an Organizing Design Principle for Large-Scale Engineering Systems" (2004)

Leveson et al., "A Systems Theoretic Approach to Safety Engineering" (2004)

1 THE NEED FOR THE EMERGING FIELD OF ENGINEERING SYSTEMS

Since the end of World War II, there have been significant improvements in the practice of engineering. The same can be said of education and research in academic engineering fields. Academic engineering was transformed into engineering science during the beginning of the period and our understanding of the foundations of traditional engineering fields, such as Electrical, Mechanical, Civil and Chemical Engineering, has greatly improved as a result. In addition, relatively new fields were formed in areas such as Materials Science, Communications and Computer Science. Moreover, several interdisciplinary approaches to engineering systems were developed during this time period. These include Operations Research and Systems Engineering. Engineering practice has sometimes led and sometimes followed advances in academic engineering. Yet all was not rosy during the past six decades. In particular, American manufacturing was under severe attack in the 1970s and 1980s from countries such as Japan. Improving the practice of manufacturing required a rather different approach from engineering science's approaches. For example, there needed to be a closer relationship between product design and manufacturing divisions within firms in industry. We learned from companies, such as Toyota, how one could use principles, such as those in lean production (Womack, Jones, and Roos 1990; Roos 2004) in order to improve the quality and reduce the cost of production. Such approaches were not to be found in the physical sciences or mathematics, the foundation fields for engineering science. Nor were they found in engineering science itself, or even in the newly founded interdisciplinary approaches. Understanding these manufacturing issues in academia required an integration of approaches in engineering and management. Teams of people working

in different parts of an enterprise (so-called cross functional teams) were created in order to improve the overall processes that led to the development of successful products and systems.

While the crisis in US manufacturing was recognized two decades ago, there are still related issues that we believe are chronic long-term problems. The products and systems being developed now are growing increasingly complex. They are increasingly difficult to design and manage, delivery schedules are being shortened, rates of change are growing, and globalization is increasing. The confluence of these factors makes design and operation of various large-scale engineering systems increasingly difficult. Industry has led academia in these areas in the past, but the changes we have mentioned have made it increasingly difficult for engineering and management practice to keep up.

Other issues that transcend a single enterprise or even a single industry are extremely important as well, such as sustainability of the environment, homeland security, and maintenance and operation of our various infrastructures. These are very complex issues with engineering systems at their core, and their solutions will involve governments and related organizations, as well as industry and academia. One might argue that the underinvestment and lack of sufficient understanding that has been a chronic problem for our national infrastructures has taken on crisis proportions as a result of September 11 and the recent blackout. We believe that it is important for industry, government, academia and other stakeholders, such as the national academies, to work together to create a new field that we call Engineering Systems to develop a better understanding of the issues surrounding large-scale, complex, technologically enabled systems.

1.1 EXAMPLES OF LARGE-SCALE SYSTEMS

Engineering systems are systems designed by humans having some purpose and are composed of interacting components. Large-scale and complex engineering systems are the ones of most interest to the field of Engineering Systems, although not all large-scale and complex systems are of interest to it. Here we rely on a classification by Magee and De Weck (2002).

The following examples of systems are of interest to Engineering Systems:

- AT&T's national telecommunications network
- Automotive plants of Toyota
- Boeing's 777 aircraft system
- China's Three-Gorges Dam
- Mexico City's transportation/air quality system
- Microsoft's Windows XP operating system

Several of the examples above are infrastructures (e.g., the telecommunication network), or are large-scale nodes in infrastructures (e.g., the dam). Large-scale technological infrastructures are clearly of interest to Engineering Systems. Some engineered products are not necessarily sufficiently complex or of large enough scale to be of interest to Engineering Systems. This is certainly true of products such as a hammer. Some might feel it is even true of relatively complex products such as an automobile. On the other hand, large automobile enterprises have production systems that are certainly of interest to Engineering Systems.

Examples of systems not of direct interest to Engineering Systems would include the four given below. The first example is close to being purely technical. It is appropriate for an engineering science field, but not appropriate for Engineering Systems. The remaining examples lack an engineering system at their core, and are thus also not appropriate for Engineering Systems.

Integrated circuit devices
Human central nervous system
German political system
US Federal Reserve

1.2 THE RELATIONSHIP OF ENGINEERING SYSTEMS TO OTHER ACADEMIC FIELDS

Engineering Systems is an interdisciplinary field, which is related to several existing fields. Engineering Systems as a field is broader in scope than traditional engineering fields, such as Mechanical Engineering or Aeronautical Engineering, since it includes factors, such as management and policy studies. In addition, Engineering Systems is more abstract than traditional engineering fields, since it deals with matters that are common to each of the traditional fields, such as the architecture of large-scale engineering systems. As noted earlier, academic engineering has relied on industry and government agencies to deal with Engineering Systems issues, certainly since World War II, but these issues have become much more complex over time, and academia needs to elucidate the issues at this point at a fundamental level, in cooperation with industry and government.

Engineering Systems is related to other interdisciplinary approaches to engineering, such as Operations Research, Systems Engineering, Technology and Policy, and Management of Engineering. Engineering Systems is broader than Systems Engineering, since Engineering Systems deals with issues such as the sustainability, which involve public policy as well as natural sciences. Engineering Systems is related to Operations Research. There are, however, certain issues, such as system flexibility or safety that Engineering Systems needs to deal with more deeply than has been the case in OR. Engineering Systems is related to several subfields of management, but is closer to engineering considerations than any subfield of management normally is. We think of Engineering Systems as a holistic view of large-scale and complex engineering systems. Hence, Engineering Systems may be viewed as an abstraction relative to the other multidisciplinary approaches to engineering problems mentioned above.

One can summarize the concerns and relationships between Engineering Systems and other issues as in Figure 1 below. Faculty interested in Engineering Systems work in the middle of the three dimensional field, but not at the surfaces. That is, they do not specialize in their Engineering Systems work on purely technologically enabled systems or purely on mathematical or social science methods or purely on enterprise level management issues or on purely societal concerns.

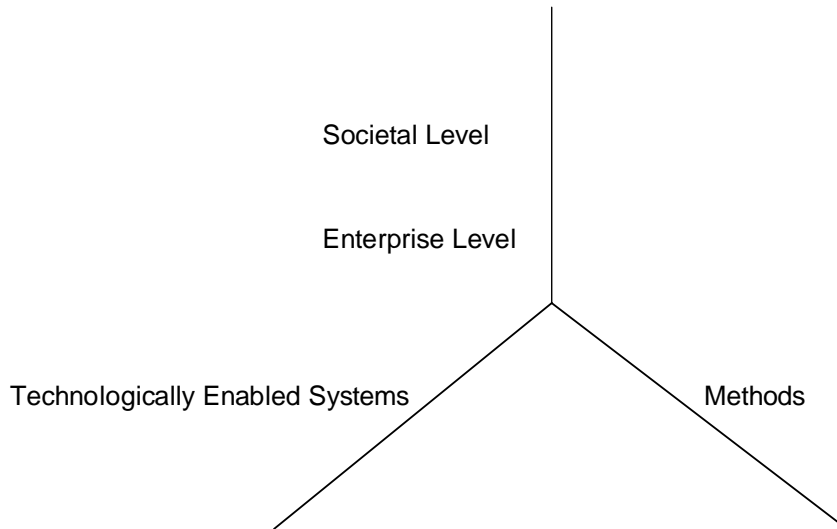


Figure 1

Engineering Systems as a field needs a foundation. Foundations are critical for success in academia in engineering-related fields and in the long run in practice as well. Deep understanding usually arises out of foundational studies, and Engineering Systems needs such deep understanding. We speak of getting at the *essence* of issues as a way to get deep understanding. While important applications of Engineering Systems are a key to the success of this field, they are not sufficient for a vibrant academic field. Some would argue that the path toward foundations requires further study of major applications, such as transportation. We believe that in some cases such studies have already taken place, often in industry, and that what is needed now is to capture the lessons from these studies in an appropriate framework. Foundational issues although abstract are essential to engage in. Much of this paper and the rest of this monograph attempts to explore foundational issues in Engineering Systems. Our goal at this point is not to solve problems but to learn how to state problems so that their essential character is clear, and so we and others can begin the process of solving them.

2 FOUNDATIONAL ISSUES IN ENGINEERING SYSTEMS, ENTERPRISES AND CONTEXT—FIRST DISCUSSION

2.1 ENGINEERING SYSTEMS ISSUES—REDEFINING THE USUAL NOTION OF SYSTEM FUNCTION

Engineers learn at universities, as well as their jobs, how one translates functional specifications into working products or systems. They also attempt to reduce the cost and improve the performance of the resulting products or systems. Much of the time the emphasis on the function, performance and cost of a system is on the moment the system is placed in the end user's hands. Over the years, customers as well as society have placed increasing pressure on engineering enterprises to take a longer-term view. One example is a **life-cycle** view. The car buyer will usually want a car that has high function and performance and good styling at a given price. The triplet of function, performance, and cost are fixed at the moment the customer gets the car. The same customer will also usually want a car that is durable and relatively inexpensive to maintain during its useful life. The government will pressure the automobile company to issue recalls that deal with safety issues during the life of the car, and the automobile company will therefore wish a design that prevents most such issues from arising, or allows most such recall modifications to be made at a low cost. In Germany, it is now required that cars be accepted by

their original manufacturer at the end of their useful life. The goal is to have cars designed so that they can be recycled, rather than scrapped. The life cycle view is also quite clear in the case of aircraft. Airlines and military customers are extending the useful life expectancy of the airplanes they buy. They realize both that the cost of operating and maintaining these complex systems far exceeds the initial purchase cost, and also that they will have to periodically upgrade to reduce performance margins compared with newer aircraft. This situation will likely extend to other systems as life cycles are extended. Thus system properties that arise in a life cycle view include **maintainability** and **sustainability**. These properties become some of the fundamental concerns in Engineering Systems since this field emphasizes the longer-term view of products and systems. The paper by Cutcher-Gershenfeld et al. in this monograph (2004) views sustainability as an organizing principle for essentially all large-scale engineering systems.

Enterprises that develop engineering systems usually recognize that these systems will undergo changes in function and performance over time. One way of mitigating the overall cost required to design a family of related products or systems is to concentrate in aspects of the system that are least likely to change—usually the macro-level architecture of the system. An additional and related way of mitigating the overall cost is to have a flexible design. One example of a system architecture that emphasizes flexibility is that of a platform, such as an automobile platform, that can be the basis of several car models, or a software platform on which many applications can reside. **System architecture** and **flexibility** are core issues in Engineering Systems.

Several issues arise once one begins to make changes to a given system design. Sometimes past changes have created a system in which interconnections or interactions between components are so complex that it is well nigh impossible to make further changes. Such systems are **overly complex**, and learning how to avoid getting into such situations is another fundamental issue in Engineering Systems. Complex systems have properties or behaviors that are sometimes not the intended ones. Such unexpected properties are called **emergent** properties. Emergent properties can in fact be desirable ones in some cases. For example, the Global Positioning System was not initially intended to have consumer applications. Such manifold applications are emergent properties of the system, arising in part by changing its context. Many emergent properties are developed by users of a system (often unbeknown to the system designer). The degree of “openness” or flexibility in the system architecture can inhibit or enhance the likelihood of such innovations occurring.

Managing the evolution of systems in an **uncertain** world is a key goal of Engineering Systems. Predicting the uncertain future is difficult, but to the extent that one can use past events as a guide to designing flexible alternatives or options into a system, the cost of adapting to similar events in the future will be greatly reduced. Viewing uncertainty as an opportunity differentiates Engineering Systems from traditional engineering that is often concerned with reducing risk.

We summarize the discussion above as follows:

1. From the existing engineering science point of view, there are several traditional properties of engineering systems. These include:
 - Function
 - Performance
 - Cost

2. Engineering Systems emphasizes non-traditional properties or goals of systems, often called “ilities.” They usually arise from taking a long-term or life cycle view of systems. These include:
 - Flexibility

- Robustness
 - Scalability
 - Safety
 - Durability
 - Sustainability
 - Reliability
 - Recyclability
 - Maintainability
 - Quality
3. Certain characteristics of systems or their context, which are usually not goals per se, are of great importance to Engineering Systems. These characteristics affect the ease with which traditional or non-traditional properties or goals can be incorporated into systems as they evolve. They also affect how the system can be initially designed and understood. These include:
- Complexity
 - Uncertainty
 - Emergence
 - Systems Architecture

Determining the relationships between goals (traditional and non-traditional) and characteristics is one of the fundamental issues in Engineering Systems. For example, determining the relationship between flexibility and complexity, or flexibility and uncertainty is a fundamental issue. Similarly, determining the relationship or trade-off between flexibility and performance is a fundamental issue.

2.2 ENTERPRISE ISSUES

One of the major lessons learned as a result of the crisis in American manufacturing was that one needed to pay attention to the processes within enterprises that result in products or systems. Traditionally, processes such as design, manufacturing, and marketing had been organized in separate divisions within an enterprise. Using the Lean Enterprise Model (Murman et al. 2002), one instead creates a cross-functional product development team with members from different parts of an enterprise working together on a new product, process or system. Such team structures avoid a problem that was identified in the prior divisional structure of having the design division throw the design “over the wall” to the manufacturing staff, ignoring much of the manufacturing difficulty that may have been created by the design. Such team structures have a substantial effect on the organization of an enterprise, and will be reflected in the products or systems themselves. Of course, the architecture of the product or system is also likely to have an effect on the organizational structure that develops it.

2.3 THE ROLE OF CONTEXT

We have just explored two elements of engineering systems—the product or engineered system itself, and the enterprises that design, produce and operate such systems. Engineering systems are not designed, produced and operated in a vacuum. There are customers of these systems, competing enterprises, societal concerns and governmental policies that also need to be considered. We consider all these factors as part of the context of engineering systems and their enterprises. There are feedback processes between systems and their context. For example, automobiles are impacted by regulations regarding speed and emission limits. Automobiles have also had a long-term effect on the growth of suburbs. Economists usually call contextual factors externalities. Engineering Systems can be said to *internalize the externalities* and make them an integral part of the design process.

Governments not only play a regulatory role, but also are crucially important in fostering certain infrastructures, such as highways. The federal government played a key, active role in the railroad system in the 19th century, in the national highway system in the 1950s, and through the funding of research and development, helped build the Internet. Infrastructures are often the largest systems of their times in terms of size and complexity, and the longest-lived, requiring careful attention to non-traditional systems issues, such as flexibility.

Figure 2 summarizes a simplified view of the relationship between engineering systems, enterprises that design, produce and operate them, and their context. The boundaries between the circles are not sharp, and all three circles are of interest in Engineering Systems.

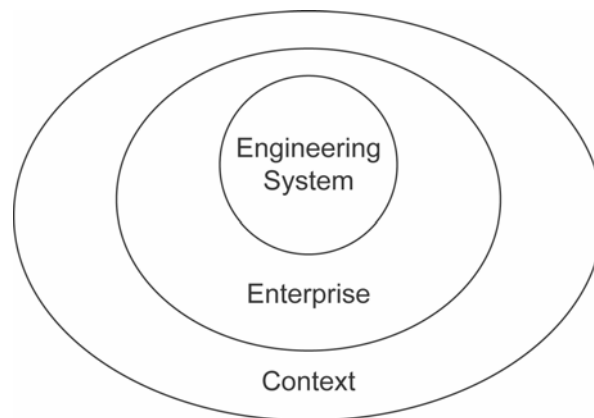


Figure 2

3 FOUNDATIONAL ISSUES IN ENGINEERING SYSTEMS—EXTENDED DISCUSSION

The five papers that follow in this monograph deal with certain Engineering Systems issues in some detail. It is fair to say that each paper approaches an issue or a set of related issues as if it were the central concern of Engineering Systems. Here we will present an overview of the approaches.

3.1 ARCHITECTURE, COMPLEXITY, AND FLEXIBILITY

Architecture, especially the architecture of the highest level of an engineering system, is of great interest to Engineering Systems. In part, this is because the macro-scale architecture is likely to remain stable while the rest of the system, the enterprises that design and operate it, and the context in which it operates change. Architecture also has an impact on both traditional properties, such as function and performance, and non-traditional properties, such as flexibility and maintainability. We believe that a system's architecture will also have an impact on the

complexity of the system, both during its initial design phase, and during the changes that will occur in its lifetime. The architecture of a system also influences the properties that may emerge when the system is fully integrated, and when changes are made to it over time.

Non-traditional system properties are of great interest in Engineering Systems, partly because some of them, such as flexibility and sustainability, have not been sufficiently studied. These properties have become increasingly important in a life-cycle view of systems. Flexibility is one of the most important non-traditional system properties. A system is flexible if it is relatively easy to make certain classes of changes to it. This property is to be distinguished from robustness. A key goal of robustness is to maintain as much as possible of a system's original function as possible when certain classes of changes are made to it. A key goal of flexibility is to make it easier to add new function, or to modify existing function. A human designer, user, or operator presumably makes the changes in a flexible system. One way of measuring flexibility is to simply count the number of distinct paths in the system divided by the number of nodes (Magee and De Weck 2002). The model of a system as connections between nodes or components and paths between such nodes is especially important in information systems, but it is useful in discussions of most infrastructures. A system, such as the telephone system, with a very large number of alternate paths per node, may be both robust and flexible. It is robust because one may be able to get around failing nodes and still maintain most of the original system function. It is flexible because one may be able to add new nodes (e.g., telephones) and connect to existing nodes using alternate paths, and thus increase the original functionality of the system.

Complexity is an issue that is much discussed and defined in various ways by many people (Moses 2002). To simplify, we use the following categories to break down uses of the term:

1. Behavioral complexity—A system is deemed behaviorally complex if its external behavior is difficult to predict. Unfortunately, it does not take much to achieve this state of affairs. Chaotic and thus unpredictable behavior can be achieved with a relatively simple mechanical arm.
2. Interface complexity—A system has a complex interface if it has numerous components, such as knobs and dials, in its interface to humans or to other technical systems. Systems with complex interfaces are usually difficult for humans to operate or successfully integrate with other systems. George Miller wrote a famous paper in psychology called *The Magical Number 7±2* (1956). An interpretation of the paper is that humans are limited in their processing ability to dealing with no more than $7±2$ different things at any one time.
3. Structural complexity—A system is structurally complex if it has numerous components whose interconnection, interaction or interdependence is difficult to describe or understand. Our discussion below will emphasize structural complexity. It is hoped that systems whose structural complexity is reasonably limited will meet the traditional, and some non-traditional, properties and goals without too much difficulty.

Kolmogorov (Li 1997) defined a way of measuring the structural complexity of a system. His definition is that the structural complexity of a system is the length of the shortest description of that system. A key problem with this wonderful measure of complexity is that it is in general difficult to figure out the length of the shortest description. Nevertheless the Kolmogorov measure hints at a key idea, which is the use of abstractions to reduce the length of the description of the structure of a system, and thus its Kolmogorov complexity. The more one can create layers of abstractions, the more likely one is to produce shorter and thus simpler descriptions. Simpler descriptions will lead to systems that are easier for the human mind to understand. Hence the interface view of complexity and the structural view are interrelated. In large part, this is due to the fact that systems are composed of subsystems, and thus have internal interfaces. We note that the mathematics closely related to abstractions is abstract algebra (Magee and De Weck 2002).

Structural complexity moves us to the notion of the architecture of a system. The architecture is a skeleton that connects the components of the system. A skeleton does not fully describe the human body or an engineering system, but it is a necessary and crucial part of the system's description. A platform-based architecture is related to a layered abstraction, with one set of components forming the platform or layer and one set using the platform or layer. Such architectures are examples of the use of standards in design. Information flow in such architectures will involve the use of protocols between components or subsystems.

One could make the assumption that a system's architecture is simply the one that exists when one completes the design of a system. We believe that it is best from a foundational perspective to study the relationships between certain generic architectures (e.g., tree structures, layered structures, networks), their structural complexity and the non-traditional properties of systems, such as flexibility.

We recognize that an emphasis on generic architectures and flexibility will usually result in some loss of performance. One argument for taking such an approach is that it is worthwhile trading some performance for the long-term value of the system properties, such as flexibility. Furthermore, there are cases where the loss in performance may not occur. For example, with the introduction of the RISC architecture for microprocessors, compilers for high-level languages became the preferred option, rather than the performance losing option many assumed they would be when they were first introduced in the 1950s. A key research question in Engineering Systems then becomes determining the trade-offs between basic functional performance and properties such as flexibility. A second key research question lies in the actual relationship between flexibility, generic architectures and structural complexity. Our belief is that some generic architectures will yield large increases in flexibility at the cost of relatively low increases in structural complexity. We also believe that such relationships will vary depending on whether the systems in question are mass/energy-centric or information-centric. In information-centric systems, such as communication systems or large-scale software systems, there is the potential for scaling the size and/or performance of the system by several orders of magnitude. For example, the number of bits being transmitted by optical communication systems has increased by several orders of magnitude in just the past two decades. Such scaling usually leads to a great increase in flexibility. Mass/energy-centric systems have not tended to have such increases in performance. For example, speed improvements in transportation systems of factors of three to ten have been considered revolutionary whenever they occurred in the past several centuries. Whitney discusses some of the differences between information-centric systems and mass/energy-centric systems (2002).

Another concern over our approach to these issues is that in most cases one cannot adopt an ideal architecture due to the existence of legacy systems. The importance and conservative nature of legacy systems should not deter academic research from exploring approaches that are relatively radical. It is useful to know how far a system might be from a relatively ideal solution. Moreover, it is sometimes possible to begin with a relatively new system architecture, and in those cases, it would be extremely useful to know the ideal solutions. On the other hand, since most of engineering practice is with legacy systems, we need to devote much effort to understanding how to comprehend and modify such systems. One key issue is how one designs systems so that it is relatively easy to integrate several of them, even when each component system was built independently of the others. The proper development of standards will likely play an important role in such efforts. Architectures that lend themselves to the integration of components will be important to such efforts.

3.3 UNCERTAINTY, FLEXIBILITY, AND ROBUSTNESS

In many cases the need for flexibility occurs during the process of designing a system, rather than at later stages of the life-cycle. This often occurs because of uncertainty in the initial design. Such uncertainty can occur for various reasons, such as the following:

1. There may be physical uncertainty, such as not knowing what lies underneath the ground one is digging into, or how well new materials will perform
2. There may be funding uncertainty, such as relying on annual appropriations from Congress for certain programs
3. There may be uncertainty regarding the acceptance of the proposed design by various stakeholders, such as the local population in the case of a highway or airport extension

One way of dealing with such uncertainties is to have built-in flexibility in the initial design so that when one is faced with a decision point one can make the various choices at relatively low cost. This is comparable to having an insurance policy for the various choices. Fortunately, the economic theory of “real options” provides the foundation for analyzing the cost of such alternatives (De Neufville 2002; Hastings 2002). There may be some loss relative to an optimal solution due to the provision of the options, but the cost is likely not unbearable. In most such cases the advantage of flexibility in dealing with change likely outweighs the performance loss.

In contrast with robustness, flexibility can be viewed as an active and largely external approach to managing change. Robustness can be viewed as a passive and internal approach to dealing with change. In each case, one can also consider approaches that are particularly suited to different time scales, such as strategy, tactics, and operations. For example, using a thermostat to control temperature is a robust operational approach, and managing a network of suppliers to deal with emerging needs of an enterprise is an example of a flexible strategy.

4 ENTERPRISE ISSUES

As we noted earlier, the organization of the enterprises that design, manufacture and operate engineering systems has an intimate relationship with the systems themselves. The idea of organizing engineers of different specialties into project teams first arose in the US as increasing product complexity required the coordination of knowledge from more than a single specialty. As systems grew in scale and scope and involved still more specialties, and as these specialties changed over time, matrix organization was created to manage the resulting difficulties. The matrix form of organization is therefore a clear result of the needs arising from the development of engineering systems.

Similar products designed by different enterprises may betray something about the structure and culture of the enterprises. The architecture of the product (e.g., a plane) may give a clue to the organization of the enterprise that designed it. The non-traditional properties or “ilities” of the product may give a clue regarding the values prized by the enterprise at the time that the product or system was designed or manufactured. For example, one might argue that Volvo’s automobile architectures are a result of the company’s great interest in safety, since the car collapses in a major accident in such a manner that it is likely to save the lives of the driver and passengers.

We have been purposely using a somewhat vaguely defined word “enterprise,” because modern approaches to engineering systems cross a variety of organizational boundaries. For example, a new airplane is likely to be built by several firms in more than one country. An enterprise could mean a firm, such as Lockheed Martin, or a multi-firm project, such as the F/A-22 fighter plane. In addition, we have learned that large-scale engineering systems need to consider a variety of stakeholders, such as employees, shareholders, customers, suppliers, the local and Federal governments, and the public in discussions of issues such as the environment

5 SAFETY AND SUSTAINABILITY

Some non-traditional properties of Engineering Systems are intellectual fields in their own right. We discuss two such properties in this section, namely safety and sustainability.

An Engineering Systems approach to safety might emphasize the processes used in enterprises, and determine whether these processes can create hazardous situations (Leveson 2002). NASA's shuttle accidents and Mars mission failures appear to indicate safety issues in its management and organization, as well as technical issues in the design, development and operation of NASA's systems. A key management process failure would be when different parts of the organization do not pay sufficient attention to what is being reported or assumed by other parts. Thus one would propose increasing feedback processes within the organization. Since NASA is funded by Congress, one feedback process would involve discussions with Congressional appropriators regarding the safety implications of proposed reductions in mission funding.

Sustainability, at its highest level, asks how economic development can take place that is consistent with environmental and social goals. The Brundtland Commission in 1987 defined sustainable development thus (Marks 2002):

Humanity has the ability to make development sustainable—to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs.

What makes sustainability interesting to Engineering Systems is the extremely long-term view expressed above—that of multiple human generations. Hence what may appear to be small effects over a period of years, such as depletion of certain resources, can become large effects over a period of a century. Furthermore, such a long-term view necessarily involves all three circles in Figure 2, with special emphasis on worldwide effects in the outermost circle.

The concept of sustainability has broadened substantially over the years. It is not simply about the environment or the possible depletion of resources, although these issues remain of fundamental importance. The notion now includes economic growth needed to retain the political and social support for sustainability. Furthermore, equitable sharing of economic gains is at the heart of modern views of sustainability. Sustainability is a holistic, if not overarching goal for engineering systems.

6 SUMMARY

Engineering Systems is an emerging field that deals with large-scale, complex technologically enabled systems. The need for Engineering Systems has grown as a result of the confluence of several factors, especially the growing complexity of engineering systems that are being designed, manufactured or operated at this time. The field of Engineering Systems uses a particular mode of thought about such systems. One of the main goals of the field is to understand how to manage the processes that make it possible to deal successfully with the changes that occur during the lifetime of such systems. One fundamental way of managing change in engineering systems is to understand the relationships of system architecture to properties, such as flexibility, and system characteristics, such as complexity. Flexibility is also used to manage the uncertainty that is always present during the lifetime of engineering systems. Fundamental issues in Engineering Systems include the relationship between traditional system properties, such as performance, non-traditional properties, such as flexibility, and characteristics, such as uncertainty or architecture. Some properties, such as safety and sustainability, are studied in their own right.

Enterprises design, manufacture and operate engineering systems. The field of Engineering Systems is interested in the relationship between the organization of enterprises and their technical systems. Contextual issues, such as the relationship between engineering systems and

economic, political and social spheres, are of interest as well. Practitioners in Engineering Systems need to be able to simultaneously navigate in the technical, managerial and societal spheres.

REFERENCES

- Cutcher-Gershenfeld, J., F. Field, R. Hall, R. Kirchain, D. Marks, K. Oye, and J. Sussman. 2004. Sustainability as an Organizing Design Principle for Large-Scale Engineering Systems. Paper presented at the MIT Engineering Systems Symposium, 29-31 March, at MIT, Cambridge, Mass. <http://esd.mit.edu/symposium/monograph>.
- De Neufville, R., 2002. Architecting/Designing Engineering Systems Using Real Options. Working paper presented at MIT Engineering Systems Division Internal Symposium, 29-30 May, at MIT, Cambridge, Mass. <http://esd.mit.edu/WPS>.
- De Neufville, R., O. de Weck, D. Frey, D. Hastings, R. Larson, D. Simchi-Levi, K. Oye, A. Weigel, R. Welsch, et al. 2004. Uncertainty Management for Engineering Systems Planning and Design. Paper presented at the MIT Engineering Systems Symposium, 29-31 March, at MIT, Cambridge, Mass. <http://esd.mit.edu/symposium/monograph>.
- ESD Symposium Committee. 2002. ESD Symposium Committee Overview: Engineering Systems Research and Practice. Working paper presented at MIT Engineering Systems Division Internal Symposium, 29-30 May, at MIT, Cambridge, Mass. <http://esd.mit.edu/WPS>.
- Hastings, D. 2002. Incorporating Uncertainty into Conceptual Design of Space System Architectures. Working paper presented at MIT Engineering Systems Division Internal Symposium, 29-30 May, at MIT, Cambridge, Mass. <http://esd.mit.edu/WPS>.
- Leveson, N. 2002. A New Accident Model for Engineering Safer Systems. Working paper presented at MIT Engineering Systems Division Internal Symposium, 29-30 May, at MIT, Cambridge, Mass. <http://esd.mit.edu/WPS>.
- Leveson, N., M. Daouk, N. Dulac, K. Marais, et al. 2004. A Systems Theoretic Approach to Safety Engineering. Paper presented at the MIT Engineering Systems Symposium, 29-31 March, at MIT, Cambridge, Mass. <http://esd.mit.edu/symposium/monograph>.
- Li, M., P. Vitanyi. 1997. *An Introduction to Kolmogorov Complexity and Its Applications*. 2nd ed. New York: Springer-Verlag.
- Magee, C. L., O. L. de Weck. 2002. An Attempt at Complex System Classification. Working paper presented at MIT Engineering Systems Division Internal Symposium, 29-30 May, at MIT, Cambridge, Mass. Marks, D. H., 2002. The Evolving Role of Systems Analysis in Process and Methods in Large-Scale Public Socio-Technical Systems. Working paper presented at MIT Engineering Systems Division Internal Symposium, 29-30 May, at MIT, Cambridge, Mass. <http://esd.mit.edu/WPS>.
- Miller, G. 1956. The Magical Number 7 Plus or Minus 2: Some Limits on Our Capacity for Processing Information. *Psychological Review* 63: 81-97
- Moses, J. 2002. The Anatomy of Large Scale Systems. Working paper presented at MIT Engineering Systems Division Internal Symposium, 29-30 May, at MIT, Cambridge, Mass. <http://esd.mit.edu/WPS>.
- Murman, E., T. Allen, K. Bozdogan, J. Cutcher-Gershenfeld, H. McManus, D. Nightingale, E. Rebentisch, et al. 2002. *Lean Enterprise Value: Insights from MIT's Lean Aerospace Initiative*. London: Palgrave.

Roos, D., 2004. Engineering Systems at MIT—The Development of the Engineering Systems Division. Paper presented at the MIT Engineering Systems Symposium, 29-31 March, at MIT, Cambridge, Mass. <http://esd.mit.edu/symposium/monograph>.

Whitney, D. E. 2002. Physical Limits to Modularity. Working paper presented at MIT Engineering Systems Division Internal Symposium, 29-30 May, at MIT, Cambridge, Mass. <http://esd.mit.edu/WPS>.

Whitney, D., O. de Weck, S. Eppinger, C. Magee, J. Moses, W. Seering, J. Schindall, and D. Wallace. 2004. The Influence of Architecture in Engineering Systems. Paper presented at the MIT Engineering Systems Symposium, 29-31 March, at MIT, Cambridge, Mass. <http://esd.mit.edu/symposium/monograph>.

Womack, J. P., D. T. Jones, and Daniel Roos. 1990. *The Machine That Changed the World: The Story of Lean Production*. New York: Rawson Associates.