ENGINEERING SYSTEMS MONOGRAPH

ENGINEERING SYSTEMS: AN ENTERPRISE PERSPECTIVE

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INTRODUCTION

Engineering has, in recent decades, taken on the development of systems of larger and larger scale and increasing complexity. Many examples can be found in transportation, defense, and power generation. Such systems, because of their size and complexity often have human or social considerations that must be accounted for in their design.

This human/social interface creates a set of boundary conditions that are not normally (or easily) considered by the engineering science approach that has dominated education for the past 50 years. This approach, while it has made and continues to make significant contributions to education and practice, is reductionist in nature. As a consequence, it normally ignores or treats as constant the human/social boundary values of many engineering problems. As the systems that engineers are called upon to design grow in scale and complexity, these systems inevitably encounter human, social, political, and managerial interface issues that can no longer be ignored.

The problem of dealing with these interface issues has become of increasing concern to engineering educators and practitioners in recent years. As frequently happens in engineering and in management, practice is leading education in this matter. Engineers designing large-scale systems have been forced to go beyond what they learned in school and take account of these factors in their designs. Educators are now taking cognizance of this and introducing new courses and programs dealing with engineering systems. In order for these new programs to be effective, we must now develop an intellectual basis for understanding the nature of engineering systems. We are presently some distance from that goal.

WHY AN ENTERPRISE PERSPECTIVE?

The interface problems that we have just described are nearly always mediated through some form of enterprise. The enterprise may be an industrial firm, or collaborative set of firms; an agency of government; or even, in some cases, an entire industry. Take for example the Boston Harbor Tunnel project just nearing completion. This $14 billion plus system was designed and built by an enterprise comprising a very large number of private and public entities, from construction firms to city, state, and federal agencies and labor unions. It was these firms and agencies, working together or separately, that mediated the myriad of social and political problems that surround a major system design of this sort. Or take the ensuing competition between the Airbus A380 Super Transport and the Boeing 7E7. The design of both of these airplanes is heavily influenced by the multi-firm, multinational enterprises that are managing the two designs. In return, the design experience, whether successful or unsuccessful, will have a major impact on the two enterprises, the firms involved, and the cultures of those firms.[1]

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[1] We will refrain from further defining “enterprise” at this point. We will use the term in a very broad sense to describe many forms of organized human activity. More specific definitions will become apparent in the examples that we will use. Lest the reader be misled, we will say, at this point, that we are not implying that an enterprise must always consist of several organizations. In some cases, this may be true but in other cases, it may be a single firm or *portion* of a firm.

In order therefore to successfully design and develop large-scale complex engineering systems, engineers must take all of the enterprise issues into account. Such designs are no longer purely technical. In many cases, the enterprise issues are far more difficult than the technical ones to solve; moreover, there must be adaptation on both sides of the relationship between system and enterprise. Given the scale and complexity of engineering systems, enterprises have had to adapt and innovate in order to accomplish their design and implementation. Engineers must be made aware of these adaptations and the causes thereof, both to enable them to better understand many of the organizational situations in which they work and to encourage innovative in the ways they organize for future system designs.

So our purpose in this paper is twofold. We want to sensitize the engineering community to the degree to which their work can be deeply embedded in enterprise issues. This is a fact of which many but not all engineers are well aware, but one that must be repeatedly reemphasized. Second, we want to influence engineering educators to bring these issues into the engineering curriculum, so that we will graduate engineers more fully aware of the complexities of enterprise life and the ways in which these complexities will affect their work. Finally, we argue that the enterprise itself can be looked upon as a system, for which many of the principles of system engineering are applicable.

We obviously cannot, in this short paper, catalog all of the effects of systems and enterprises on each other. So, what we will do is describe a few limited examples of these interactions. Our hope is to give the reader a sense of the nature and magnitude of the effects that engineering systems have had on the ways in which we conduct major enterprises and of the effects that enterprise structure and culture have on system design. In the former, there are lessons for management scientists, sociologists, and students in organizational behavior. In the latter, there are lessons for the system designer, illustrating the degree to which enterprise structure and culture have to be anticipated and provided for in system design and operation.

ENTERPRISE ISSUES IN ENGINEERING SYSTEMS

As we have argued in the last section, there are two broad ways in which engineering systems and the enterprises responsible for them interact. First, there are many enterprise issues that cannot be ignored in system design and implementation. They therefore affect the design of the system. Second, there are system issues that must be taken into account in the management of the enterprise. Enterprise structure and functioning must adapt to the needs of large-scale complex system design. In other words, we must take the nature of the enterprise into account when designing the system, and we must take the nature of the system into account when designing the enterprise. In this paper, we will examine the relations between enterprises and engineering systems and provide some illustrative examples in which these two perspectives were or were not managed properly.

ENTERPRISE EFFECTS ON SYSTEM DESIGN AND IMPLEMENTATION

A wonderful example of the way in which the nature of the enterprise affects system design can be found in the design of the original IBM personal computer. Everyone knows the story of how IBM set up a relatively independent organization in Boca Raton, Fla., to accomplish the design. This was to enable this new business venture to survive without being suffocated by the interests of the rest of the company. What has received far less discussion and credit is the nature of the design. The design was a very open one, allowing the addition of many new features in the form of add-on boards designed and marketed by a wide range of other companies independently of the computer itself. The system had to be designed to accommodate and accomplish this. The add-on boards had few constraints on their design. They had to meet a very limited number of interface specifications, and beyond that they were almost unlimited in the number of features that could be designed into the board. In other words, the add-on boards were “black boxes” that were connected to the main circuitry (motherboard) of the computer. This arrangement minimally affected the computer's functioning while allowing many new features of which the basic design was incapable. The open design enabled a great amount innovation that would probably have not occurred had the entire design been controlled by a single company. This was made possible by a broad enterprise comprising the whole assemblage of IBM and the independent designers and marketers of add-on boards. The design of the computer not only took this possibility into account but enabled it to happen and was in turn improved by it.

There are many other examples in which we find that the nature of the enterprise responsible for development and implementation has a profound effect on the nature of the system being developed. This effect can be beneficial or harmful. The types of enterprise created by Kelly Johnson at Lockheed or by Marcel Dassault, it could be argued, had a very beneficial effect on the complex systems developed in their organizations. On the other hand, both the Challenger and Columbia investigations point to the conclusion that enterprise issues were at least as important as technical issues in leading to system failure in those two instances.

MULTIPLE STAKEHOLDERS

An enterprise perspective on system design makes us aware of the fact that most such designs engage multiple stakeholders. These can range from shareholders to suppliers to members of the workforce to customers to society. What impact can this far-reaching effect have on system design? First of all, stakeholders' interests are not always in alignment. System design may have to take this into account, balancing the interests of the various stakeholders. As a result, the design process is far more complex than one would be led to believe from the engineering science model that we teach to undergraduate engineering students. The best technical solution to a design may very well not be the best overall solution. In fact, it seldom is, and there may not even be a best technical design. Take for example the current F-35 aircraft design. With several customers, each having different missions for this system, the designers cannot optimize the design for any one of the customers' desires. In addition, since recruiting customers in different countries often means engaging suppliers from those countries, adaptations may need to be made in the design to match the capabilities of those suppliers.

The major contractors of the F-22 program (Lockheed Martin, Boeing, Pratt & Whitney) outsource 60-70% of their product by value to thousands of suppliers in almost every state of the United States. When the F-22 program funding was seriously challenged in Congress, the political support generated through these suppliers was a major factor in the final vote. Similarly, in the commercial arena, the choice of international suppliers can significantly influence the likelihood of aircraft purchases. Taking this to an extreme, we have the question of what are labeled "offsets" connected with export sales. Aerospace companies, in order to sell their products, often have to engage in helping potential customers to develop, manufacture or export products that have absolutely nothing to do with aerospace. Wayne (2003), in a New York Times report, describes these as simply bribes in a different guise. But they are necessary to do business in some social systems.

ENTERPRISE CULTURE

Anyone in the business of purchasing or operating large systems, such as aircraft or heavy construction equipment, can testify that the products of different manufacturers differ in significant and predictable ways. This is to a large degree due to differences in the cultures of the enterprises that produce the systems. Culture affects system design through its value system. Different organizational cultures hold to different values. These values are often expressed in terms of what Joel Moses, in the introduction to this monograph, labels “ilities.” Some cultures may stress durability in their products. Others will emphasize flexibility, reliability, maintainability, price, robustness, and so on. In this way, enterprise culture can have a powerful effect on engineering system design.

Several years ago, the French auto manufacturer Renault made an attempt to acquire the Swedish auto firm, Volvo. The deal fell apart, but not from a clash of national cultures. Rather, as hearsay would have it, it was over one of the ilities. Safety is so deeply ingrained in the Volvo culture and designed into their products that any merger or acquisition that did not take this value seriously into account was doomed. Safety is a critical design and marketing feature of Volvo cars. Any change in the priority of this value would profoundly affect the design and marketing of the product.

Challenger and Columbia. Following both of these space shuttle accidents, investigations were made into the cause of the failure of these complex systems. In both cases, the investigations concluded that enterprise issues were at least as responsible as were technical. The Columbia Accident Investigation Board (2003) states very clearly in its report the role it believes the National Aeronautics and Space Administration enterprise played in the space shuttle disaster.

> In the Board’s view, NASA’s organizational culture and structure had as much to do with this accident as the External Tank foam. Organizational culture refers to the values, norms, beliefs, and practices that govern how an institution functions. At the most basic level, organizational culture defines the assumptions that employees make as they carry out their work. It is a powerful force that can persist through reorganizations and the reassignment of key personnel (CAIB 2003, 177).

Digital Equipment Corporation. Edgar Schein (2003), in his recent book on Digital, demonstrates very convincingly that an organizational culture that aided the company immensely in its early days had just the opposite effect in later years. Digital knew its market of technically competent engineers and scientists exceptionally well in its early years and not only structured itself to serve that market but developed a strongly supportive culture. That structure and culture enabled Digital to outstrip its competitors in serving that sophisticated market. When the market environment changed, however, Digital found great difficulty in adapting and was never able to achieve success in the personal computer world, in which the product was sold to relatively unsophisticated businesses and households. When a culture develops to support an enterprise structure, it becomes extremely difficult to adapt since culture has a much greater inertia than organizational structure.

ENTERPRISE STRUCTURE

UK Railways. The way in which an enterprise is organized can also affect system design and operation. When the British government, for example, privatized the nation’s railways, they separated the maintenance and operation of the rights of way from the operation of trains. This has had a strong effect on the way in which the system functions, and some would argue that it has affected rail safety. Following several serious accidents, the arrangement has come under heavy criticism. For example,

> In the aftermath of (a major accident), (a subcontractor) said that it had informed Railtrack (the “owner” of rail right-of-way) nine months earlier that the

> stretch of track needed replacing. But the work was delayed and nobody put a speed restriction on the line. Critics said that debacle revealed flaws in maintenance procedures under privatization, with responsibility blurred between the owner and the contractor (Clark 2003).

The Electrical Transmission Grid. In the wake of the major East Coast blackout of August 2003, many are attributing the cause to the way in which the enterprise is organized and its effect on technical operations. It is still too early to pinpoint exact causes, but it is becoming clear that the origins will neither be purely technological nor purely organizational. The *New York Times* of 24 August 2003 quotes a public policy professor as saying that the cause lies in the fact that the effort to create wholesale electrical power markets has not gone far enough (an enterprise perspective). Others are quoted as saying that the real cause lies in the fact that the transmission grid is now being put to uses for which it was not designed. While the latter explanation may at first glance appear to come from a technical perspective, reflection shows that it is really an interactive perspective. It is the interaction between the way in which the redesign of the enterprise no longer matches well with design of the physical system. In this explanation there is recognition that the engineering system can affect the functioning of the enterprise and vice versa. We can afford to neglect neither.

LIFE-CYCLE COST AND VALUE

Engineering systems are generally very expensive to develop. Beyond that, they are often even more expensive to operate and maintain over their useful life. Due to the high initial investment, operators of such systems hope to extend the useful life of the systems considerably. Witness the life span of aircraft today.[2] Many are approaching 40 or 50 years. This is only possible with the periodic remanufacture and upgrading of aircraft subsystems. The major subsystems of an aircraft have differing rates at which their technologies are advancing. Airframe technology is relatively stable. The technologies of gas turbine engines and the electronics or avionics advance far more rapidly. As a result, an airframe may house several generations of navigational and communication hardware and software over its lifetime. Airframe and engine parts also wear out and must be periodically replaced. This has created an entirely new enterprise dedicated to remanufacture. A system is completely disassembled, worn parts are machined or replaced, and the system is reassembled. This process differs in many ways from initial assembly. It thus requires different management tools and approaches (Lee et al. 2002).[3]

Periodically bringing the most rapidly changing subsystems up to the current state-of-the-art is a very expensive undertaking—primarily because this possibility was not taken into account during the initial aircraft design. Having learned this lesson the hard way, aircraft designers are now recognizing this enterprise need and are working to make initial designs more amenable to periodic upgrade.

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[2] There recently appeared in *Airman* magazine a photograph of a grandfather and grandson standing beside a B-52 airplane, which both of them had piloted.

[3] Just-in-time inventory management, for example, is very difficult to accomplish in remanufacture, since the need for parts is not fully known until the “carcass” is disassembled.

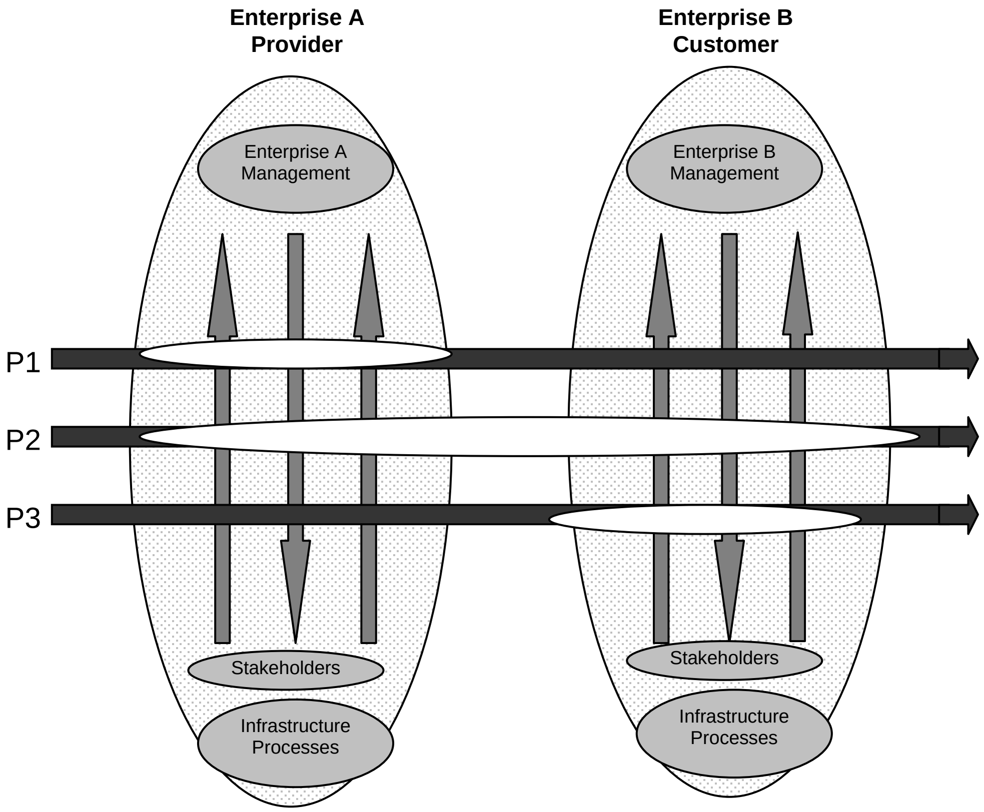

Figure 1: Life-cycle Approach to System Design
Adapted from Murman et al. 2002

Taking a life-cycle approach to system design requires the coordination of effort across multiple enterprises and stakeholders (Murman et al. 2002). In Figure 1's product line 1 (P1), for example, the provider enterprise A takes no interest following delivery to the customer. In contrast, for product line 2 (P2), the value stream extends across both provider and customer enterprises, and both enterprises benefit from concern for the product throughout its life span.[4] In product line 3, the provider is in the business of marketing its maintenance services for the products of other providers. To an increasing degree, engineering-system providers are moving toward the model shown as product line 1. This, of course, has important implications for initial system design. Once again we see the changing nature of the enterprise interacting and affecting system design.

ENTERPRISE ADAPTATIONS FOR ENGINEERING SYSTEM DESIGN

The development and deployment of engineering systems can have a profound effect on the structure and functioning of engineering organizations. New forms of organizational structure have been created for this purpose. Since their development is seldom contained within a single organization, new forms of supplier and co-developer relations have had to be created. Because

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[4] There can often be a very important payoff to the provider enterprise in the form of product improvements. As von Hippel (19) has pointed out, customers can be very innovative and improve or find new applications for systems. The provider that does not give attention to the system after delivery can be closing a very important door and neglecting a very important source of innovation.

they frequently involve high cost and complex scheduling of component and subsystem development, new forms of control and reporting have also been developed. These and many similar issues might also arise with less complex products, but they have attained prominence and attention largely as a result of the development and implementation of engineering systems. Developing a large-scale complex system often requires a complex organizational structure. This has stimulated organizational innovation resulting in entirely new ways of organizing work.

Simpler products can be developed by individuals or groups from single disciplines or sources of knowledge. Lacking in complexity, such products do not need very serious attention to the coordination of effort among the engineers responsible for their development. As products have become more complex and involve many more parts and subsystems, fitting our definition of what we call engineering systems, they require the attention of multiple disciplines. The work of these disciplines must then be carefully coordinated. The need for coordination can be satisfied in part by information systems, but more frequently it is met by the way in which the work is organized. The grouping of engineers into organizational units can either aid or inhibit the task of coordination. For example, the way in which universities and research laboratories have traditionally organized, with disciplines and specialties separated into dedicated departments can make coordination very difficult. For this reason, industry began removing engineers from departmental units and bringing them together in interdisciplinary teams. This project team form of organization brings together in a dedicated unit all of the engineers working on a system development. They report to a single manager as opposed to several department managers and are often located physically close to one another. This eases the task of coordination, which is one of the main difficulties in designing large complex systems

Project and Matrix Organizations. The use of project teams must be as old as the pyramids; however, in mid-twentieth century the formation of interdisciplinary teams in industry was a totally new form of organization. It has since been used in many forms of enterprise from product marketing to movie production. This was the result of a need that first appeared in the development of engineering systems. Interdisciplinary product development teams soon became the dominant form of organization in many industries. Aerospace, heavy construction, and computers were the leaders since most of their products can be classed as engineering systems. It was not very long, however, before a problem arose. The development of even the most complex systems does not continue forever. Developments are completed, and the services of the project team members are no longer needed. These engineers must now be reassigned. The world, however, may have changed considerably over the lifetime of a large-scale system development. There may be new advances or even revolutions in the engineers' disciplines that were not relevant to the engineers' old assignments but will be for any new ones. The engineers may have come to understand the application of their discipline in the context of their product development and focused on that to the exclusion of most new knowledge. As a result, the engineers obsolesced. Now their employers are led to either lay them off or engage in expensive and questionably effective reeducation programs. Of course, the more rapidly that a discipline is changing, the greater this problem becomes.

Worse still, at an organizational level for those enterprises that had engaged too heavily in this form of organization, when the effect is integrated across a substantial portion of their technical staff, the result is an erosion of the technology base. When large portions of the staff obsolesce, the organization obsolesces. This became painfully apparent in the aerospace industry of the late 1950s. At least one innovator (T. Wilson of Boeing) took on this challenge and created what has come to be known as a matrix organization.

Let's back away for a minute and see how the matrix was derived from the needs of complex system development. If the only organizational issue presented by engineering systems development were the need to coordinate the work, grouping engineers together in project teams would be all that need be done. Engineering systems, however, frequently employ technologies that are changing very rapidly. To keep abreast of rapidly changing technologies, engineers must rely very heavily on colleague contact (Allen 1984). In an interdisciplinary project team, the engineer is often isolated from colleagues who share the same discipline. So contact with colleagues in one's own specialty can be difficult.

The matrix organization deals with this dilemma by organizationally connecting the engineer back to the disciplinary department, thereby enhancing colleague contact and discouraging obsolescence. In the matrix, engineers live at least two lives.[5] They have both a departmental "home" and a project team "home." As a consequence, each engineer has more than one manager to whom he reports. Having multiple homes accomplishes two things. The project team home keeps the engineer in contact with the engineers from other disciplines and helps to coordinate his work in the development. The departmental home retains contact with colleagues in the engineer's own discipline and keeps him up to date.

This organization grew out of a need that arose in the development of complex engineering systems. When we describe an engineering system as complex, we are referring to the fact that it comprises a wide variety of subsystems and components and that these subsystems and components are interdependent and interact with one another—thus, the need for coordination among the designers of the subsystems and components. In addition, complex system design often draws upon technologies in which new knowledge is being generated very rapidly—thus, the engineer needs to keep informed regarding these changes. The matrix organization addresses both of these needs simultaneously.

Integrated Product Teams. A system product development team is but a small part of a much larger enterprise. In addition to developing the system, the enterprise must develop specifications based on customer need, maintain abreast of changing customer needs, manufacture the system, and often maintain it after the point of sale. This is certainly true of all products, but the scale of engineering systems can make this more important and more difficult. Just as many engineering disciplines must be brought together in the development process, so the activities of marketing, process development, manufacturing, finance, and other functions must be integrated. Moving a system from the early conceptual phase to the commercial development phase to manufacturing and marketing can be a very difficult and problem-laden process. Those who oversee enterprises have learned that they must manage this process carefully and avoid abrupt transitions. The integrated product team (IPT) was created to avoid abrupt transitions and to integrate knowledge from all of the relevant functions throughout the process of developing, manufacturing and marketing the system. So representatives of the various functions are brought together in IPTs to jointly manage the process from conception to customer delivery. Browning (199_) has shown that the use of IPTs can significantly shorten system development time. The IPT first resulted from the needs of large-scale systems and, as in the case of the matrix, has now found use with less complex products as well.

Project Monitoring and Control. In addition to the organizational responses to system complexity, something remained to be done to manage the scheduling, sequencing, and coordination of activities during system development. Engineering systems are notorious for their accumulation of cost and schedule overruns. To improve sequencing, scheduling, and coordination of subsystem and component development, a number of tools have been developed. These include the program evaluation and review technique (PERT), the critical path method (CPM), and the design structure matrix (DSM) for tracking project developments. These tools were responses to evidence of frequent schedule and cost overruns on engineering system developments and provide means of tracking cost and schedule as the development progresses.

Originally developed for the US Navy's Polaris Missile Program, PERT and CPM provide methods to track the effects of subsystem and component development times on overall project schedule and the consequent cost.

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[5] For a more extensive review of matrix organization for product development, see Allen (2002).

The Design Structure Matrix, while not resulting directly from an engineering system development (Eppinger, et. al., 1994), has proven a particularly valuable tool in the design of complex systems. The DSM maps not only the sequencing of tasks, but more importantly the interdependence among tasks in a development and provides a very powerful way to determine, among other things, the need for forming a project team and for guiding the partitioning of the project into subtasks.

Platform Design and the Restructuring of the Automobile Industry. The introduction of "Platform Design" into automobiles has enabled many mergers and acquisitions and greater centralization of an entire industry. The Lincoln, Jaguar and Thunderbird are built from a single platform, as are the Chevrolet Malibu and Saab (Murman, et. al. 2002). The use of single platforms across what were once separate companies has lowered development costs and enabled many of the mergers that are occurring in that industry.

Emergent Properties. Earlier discussion in this monograph pointed out emergent properties as frequently characterizing engineering systems. These largely unpredictable behaviors often occur within the enterprise as well as within the system itself. Not all of the effects of engineering systems on the enterprise are as predictable or understandable as the needs for new management techniques and strategies. Often an engineering system will display properties or behaviors that were not predicted and completely unanticipated in the initial design. Because of the complexity and scale, the behavior of engineering systems cannot always be perfectly predicted. Such emergent properties are frequently observed in the enterprise that is operating or using the system. Emergent properties can have profound effects on the enterprise. An example of this can be found in a system that was created for airline scheduling.

The Hub and Spoke System for Airline Scheduling. In recent years, the air transport system worldwide has undergone a major transformation. The hub and spoke system of scheduling and routing commercial airline flights has converted many airports into shopping malls. Under this system,[6] flights are scheduled to operate between hubs where passengers are discharged and enabled to board flights connecting to their eventual destinations.[7] Since there is often a time lapse between arrival and departure times, passengers have to spend time in the airport. It wasn't long before a few enterprising restaurateurs saw this as a business opportunity. They were soon followed by usually up-market shops whose management saw a good potential in the swarms of bored affluent passengers. This has proven to be a boon to both the businesses and to the airports that rent them space.

This is what we would call an emergent property of an engineering system. If we consider the airline transportation system as an engineering system, the introduction of hub and spoke scheduling was a major design modification. This then led to the proliferation of airport shops and restaurants and changed the behavior of travelers. Furthermore, it will now make it very difficult to modify the system. If a more economic method of scheduling flights were proposed, one could anticipate considerable resistance not only from the airport businesses but from the airport management. The latter derive a significant portion of their income from the rental of space to the retail shops and restaurants. Thus this emergent property creates a degree of inertia in the system design that was also unanticipated.

The Internet and Spam. As the Internet has grown from its birthday some 15 years ago, a number of emergent properties have appeared. Perhaps the most annoying of these is the heavy traffic in unsolicited messages marketing every kind of product or service from the marginally

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[6] Originally developed for package delivery. This, it might be noted, is a layered system, as discussed by Moses (2004).

[7] The airline industry is changing once again due to the emergence of low-cost airlines that do not rely, to the same degree, on hubs and spokes.

desirable to the downright offensive. The use of the Internet for this so-called spam has grown to such an extent to become a general nuisance, and in the European Union has led to legislation regulating it. Not all emergent properties are negative in their impact. Many unanticipated properties of systems have been beneficial and have led to entirely new uses for the system (von Hippel 1988).

A SYSTEM PERSPECTIVE ON THE ENTERPRISE

Katz and Kahn in their classic *The Social Psychology of Organizations* (1978) describe organizations as open systems with specialized subsystems that resemble physical systems in many ways.

> The open system approach…begins by identifying and mapping the repeated cycles of input, transformation, output, and renewed input which comprise the organizational pattern. This approach to organizations represents the adaptation of work in biology and in the physical sciences by von Bertalanffy (1950) and others.
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> Organizations as a special class of open systems have properties of their own, but they share other properties in common with all open systems. These include the importation of energy from the environment, the throughput or transformation of the imported energy into some product form that is characteristic of the system, the exporting of that product into the environment, and the reenergizing of the system from sources in the environment. (33)

This observation was strongly reinforced by the authors' experience with the Lean Aerospace Initiative. The Lean Aerospace Initiative is a program begun at MIT in the early 1990s initially to transfer the principles of the Toyota production system as described in *The Machine That Changed the World* (Womack et. al. 1990) to aerospace manufacturing. It wasn't long before the investigators engaged in the program realized that to be successful, they would have to range beyond the plant floor and consider the entire complex enterprise (Murman et al. 2002). Moreover, it also became very clear that the lean enterprise is really a system, in itself. To fully understand it, one must take a holistic view, considering in parallel these aspects of the enterprise:

- Processes
- People and Organization
- Information
- Technology
- Products

Nightingale (2003) describes enterprise architecture in terms of these. She, for example, describes four kinds of processes that must be considered.

- Life-cycle Processes: These processes define the product life cycle, from initial conception through design, development, production, and operational support. These are the value-stream activities that contribute directly to the creation of products, systems, or services delivered to the enterprise's customers. These processes reflect the lean view of an overall product life cycle within which functions serve, as opposed to the more traditional paradigm that allows each function to sub-optimize around its own operations.

- Enabling Infrastructure Processes: These support the execution of enterprise leadership and life-cycle processes. The enabling processes provide supporting services to other organizational units that the processes serve as internal customers. Since they enable rather than directly result in enterprise success, they can be easily overlooked.
- Enterprise Leadership Processes: These processes are developed and maintained by leadership to guide the activities of the enterprise. They cut across all of the entities that make up the enterprise. Enterprise leadership provides the direction and resources to break down barriers among and within life-cycle processes in order to create increased value to customers and stakeholders. They also provide the leadership to apply the enabling processes to improve responsiveness to the rest of the enterprise.

Interestingly, Katz and Kahn (1978) labeled these as classes of subsystems, viz., the *production or technical* subsystems (concerned with throughput); *supportive* subsystems (concerned with environmental transactions); *maintenance* subsystems (concerned with maintaining "…the fabric of interdependent behavior necessary for task accomplishment"); and *management* subsystems (concerned with directing, controlling, and coordinating the many subsystems of the enterprise system). From this it is not difficult to see the analogy with the technically enabled large-scale complex systems, which are the focus of the MIT Engineering Systems Division. There are many other points of resemblance that may be pointed out.

Suboptimization. Just as in an engineering system, there can be suboptimization. As in a physical system, in which a subsystem can be optimized to the detriment of the overall system, organizational functions can suboptimize around their operations to the detriment of the enterprise. Organizational units often operate with little regard for other units in the enterprise, just as engineers may introduce changes in a subsystem without regard for its effect on other subsystems.

From an enterprise perspective, there may also be suboptimization across specific programs or product platforms. In aerospace, for example, a specific airframe, engine, or avionics program could optimize its design and operations without regard to its impact on other similar programs. Leadership and setting organizational expectations become key enterprise constructs for optimizing across the entire enterprise.

Standardization. Standardization is another issue, but in this case, it is one that can pay dividends.

> Take for example a major airline, which operates a fleet comprising around twenty-five different models of commercial aircraft. Its customers, the flying public, expect to be transported to their destinations on schedule with a minimum of problems and at a competitive price. It is no small feat to coordinate more than 2,300 flights each day with complicating factors such as connecting flights, weather, airport hub congestion, alliance partner operations, mechanical problems, crew shortages, and so on. Given all this, what are the boundaries of the enterprise involved in delivering value to the traveling customer?
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> Clearly, the airline plays a central role. The supporting infrastructure, including airports and air traffic control, is critical—as travelers are increasingly discovering. The upstream aircraft manufacturer plays an essential role in the airline's enterprise value streams and support capabilities. The product architecture and reliability, for instance, determine how much maintenance and repair infrastructure is needed. If every aircraft platform is a unique design, it

> may provide higher performance, but at the cost of a massive training infrastructure to train all the employees who must work with the diverse product array in the fleet. The same is true for spares inventory and location and, indirectly, for the short-term adaptability of the airline to changes in market demands on specific routes by reassigning aircraft and aircrews. Consequently, the upstream product architecture (and by extension, the upstream enterprise's organizational architecture) can have a significant impact on the downstream enterprise and the creation of value in use of the product. One particular element that stands out is the extent to which the upstream product architecture either enables or inhibits the standardization or streamlining of the downstream enterprise processes and/or infrastructure (Murman et al. 2002].

From this excerpt, we see not only the similarity in functioning between physical systems and enterprise systems but once again the ways in which the design of each can affect the design and functioning of the other. This is particularly important in considering the total life cycle of the system, including support and sustainability issues.

The Need for Integration. As subsystems must be integrated to function in a physical system, structural units in and across enterprises must be integrated to function together as a whole. This was seen in our earlier discussion of matrix organization. There we discussed the difficulty of coordinating across knowledge-based departments. This problem can also manifest itself at higher levels of organization. The functions of marketing, product development, purchasing, and so on have a tendency to act as “silos” with each function acting independently of the others. The necessity of preventing such parochialism is self-evident. Integration is often needed across enterprises as well as among programs within an enterprise. There can be multi-program enterprises and multi-enterprise programs. The latter are common in aerospace and heavy construction.

This discussion could be carried on much further, but the point of seeing the similarity between engineering systems and enterprises has been made. The reader is directed to the works of Murman and his colleagues and of Katz and Kahn for more details and an extended discussion.

CONCLUSION

The chapter is intended to show the clear, almost definitional role of the enterprise in the concept of an engineering system. Attention must be paid to this fact in pursuing both research and education in this new field. The engineer of the twenty-first century must be equipped with an understanding of how enterprises function and the impact that enterprises have on what has formerly been considered purely “technical” design. For this to happen, those in the educational enterprise must direct research efforts toward better understanding the relationships described in this chapter. The results of this research must, of course, be incorporated in the curriculum presented to future engineering students.

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