# Engineering Systems: An Aircraft Perspective

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## Abstract

Engineering has, in recent decades, taken on the development of systems of larger and larger scale with increasing complexity and longer product or system lifetimes. 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 paper will treat aircraft as exemplars of Engineering Systems with the objective of providing a better understanding to help guide research and educational undertakings. The analysis considers a framework comprising three dimensions - Technical, Social and Lifecycle - each composed of substructures which characterize aircraft. An observation is put forth that interrelationships within and between the substructures of these dimensions, and among the dimensions, are critical. With the engineering systems framework in mind, consideration is given to implications for research and educational undertakings in engineering system, illustrated by examples drawn from the authors' recent experience. The preliminary thinking captured in this paper may serve as a useful starting point for deeper analysis and study of aircraft engineering systems, and perhaps other domains.

## Introduction.

Engineering has, in recent decades, taken on the development of systems of larger and larger scale and increasing complexity with lifetimes often exceeding those of the designers. 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 and normally ignores or treats as constant the human/social boundary values of this engineering problem.

This is an issue that has come increasingly to concern engineering educators and practitioners in recent years. In what has become the traditional manner in engineering, 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 a long way from that goal.

In the present paper the authors hope to provide a small step toward understanding engineering systems by examining one type of complex system, an aircraft. Particular emphasis is given to examining the nature of its human/social interfaces at different levels of social and technical complexity. It will be seen how modern aircraft design must be centrally concerned with the human/social aspects, as these often present the most difficult parts of the design problem. After introducing a engineering systems framework illustrated by numerous examples, the paper briefly addresses implications for undertaking research and education initiatives. The authors illustrate how such undertakings differ from those characteristic of engineering science, leading to new models for executing research and new demands on pedagogy.

## Engineering Systems Framework

By almost any measure one would choose to examine, e.g. part count, cost, number of subsystems, product lifetime, etc., aircraft are technically sophisticated, large scale products. Large organizations comprising many functional areas develop and produce aircraft, and they have extended enterprises encompassing thousands of suppliers. Aircraft also have important societal impact, being central to the movement of people and goods and to national defense. Arguably, they also have significant environmental impact at both the community level (noise, emissions) and the global level (emissions, resource consumption). With aircraft lifetimes measured in decades, decisions made early in their product lifecycle have impact for many years. For these reasons, aircraft represent an informative example of an engineering system.

Based on the authors' insights, a framework composed of Technical, Social and Lifecycle dimensions is proposed to characterize engineering systems within the context of aircraft. The dimension representing the **technical** realization of the system is comprised of six levels ranging from individual parts or lines of code to the global environment. The **social** dimension embodies all the stakeholders - from individuals to society - again in six levels. The third dimension called **lifecycle** represents the time axis of the framework, from first concept to final disposal of the aircraft. Lifecycle aspects of both the physical and the social dimensions are important. One might suggest that a dimension representing economics is also needed. However, the technical dimension encompasses cost elements and the social dimension encompasses stakeholder value expectations. Together these represent the important drivers of engineering system economics. It is therefore suggested that aircraft engineering systems can be mapped into this three dimensional Technical-Social-Lifecycle space for analysis.

More important than the sheer scale of these dimensions are the interrelationships - the “inters” - that exist between the dimensions, or between levels within the dimensions.

Interrelationships within the technical dimension are a well known aspect of systems engineering (e.g. see INCOSE 2000) and will not be dwelt upon in this paper. While it would be interesting to examine the interrelationships within the social dimension, that would be a more likely topic for a paper on organizational sociology, per se. In this paper, we are beginning from a base of a complex technical system and examining the interrelationships of the technical and lifecycle aspects with the social world.

An interrelationship is a "mutual or reciprocal relation or relatedness".[1] Interrelationships are many and varied, and might be characterized by:

- Interconnection: "a state of being connected reciprocally" or Interface: "a surface forming a common boundary between adjacent regions, bodies, substances, or phases"
- Interaction: "mutual or reciprocal action or influence"
- Interdependency: "mutual dependence".

The relationship implied by interdependence is stronger than that by an interaction/interface or interconnection. For this reason interdependencies will be our primary, but not sole, focus. It is often suggested that the "inters" are the prime source of complexity in engineering systems[2]. For interesting discussions of complexity, see Sussman (2002) and Mindell (2002).

Another relevant consideration is the relationship between engineering systems and systems engineering. Mindell (2002) addresses this topic in depth. Mindell's paper contends that systems engineering addresses the internal organization and technical dynamics, while engineering systems include the broader societal and social contexts. INCOSE (2000) provides a good discussion of the origins and scope of systems engineering, noting that it is still evolving, and states:

> "Systems engineering is an overarching discipline, providing tradeoffs and integration between system elements to achieve the overall best product and/or service. Although there are some important aspects of project management in the Systems Engineering process, it is still much more of an engineering discipline than a management discipline. It is a very quantitative discipline, involving tradeoff, optimization, selection, and integration of the products of many engineering disciplines."

This characterization support Mindell's distinction between engineering systems and systems engineering. However, it is worth noting that a systems engineering pioneer Simon Ramo stated (Jackson 2000):

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[1] Definitions are from http://www.dictionary.com

[2] Integration is an important topic, as are interrelationships, but not considered further in this paper. Aircraft are highly integrated, both in technical and social metrics. Integrated Product Teams, Integrated Flight Systems, Integrated Databases and other terms such as these abound in the aircraft field.

> "Systems engineering is a branch of engineering that concentrates on the design and application of the whole as distinct from the parts.....looking at a problem in its entirety, taking into account all the facets and all the variables and relating the social to the technical aspects."

The distinctions between systems engineering and engineering systems may be more in how they are practiced and less in how they are defined. Towards the end of this paper we address the topic of stakeholder value and lifecycle value creation. Perhaps the consideration of the number of stakeholders and their value expectations helps to sharpen the distinction between system engineering and engineering systems. In this paper, the authors take the perspective that large scale engineering systems have significant interaction of the social with the technical and lifecycle dimensions, and this is an important aspect of engineering systems.

## Technical Dimension

Aircraft are physical objects, existing in a physical world consisting of matter and information - properties that can be quantified, manipulated, and produced. A typical aircraft has millions of parts and millions of lines of code. Each of these is engineered to perform a needed function so that the aircraft as a whole can fulfill its expected mission - be it civil or military. With several dozen subsystems (fuel, flight control, air data, payload, weapon, ....) aircraft could be characterized as a system of subsystems. But each aircraft is only one engineered system within a larger transportation or defense system, which are often characterized as systems of systems. The technologies embedded in an aircraft span the full range of those found in a major school of engineering. Indeed, the majority of engineers in an aircraft company are not aerospace engineers. Electrical, mechanical, material, computer, civil, chemical, industrial, manufacturing, and other engineering disciplines are all represented in the design, production, and support of aircraft. Aircraft certainly represent an interesting example of an engineering system from a technical viewpoint.

With such a large scale system, it may be helpful to introduce a series of levels representing the scales of the technical dimension·

| | |
|---|---|
| Level 0 | The physical environment of the world |
| Level 1 | The air transportation system (aircraft, airports, air traffic management ...) or the air defense system (aircraft, satellites, missiles, ground stations....) |
| Level 2 | The aircraft and/or related systems (trainers, manufacturing systems, maintenance systems,...) |
| Level 3 | Major aircraft subsystems or subassemblies (radar, flight control, propulsion hydraulic, power, flap, landing gear....) comprised of both hardware and software (e.g. Operational Flight Programs) |

Level 4 Components (pumps, nacelles, control surfaces, LRUs.....) and major software units
Level 5 Parts (fittings, fasteners, turbine blades,.....) and lines of code.

Although presented as a hierarchy in scale, the various levels have some analogy to layers found in software systems. Elements within each level interface directly with the levels above and below. Interface definitions between levels permit some degree of interchangeability of elements within the layer. For example, different models of aircraft can all operate within the air transportation system. An air traffic controller can handle a large jet or a small general aviation aircraft. Or a given aircraft designer is able to choose between multiple engines or hydraulic subsystems. However, the layer analogy may not hold rigorously and it is best to consider the levels as a hybrid hierarchical and layer structure.

Although interrelationships within the technical dimension are not the focus of this paper, a few illustrations are offered for completeness. For example, within Level 3, the wing and engine are interdependent. The engine is dependent upon the wing structure for staying aloft, while the wing is dependent upon the engine thrust for staying aloft. And the performance of each is dependent upon the other through aerodynamic interaction. To continue, the electrical system is dependent upon the engine for generating power, while the engine is dependent upon the power system for operation. There are also interdependencies between levels. For example, the failure of a part at Level 5 can spell disaster at the aircraft Level 2. This was illustrated by loss of Alaska Airlines flight 261 in January 2000 off the coast of Southern California. It is believed that stripped treads on a gimbal nut for a jackscrew in the tail of the MD 80 caused loss of elevator control. A failure to properly lubricate the jackscrew, which was a failure of the interdependent "Maintenance System", resulted in the catastrophe. As another example of interdependence between levels, aircraft propulsion relies on petroleum extracted from the natural environment. But emissions from individual aircraft engines at Level 3, when multiplied by the size of the air transportation system of Level 1 can make a measurable impact on the global environment at Level 0.

## Social Dimension

Large, complex engineering systems almost inevitably interact with humans, individually or collectively. Aircraft are certainly not an exception to this rule. Aircraft are created through the genius of people and the capability of human organizations, and aircraft are operated by, and serve the needs of humans. These human stakeholders play out their roles at different levels of *social* complexity. There are individual designers, operators and users. There are design teams, flight crews and cabin crews. There are organizations that develop, manufacture, operate and support the systems. Finally, there is society which interacts with this type of system in many ways. These stakeholders for aircraft systems are many as shown in Figure 1, and their interests vary widely. In particular, stakeholders have different expectations for the value they will receive from an aircraft - a consideration we will return to later in this paper [3].

As with the physical dimension, it is useful to introduce levels of the social dimension along a scale of social complexity.[4]:

| | |
|---|---|
| Level 0 | Society, nations, communities, etc. |
| Level 1 | Extended multi-organization enterprises including partners and suppliers (could either be extended program enterprise or corporate level multi-program enterprise with several different business units) |
| Level 2 | Single organizations (could be a division or business unit - may have one or more programs, projects, etc.) |
| Level 3 | Organizational units (programs, projects) |
| Level 4 | Working groups (teams, etc.) |
| Level 5 | Individuals |

Moses (2002) discusses the ways by which engineering system are organized, noting three basic forms: hierarchies, networks, and layers. This scheme can be applied equally well to the organizations that produce aircraft systems. In this sense, the levels of aerospace organizations are a hybrid of the first two. A single aircraft program follows a basic hierarchy. However the extended enterprise of suppliers is more of a network. Within a program, an Integrated Product Team is network-like, but the levels within a program represented by a Work Breakdown Structure are certainly hierarchical. A single aircraft program involves thousands of suppliers, hundreds of Integrated Product Teams, tens of thousands of individuals, and many industrial and government organizations. As with the technical dimension, the scale of the social dimensions for aircraft makes them interesting examples of engineering systems.

## Lifecycle Dimension

Aircraft are characterized by long lifecycles that introduce additional factors adding to their interest as candidates for engineering systems studies. The lifecycle begins with conceptual design, progresses through detailed design, and production, testing, into operation, maintenance and eventually to disposal. Many aircraft models re-enter this cycle periodically, with upgrade programs. Both commercial and military aircraft are typically designed for about a 30 year lifetime. But experience shows their lifetimes exceed this design objective. Military fighters such as the F-14, F-15, F-16 and F/A-18 are being programmed for 40 to 50 year lifetimes. Civilian jet transports are experiencing similar lifetimes. 85 percent of Boeing 707 models, first introduced in 1957, are still in service as are 67 percent of DC-8 models, a comparable product (Rubel, 2002). On the

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[3] An interesting discussion of aerospace enterprises and stakeholders can be found in (Nightingale, 2002).

[4] The authors acknowledge Alexis Stanke for thoughtful comments on the social levels

extreme end, the B-52 is now in middle age. It reached its 50th Birthday on April 11, 2002 and is projected to be in service until it is 94! Such long lifetimes point to a number of factors which must be considered when designing engineering aircraft systems. Let us consider two of these: lifecycle costs and the “ilities”.

A rough characterization is that the costs of operating and maintaining an aircraft are about twice the cost of purchase (including financing for civilian aircraft). Civilian and military end users want to minimize total lifecycle costs to provide greater returns on investments. Figure 2 taken from Fabrycky and Blanchard (1991) illustrates that one has the greatest leverage to reduce lifecycle costs at the very beginning of a program. By the end of conceptual design, two-thirds of the lifecycle costs have been determined, even though only a small fraction has yet been realized. And by the time production starts, 80 percent of the lifecycle costs are locked into the product. The ability to affect substantial change in lifecycle costs quickly diminishes with time. Such insights illustrate the important role of the system architect and preliminary designers who make the critical decisions determining lifecycle costs, such as number of engines, types of material, modularity of subsystems, ease of maintenance, etc.. Lifecycle cost represents an important area of research by those dedicated to the study of engineering systems and an important topic to include in engineering systems curriculum

Maintainability, supportability, reliability, flexibility, upgradability are but some of the “ilities” that arise with long lifecycles. Such topics don’t appear in traditional engineering science subjects. They are part of systems engineering and therefore part of engineering systems. In fact, the ilities alone could justify considering the lifecycle dimension as central for engineering systems framework. Consider just one example, the impact of flexibility and upgradeability on an aircraft such as a B-52. It was originally designed as a long range, high flying bomber for delivering nuclear bombs. In the Vietnam War, the B-52 was modified to deliver conventional bombs in controversial carpet bombing sorties. In Afghanistan it provided close air support at the direction of ground troops using the smart Joint Direct Attack Munition. What was originally designed to be the ultimate strategic weapon has now adapted to a very effective tactical role. Such different missions use a B-52 with the same basic airframe and engines, but with totally new offensive and defensive electronics and weapons integration - a combination of flexibility and upgradeability. The example also illustrates the concept of clockspeeds for different technologies (Fine 1999). Airframe technology evolves much more slowly than electronics technology, and engines are somewhere in between. Product design must take this into consideration. Such examples are frequent in aircraft - both civilian and military.

These two illustrations of lifecycle considerations primarily represent factors of the technical dimension which evolve with time. Subsequent sections will provide some illustrations of interrelationships of social factors with the lifecycle dimension.

## Technical/Social Interrelationships

Interrelationships between the physical and social dimensions are critically significant. In fact, these lie at the heart of what many, such as Mindell (2002) would hold out as a defining characteristic of engineering systems. Consider for example the interdependence between the technical architecture and an individual architect such as Kelley Johnson who conceived of aircraft such as the U-2 and SR-71. Rechtin (1991) points out in his book on *Systems Architecting* that the architect must interact with both the technical system and multiple levels of the social system. The architect can only achieve what is possible given the state of technology within the technical dimension. It is interesting that the product architecture itself can influence the social dimension. In the military market, the choice of manufacturers for subsystems and components, largely determined by the modularity of the product, can influence the political support for the program. 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.

Examining the interrelationships across the technical and social dimensions can go a long way in helping us to understand and better develop complex systems. In Table I, we can see a selected set of interrelationships between the two dimensions. This set is far from exhaustive. It serves to illustrate and suggest of the number and kinds of interrelationships that can develop between a complex technical system such as an aircraft and the human/social context in which it operates. It would be interesting to map out which are interactions and which are interdependencies.

**System Components/Individuals.** Consideration of interactions at the level of system components and individual humans is neither new nor proprietary to engineering systems research and analysis. It is the territory of what has been labeled for many years the "man-machine interface" or more recently human centered engineering. Nevertheless, it is an important issue that must be accounted for in the design of engineering systems. One need only consider the fatal crash of the A320 aircraft in Strasbourg in 1992 (Carhart, et. al., 1999) to realize this. The crash is attributed to the misreading of a "Dual Mode" instrument in the aircraft's glass cockpit instrument system. The aircraft was in final approach to landing when the pilots apparently misread the instrument, which could be set to read either glide slope angle or vertical speed. The two modes had very similar formats and the pilots apparently confused them. While the cause of the crash was officially classified as "pilot error" it might better be attributed to a faulty design of the user interface.

**Subsystems/Flight Crews**. Flight crew dynamics have long been known to be a cause of difficulty in operating aircraft. Social psychologists have applied the principles of group dynamics to activities on the flight deck and have had substantial success in developing training programs based on the resultant increased understanding. Richard Hackman (1993) did a very interesting series of studies, in which he flew on the flight deck of several commercial airliners, He, reports on his observations:

> "Anyone who has logged much time watching cockpit crews has experienced both uplifting and depressing feelings. The first officer, who is flying the leg, calls for retraction of the flaps even as the captain's hand is moving toward the lever. The coordination is smooth and seamless. Or the captain, reflecting privately on the deteriorating weather at the destination muses "Probably we ought to take a look at the approach plates for the alternate," and the first officer, without a moment of hesitation responds "Yes I've got them right here…" Watching a great crew operate can be as impressive as watching a superb dance company perform a well-rehearsed ballet.
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> "Watching other crews can make you wish you were somewhere else. The captain's hand moves towards the lever and then stops halfway, waiting, while the first officer pointedly keeps his eyes outside and his mouth shut. After some seconds of awkward silence, the first officer announces, "When I'm ready for flaps I'll call for them." And things go downhill from there. Or when a last-minute runway change results in both pilots, heads down, flipping pages hurriedly to find the new plate while the observer, his eyes alternating between the gauges and the traffic outside, hopes that one of them finds it soon".

These are examples of interaction between level 3 of the technical system and level 4 of the social dimension. These activities may seem to be independent of the technical design and to some degree they are. That design should, to the degree possible, take account of these possibilities and try to create an environment supportive of effective teamwork. This is an instance in which an engineering system perspective and approach to design can potentially yield great benefit. Without a solid understanding of the social/behavioral effects, however, the technical designer is working under a handicap.

Responding to human error and group relations on the flight deck, aircraft designers have incorporated more and more navigational decisions and even approach and landing decisions into the flight control software. So, as flight control software becomes more capable, there develops a design tradeoff over how much of the decision process to automate and how much to leave to humans.

Bowers, et. al., (1993), in an interesting experiment using high fidelity flight simulators, found that for truly critical decisions less automated systems still outperformed more automated ones. These results and analyses of the causes of crashes such as the one in Strasbourg have brought criticism on the degree of automation incorporated into many modern aircraft. Carhart, et. al. (1999) argue that

> "…the plane is so automated that the pilot is for the most part reduced to the role of system manager, programming in flight paths and such, while the computer actually flies the plane. With little to do, pilots become complacent."[5]

This is an important area that warrants further study and one which should help lay out guidelines for software improvement.

Turning from commercial passenger aircraft to military, we find, for at least high performance fighter aircraft, an essential need for an extreme degree of automation. Flying these high performance aircraft is simply beyond the capability of human beings. The plane has to be flown by computer. The human is along to provide computer inputs (functioning in other words as a type of complex sensor) and to perform the few remaining critical decisions. Carried to its extreme, we have the unmanned aerospace vehicle or UAV such as the Predator and Global Hawk which has captured the headlines in recent campaigns in Kosov Afghanistan, Iraq as well as incidences inYemen. Plans go far beyond what we have seen so far, however. Boeing is now testing a far more advanced unpiloted Reconnaissance/Attack Unmanned Combat Aircraft, the X-45, and talks of the eventual production of pilotless cargo aircraft, which would be able to deliver express parcels from New York to Frankfurt with no one aboard.

Here is an effort to deal with a particularly troubling system interface by eliminating it. It would seem, however, that as we eliminate interfaces at higher levels (e.g., Levels 4 and 5) of social complexity, we will not only retain those at lower levels but may indeed complicate them. Eliminating human operators from cargo aircraft will certainly raise concerns at Level 1 (air traffic system) of the technical dimension over the safety of people on the ground and in other aircraft that may be flying at the same time. It will also extend the limits of the engineering system to include an extended ground-based navigational system and ground-based Non-Pilot Operator personnel[6]. The technical interface with Social Levels 4 and 5 may not be entirely eliminated but shifted to a new

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[5] A close colleague, who has flown in the jump seat on transpacific flights, tells us that on such flights the flight crew has little to do but check in by Satcom once per hour.

[6] The potential payoff to this is huge. It is estimated that total unit production cost of an Unmanned Combat Aerospace Vehicle (UCAV) could be 50 percent of a comparable piloted aircraft and the lifecycle cost could be reduced by 75 percent, since it is no longer required to train and maintain proficient pilots.

location and Level 3 difficulties may be increased. It will be interesting to see how this develops.

At a still lower level on both the technical and social dimensions, the Hub and Spoke System of scheduling and routing commercial airline flights (Technical Level 1) has converted many airports into shopping malls (Social Level 1). Under this system,[7] flights are scheduled to fly between hubs where passengers are discharged and enabled to board connecting to their eventual destinations. Since there is often a time lapse between the arrival an departure times, passengers have to spend in the airport. It wasn't long before a few enterprising restaurateurs saw this a business opportunity. They were soon followed by usually up-market shops that saw a good potential market in the swarms of bored affluent passengers, inhabiting hub airports. This has proven to be a boon to both the businesses and to the airports that rent them space.

## Lifecycle/Social Interrelationships

The elements of the social dimension evolve with time leading to lifecycle/social interrelationships. One interesting example is knowledge management, an area of high current interest due to loss of employees through retirements and downsizing. Capturing and retaining knowledge pertinent to a particular aircraft over a lifecycle span of several human generations is a major challenge. For engineered products whose lifecycle is comparable to the design cycle (e.g. personal computers), knowledge is generated and refreshed in an ongoing fashion. Most engineers look forward to working on a program for several years and then advancing to their next career opportunity. But when the product lives on beyond the original designers or manufacturers, critical knowledge may be lost. With the wave of consolidations and mergers in the aerospace industry during the 1990s, a number of organizations started knowledge management activities. Most of these rely on electronic information systems to capture and categorize the knowledge residing in higher levels of the social dimension. The success of these is still to be determined.

One approach which accomplishes the re-generation, capture and transfer of knowledge is the use of product upgrades. The F-16 program began in the early 1970's and went into production in 1977 with the A/B models. Since then, there have been nine major upgrades, each incorporating many new features. The knowledge embedded in the current F-16 team at Lockheed Martin is excellent (Stanke, 2002). A similar process occurs with commercial aircraft products. The Boeing 737 was designed in the 1960's. There have been two major upgrades with the 737-300/400/500 and 737-600/700/800/900 series. Currently the 737 program is undergoing major production changes with the incorporation of lean practices, including transition to a moving production line. Whatever the strategy,

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[7] Originally developed for package delivery.

capture and retention of engineering knowledge about a particular aircraft system becomes an important consideration when lifecycles are long.

As another example representing an interrelationship at the lower level of the social dimension, products with lifecycle of many generations need to be robust to changes in society's attitudes and values which generally evolve over time scales measured in generations. A good example of this for aircraft falls in the environmental area. The early generations of jet transports had low bypass ratio jet engines which by and large were very noisy by today’s standards. Although such aircraft as the DC 9 and B-727 are still fit for operation, they simply don’t meet today’s Stage III noise regulations. The fix has been to install after market hush-kits to quiet the engines. However, these products are doomed to disappearance from many countries because society will no long accept the impact on their community environment. New generations of aircraft must meet increasingly stringent community noise standards which have led to a reduction of 10 dB since 1980 and will need to have an additional 6 dB reduction by 2020.

As a final example, consider the effect of individual hijackers or small groups of terrorists on aircraft design and operation. D.B. Cooper’s hi-jacking of a B-727 on November 24, 1971 made rear exit ramps obsolete. Subsequent hijackings led to the need for the extensive and expensive airport security systems the traveling public is all too familiar with. And the terrorist incidents of September 11, 2001 turned commercial airliners into cruise missiles. This is leading to design changes and upgrades to cockpit access and other features of commercial aircraft. And it may well lead to a new balance between large scheduled carrier jet transport and smaller charter or fractional ownership business jets. The lessons learned from these examples indicate that engineering systems architects and designers need to understand the “expectations” of people who seek to undermine society as well as the intended users of the products.

## Product Development

Product design and development is certainly the aspect of engineering systems where the human/social interface is, in many ways, strongest. At an individual level (Level 5) there are the issues of creativity, problem solving, personnel selection, motivation and rewards and many other aspects that are for the most part not peculiar to engineering systems. It is much more at levels 2 and 3 of both the technical and social dimensions that engineering systems have a different effect on product development. As size and complexity grow so too does management difficulty and complexity in organizing. We are no longer dealing with individuals, as individuals. The important social entity now is the group or the group of groups that we call an organization. The needs of engineering system developments have stimulated innovation in organizational structure. It was the development of an engineering system in aerospace that produced the first matrix organization, for example. So what are the characteristics of engineering systems that have the greatest effect on organizational structure? One is certainly the high degree of interdependence inherent in their architecture. Another is the degree of interfunctional relations that are inherent in large scale aerospace system development. A third is the difficulty that is often encountered in transferring large systems such as aircraft from product development and into manufacturing. Let us first focus on two of these issues together, viz, architectural interdependence and interfunctional interdependence. However we note that major improvement have been realized in the third area through the use of integrated product teams described below. An effective way to bring knowledge about "downstream activities" such as manufacturing and operations into the early design decisions is to include experts from these domains on the engineering design teams. This illustrates the social interrelationship with the lifecycle and technical dimensions.

The form of group that is most important in product development is the project team. Both of these lead to a requirement that development work be done in teams or groups. These are generally labeled "project teams". A project team is a group of individuals, mostly engineers, working together to develop a new product, in this case an airplane. The total project team can be very large and comprise many smaller groups or teams. The smaller groups are often projects, in themselves, each working to develop some element or subsystem in the aircraft. Since interdependence among the subsystems (fuselage, wing, navigational subsystem, communication subsystem, flight deck, etc.) is very high, the work of the various subgroups is also very interdependent. Therefore, if these groups are left to reside in separate departments, coordination among them becomes very difficult, leading to interface problems, errors in design and so on. For this reason, the project team form of management was developed. It soon turned out that the project team presented a different set of difficulties. Engineers became too focused on a particular product development and tended to lose sight of new developments in their specialty beyond their particular project. They needed to have greater contact with their disciplinary colleagues back in their "home" department. Thus was born the matrix organization. It first appeared in the aerospace industry, largely due to the complex nature of the engineering systems that industry develops (Cf. Allen, 1986).

At the outset, a single individual, the project manager or program manager, managed the project side of matrix organizations. This is where budget responsibility usually lay and where the responsibility for coordination across engineering departments also resided. While this could be made to work within the product development or system development function, it contributed little to managing relations with other functions such as marketing and manufacturing. To address this issue, companies began to create a joint program management function in which managers from more than one function shared project responsibility. Motorola was one of the first to adopt this scheme by giving joint responsibility for developing a product to a pair of managers, one from product development, the other from marketing. This later expanded to become what are now called "integrated product teams", or IPTs, which include managers from engineering, manufacturing, tooling, marketing and other functions. The next step in this development was to extend the IPT to include all of the design engineers and others who would be involved in the development and manufacture of the system. Such teams were then created at both the system and subsystem levels, resulting in a layered hierarchy of Integrated Project Teams. Browning (1996) provides data that makes a strong argument for the effectiveness of IPTs operating at different levels, e.g. subsystem project teams, system level teams and program level teams (corresponding to Levels 4 and 5 in our structure). IPTs can perform an effective integrating function within the organization, provided there is a full commitment and participation on the part of all members. The difficulty often sets in when team members are too distracted by or overly committed to activities within their specialized functions.

It is very important to remember that it is the very nature of large, complex engineering systems that forced the creation of all of these organizational innovations for use in their development[8]. Simpler developments, involving fewer technologies and smaller engineering teams just do not warrant or need the degree of organizational complexity described here. It wasn't until engineering encountered the difficulties of large scale architectural interdependencies and the resulting need for close coordination across many dynamic technologies that such organizations had to be created.

Another organizational area that is affected by engineering systems development is that of supply chains. While suppliers of parts, components and entire subsystems are needed for even the simplest of projects, the scale and complexity of engineering systems certainly increases the need for and dependence upon suppliers (Fine, 1999). Vertical integration back along the supply chain is possible but with the diversity of requirements in a large complex system it becomes very difficult and possibly undesirable to attain. Ford Motor Company, in fact, recently devolved by spinning off their parts division as a separate company. (Henry Ford must have rolled over in his grave.) With the growth in size and complexity and investment requirements, aircraft manufacturers have confronted a need for greatly increased reliance on suppliers for even very large subassemblies (fuselage sections, empennage, etc.) and entire subsystems (electrical system, hydraulic system, flight control system, etc.). Suppliers are now being integrated into customer IPTs. This is to provide early information to both customer and supplier. Once again, we see the complex needs of engineering system development fostering creativity in organizational design.

Engineering System development, particularly in aerospace, is responsible for a host of other management innovations. PERT and the Critical Path Method of project scheduling and monitoring are obvious examples. The complex requirements of developing such large complex systems pushed beyond existing managerial knowledge and capabilities and forced innovation. Many of these innovations are now diffused widely, to the general

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[8] Some of these, such as matrix have been applied much more broadly beyond system development, with at best mixed results.

benefit of other industries and firms. This is a contribution stemming from the development of engineering systems that is largely unrecognized.

## Implications for Engineering Systems Research

(Note: This section is a draft. It has to be expanded and tightened up)

By its very nature, the study of engineering systems must be holistic. If it is to contribute meaningful insight to theory and codification, research needs to address many interrelated social, technical and lifecycle issues. Yet multidisciplinary research at such a holistic level is difficult, particularly in an academic environment optimized for reductionist thinking.

The 1997 Aero-Astro strategic plan identified a seven level hierarchy of knowledge: starting with observation, proceeding through classification, to abstraction, quantification and measurement, symbolic representation, symbolic manipulation, and finally prediction. Engineering systems as a field would currently fall towards the lower end of this scale, implying research will be more observational than symbolic in nature. For the intellectual foundations to be grounded in reality, observations must be made of real engineering systems, with all their complexities. Variables are not under the control of the researcher, it is difficult to study enough systems to generalize results, the systems studied may be in different phases of evolution, etc.. In general, engineers are more used to laboratory and theory research than studying real systems, adding another challenge.

The first two challenges, holism and the study of real engineering systems, lead to a third challenge, namely the laboratory for engineering systems research is the real world - off-campus in the industries and government agencies that own the systems under study. This introduces challenges of dealing with multiple stakeholders, high costs for coordination and travel, developing relationships of mutual trust and respect, dealing with proprietary information, etc..

In the past decade, the authors have participated in a very large scale research project known as the Lean Aerospace Initiative (LAI)[9]. LAI is a consortium of numerous aerospace industry and government organizations teamed with labor and academic groups. Consortium activities span the spectrum from scholarly research to implementation of lean practices and principles in large scale aerospace projects. LAI addressed the challenges outlined above through its organization structure including multi-stakeholder teams, alliances between engineering and management faculty, creation of a closed circle of knowledge transfer within a learning community, and by establishing protocols and instruction for executing real world research. Over eighty masters and doctoral theses have been completed which, together with additional research, have produced over 200 papers and one book (Murman, Allen, et al 2002). However these accomplishments have

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[9] http://web.mit.edu/lean

been difficult to achieve and the final paper will provide more insight from LAI lessons learned.

We briefly describe findings from a select few of these research projects to illustrate some of the knowledge gained from LAI about engineering systems. The projects expected to be included in the final paper are:

Bozdogan and Deyst studied two program where suppliers were fully and integrated into the engineering design team early in the design cycle. Their findings included that the detail product architecture was changed by early supplier integration, there was a 25% reduction in the product development time, a 40-60% cost avoidance, and superior product quality.

Dare (2003) studied how collaboration among multiple stakeholders (end user, customer, developer) can lead to effective adaptation of information intensive systems during the design phase through the use of a “systems representation” (prototype, beta release, etc..). Factors enabling adaptive design and knowledge sharing were identified from 8 case studies. The evidence of complex adaptive system elements to stakeholder collaboration was also studied.

Nuffort (2001) thesis (1) explored the benefits and costs of increased subsystem commonality in the aerospace industry, (2) addressed when it is appropriate, and (3) examined the organizational structures necessary to achieve greater commonality. The analysis drew on eight case studies of both commercial and military aerospace organizations to address the three primary research topics from a total life cycle perspective. Product acquisition cost reductions of 15-40% and annual operation and support costs of 25-40% have been realized by subsystem commonality. Some of the biggest barriers to realizing these cost arise from the social dimension of the engineering systems framework.

Stanke (2001) studied four aircraft programs (F-16, F/A-18E/F, B-777, Saab JAS 39) to gain understanding of effective processes for achieving best lifecycle value. Findings revealed a combination of system engineering and program management practices well aligned with those representing lean principles and practices were evidenced in all four programs. A framework for life cycle value creation was developed in parallel with the authors of the LAI book (Murman, Allen et all 2002) as displayed in Figure 1. The value creation framework is finding application in education and practice.

## Implications for Engineering Systems Education

(Note: This section is a draft. It has to be expanded and tightened up)

In developing aircraft engineering system courses, educators face challenges in content and pedagogy that differ from disciplinary subjects in the engineering science domains. Challenges are closer to those found in capstone design courses, but are more extensive. The content challenges can be summarized as;

- Treating a wide range of technical disciplines and technologies
- Addressing a hierarchy of system/subsystems and their interactions, ranging from the air transportation or air defense system (Level 1) at least through major subsystems such as flight control, propulsion, landing gears, etc. (Level 3).
- Covering the entire lifecycle from conceptual design through operations.
- Including process related topics such as system engineering and lean practices.
- Encompassing knowledge from domains such as economics and finance, political and regulatory factors, management and labor relations, market analysis, etc..

Pedagogical challenges include:

- Addressing the synthesis and design of highly complex systems.
- Developing student assignments encompassing substantive learning.
- Lack of textbooks and other codified knowledge sources.
- Dealing with "real systems" rather than imperfect abstractions.
- Addressing learning objectives for a wide range of topics

Brief summary will be given of several recent offerings in the Aero-Astro Department

- CDIO (Conceive-Design-Implement-Operate) is a comprehensive restructuring of the undergraduate curriculum to center in in the context of the product lifecycle. Traditional engineering disciplines are taught, but with a new pedagogy involving the three dimensional framework introduced in this paper.
- *Aircraft Systems Engineering* is a graduate subject addressing the entire aircraft system including: system level requirements, performance, weight, cost, safety; subsystems and their interfaces; testing and certification, lifecycle issues, risk management; systems engineering and program management. A teaching approach borrowed from architecture called "retrospective analysis" is used. Student teams undertake a semester long case study of an existing aircraft to understand the systems aspects and key design drivers.
- *Air Transportation Systems Architecting* is a sequel graduate subject addressing the conceptual design of a realistic system taking into account all relevant aspects; technical, economic, market, political, social, etc.. A semester long conceptual design study is undertaken by the class leading to a business case and systems

requirements statement. Examples include the large jet transport, a supersonic business jet, and next generation cargo systems.

## Summary

A three-dimensional engineering systems framework based on technical, social and lifecycle factors has been introduced in this paper. It seems clear that technical and lifecycle dimensions are important to engineering systems. To the authors, it also seems clear that social issues are important. More important than the individual dimensions and their substructure are the interrelationships that occur within and between them. Numerous examples have been cited to support these contentions. Both research and pedagogy for engineering systems are significantly more challenging that those of classical engineering sciences approaches. While the latter is based upon a reductionist approach, the former requires a holistic one. Examples drawn from the authors' undertakings illustrate strategies and outcomes for engineering systems research and teaching.

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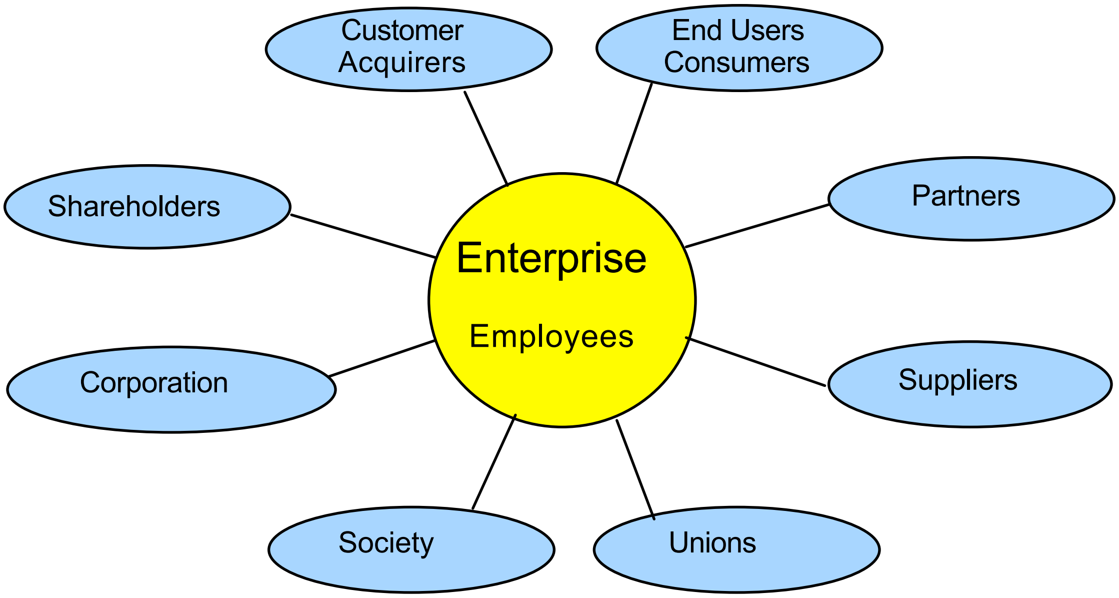

Figure 1 - Aircraft Enterprise Stakeholders (Murman, et.al, 2002)

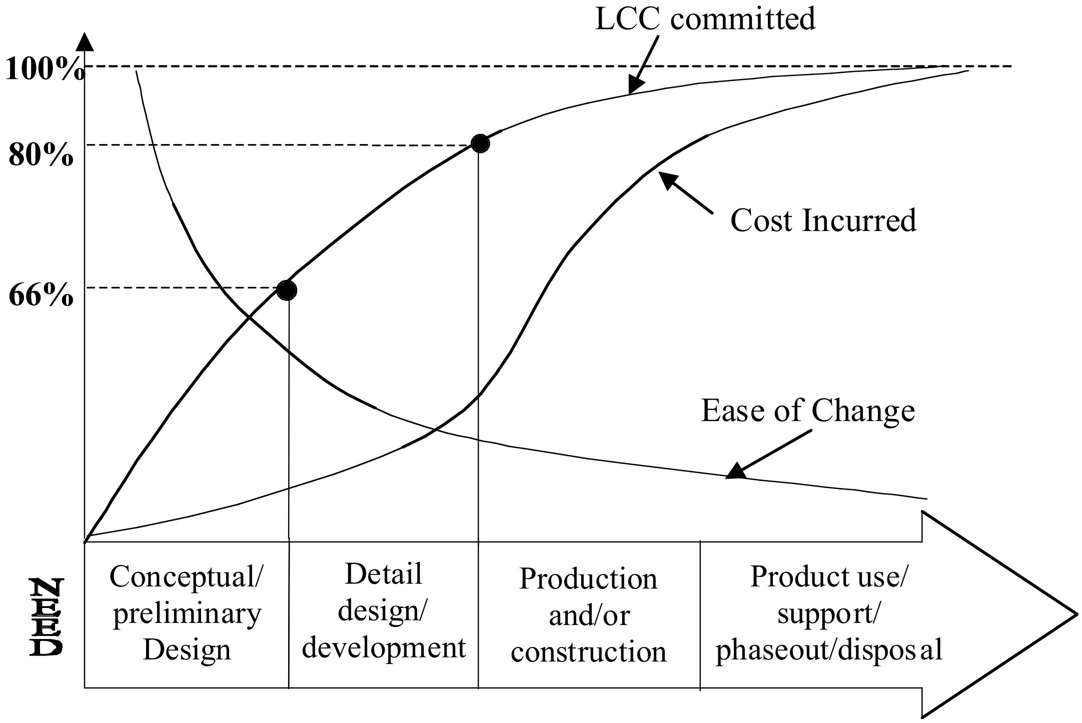

Figure 2 - Lifecycle cost committed vs incurred (Fabrycky and Blanchard, 1991)

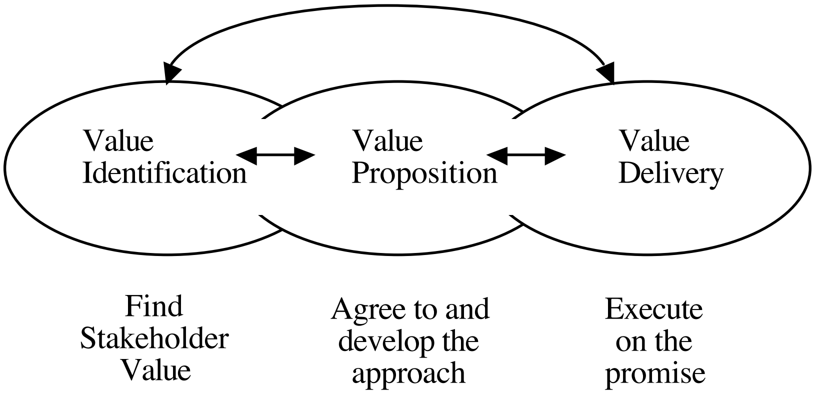

Figure 3 - Value Creation Framework (Murman, et. al 2002)

Table I
A Sampling of the Interrelations That Exist Between the Technical and Social Dimensions of Aircraft

| Level | | 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|---|
| | | **Individual** | **Group** | **Organizational Unit** | **Organization** | **Multi-Organization Enterprises** | **Society** |
| 0 | **Parts** | | | | | Supplier Relations | |
| 1 | **Components** | Instrument/ Pilot | Design Teams | | | Supplier Relations | |
| 2 | **Subsystems/ Subassemblies** | | Flight Crew | Integrated Product Teams (IPTs) | Matrix Organizations | Supplier Relations | Noise & Emissions |
| 3 | **Aircraft** | | Project Teams IPTs | | Matrix Organizations | | Noise & Emissions |
| 4 | **Air Transport System** | | | | | Traffic Control & Airport Malls | Hub/Spoke System & Airport Malls |
| 5 | **World Environment** | | | | | | Cumulative Environmental Effect |