# The Development of Systems Engineering

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**Systems engineering is described as the design of the whole as distinguished from the design of the parts. Systems engineers create the architecture of the system, define the criteria for its evaluation, and perform tradeoff studies for optimization of the subsystem characteristics. In addition to their own brains, the principal tool of systems engineers is the computer. Systems engineering has evolved during a long series of major developments, in particular the intercontinental ballistic missile (ICBM) program. The major growth of systems engineering is expected to be in the improvement of its tools and in the enlargement of the range of problems to which it is applied.**

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## I. WHAT IS SYSTEMS ENGINEERING?

Systems engineering is the design of the whole as distinguished from the design of the parts. The systems engineer harmonizes optimally an ensemble of subsystems and components—machines, communication networks, humans, space—all related by channeled flows of information, mass, and energy. Of course, the designer of a chair, a watch, or even a necktie deals in the end with the whole; so, in a sense, every designer is partially a systems engineer. But where that whole has many components and many complicated interactions occur when they are connected, real systems engineering is required. Then systems engineering becomes a demanding intellectual discipline.

In complex systems, the large interactions will often dominate, but equally often a surprisingly large accumulation of individually small factors will exert tremendous influence on performance. A large system with many parts, each of which appears to be adequately accurate, may turn out to produce unacceptably inaccurate overall results. In a similar way, a system of many apparently reliable parts may add up to an unreliable system. Again, many feedback loops may be necessary in a system, but their presence also may produce unexpected phenomena far from what the designer intended. These and other system characteristics make systems engineering a challenge.

## II. WHAT DO SYSTEMS ENGINEERS DO?

Systems engineers create the system architecture by configuring the elements of the system to meet the performance requirements most satisfactorily and in the process incorporate a multitude of necessary technologies that must cohere in the final design. Their efforts begin with an attempt to comprehend thoroughly the problem to be solved, the tools available to solve it, and all constraints linking the parameters. Careful consideration goes beyond the gross relationships. The systems engineer must understand the subsystems and the various concerned phenomena well enough to be able to describe and model their characteristics in detail. Patch-up analysis rarely can overcome the limitations of models that do not reproduce the basic characteristics of the subsystems.

In the development of a system, systems engineers carry through a fairly well defined set of steps. They begin by considering what the user or purchaser of the system thinks is wanted. Of course, the systems engineer knows these objectives may be overly difficult or even impossible to meet, at least within a reasonable time and at a reasonable cost. The first job of a system engineer thus frequently is to modify the requirements to permit a practical development.

Often the essence of systems engineering is to handle the "chicken and egg" dilemma, to design the system so it meets the criteria while simultaneously selecting the criteria that are really appropriate. Frequently, it is simply not possible to set up sound criteria until clear ideas exist of the system that can meet the criteria. An approximation of the final objectives, usually achieved through considerable trial and error, is the systems engineer's first task.

Next, more detailed paper designs and computer simulated versions of candidate system configurations are generated. Ideally, several potentially useful solutions are derived and tradeoff studies are conducted in an attempt to surface the best one. Computer simulation is increasingly the key tool in conducting the optimization studies.

Once the system configuration begins to jell, the specifications that define the desired system performance are allocated to the subsystems. These specifications are expressed in terms of quantities such as weight, prime power, RF power, bit error probability, and, of increasing importance, cost. After the initial specifications are established, these quantities are the ones in terms of which design trades are expressed and which the systems engineer tracks throughout development, fabrication, assembly, and test. During the hardware design phase, the systems engineer constantly adjusts subsystem specifications as certain ones are discovered to be harder or easier to meet than anticipated. The final step is to evaluate test results and to verify system performance. This usually ends in actions to convince the customer that the system meets the needs in a sensible compromise.

A major factor that complicates the development of real systems is the frequent need for concurrency in steps that ideally are sequential. In an ideal world, no phase of a program would begin until previous phases are complete and all required data are available. In practice, however, parts must be ordered and prototypes built before the design is complete. Manufacturing must begin before prototype testing is finished. Test equipment must be built before the equipment to be tested is fully defined. Making decisions as correctly as possible under such trying circumstances is a critical portion of real systems engineering.

## III. WHAT ARE THE TOOLS OF SYSTEMS ENGINEERS?

The principal tools of the systems engineer are the human brain, the electronic computer, and numerous mathematical analysis techniques. In the early history of serious systems engineering, mathematical analysis was typically very tedious and time consuming, with numerical calculations performed with slide rules, desk calculators, and then with primitive mainframe electronic computers. Today numerical analysis is carried out with programmable calculators, personal computers, minicomputers, and mainframe computers all of rapidly increasing power.

The systems approach has become a powerful design discipline mainly because of the accelerated development of the tools of systems engineering in recent years. This development fortunately has been timed to the accelerating need for this kind of methodology to handle the highly complex and costly defense and space programs. Large computers make possible the information processing and quantitative analyses basic to successful real-life system architecture. Next to skilled human brains, the computer now is the most vital tool of systems engineers.

## IV. WHERE DOES SYSTEMS ENGINEERING COME FROM?

The beginnings of systems engineering undoubtedly go back to the construction of the pyramids, if not earlier. Any large development effort must employ some elements of the systems approach. Several technological implementations of the nineteenth and early twentieth centuries clearly were major systems: the railroad transportation system, the electric power generation and distribution system, and the telephone system. The development of the telephone system gave birth to many of the techniques useful for design of communication systems in general. The development of radar and the atomic bomb in World War II clearly involved systems engineering as well as extensions in the field of applied physics. Analytical techniques grouped under the title of operations research, developed during World War II for adjustment of parameters of a system to optimize its performance, have proven to be useful tools for the systems engineer and have been steadily extended. However, systems engineering really was not recognized widely during these earlier periods as a major branch of engineering.

Large scale attention to modern systems engineering occurred in the post-war developments of ground-to-ground, ground-to-air, and air-to-air missile systems, where the technologies involved included communications, radar, controls, aerodynamics, structures, and propulsion. The intercontinental ballistic missile (ICBM) program, which began with ATLAS, then spread to include TITAN, THOR, and Minuteman, and most recently Peacemaker (MX), particularly required the development of systems engineering as the discipline is understood now. The Apollo program, which in a sense was an extension of the ICBM program and involved many of the key engineers and industrial organizations responsible for the ICBM program occurred next and was the first major nonmilitary government program in which systems engineering was recognized from the outset as an essential function.

Today all major space and military development programs recognize systems engineering to be a principal project task. An example of a recent large space system is the development of the tracking and data relay satellite system (TDRSS) for NASA. The effort (at TRW) involved approximately 250 highly experienced systems engineers. The majority possessed communications systems engineering backgrounds, but the range of expertise included software architecture, mechanical engineering, automatic controls design, and design for such specialized performance characteristics as stated reliability. In comparison, Pioneer I, one of the earliest space projects and a much simpler system, probably employed no more than 10 people who properly could be called systems engineers. The increasing complexity of space projects indicates that the size of the systems engineering effort on each probably will increase in the future.

Because of the heightened role of systems engineering in aerospace and electronic systems, many papers in this issue relate to this topic. In particular, success in the areas of remote sensing, radar imaging, passive sonar, digital avionics, and $C^3$ are extremely dependent on the quality of the systems engineering team. Kalman filtering has become a key analysis tool of systems engineering.

## V. WHERE IS SYSTEMS ENGINEERING GOING?

Two major trends may be expected in system engineering. First, the capabilities of the analytical tools available to the systems engineer will continue to increase. Powerful mainframe computers now are routinely used, with personal computers rapidly replacing the scientific calculator, which in turn had earlier replaced the slide rule and the electromechanical calculator. Networking of personal computers with mainframe computers is a step now developing. Software techniques have developed in parallel with the hardware developments. Although the acronym CASE (computer-aided systems engineering) is not often used, whereas its counterparts CAD (computer-aided design) and CAM (computer-aided manufacturing) are well known, computers were essential tools of systems engineering before they were extensively used to assist engineers in detailed design and in manufacturing control. Without the computer, efforts such as the ICBM program would have been impossible. The thousands of trial and error launches required to work out subsystem compatibility and reach harmony between desired requirements and attainable performance would have led to absurd costs and time frames.

The development of artificial intelligence techniques promises to further expand the capabilities of the systems engineering tools, although it probably will not move so rapidly as to produce the "artificial systems engineer" in the next decade or two. The techniques of artificial intelligence should be devoted to making the partnership of the human and the computer into an overall smarter and faster hybrid systems engineer.

A key question is how to divide the effort between the human and the computer. For a long time, if not forever, activities involving creativity, judgment, and interface with other humans may be carried out best by the skilled human. Computers will be superior at carrying out computations, remembering and recalling a large number of facts, and keeping a multitude of relations clear. If a highly complex new system is being considered, say an antiballistic missile system, the human clearly will dominate in determining the overall system configuration and deciding whether the range of solutions should include defensive missiles, beam weapons, or possibly other devices. Once conceivable configurations are roughly defined, the computer of the future may assume the role of detailed evaluator. Establishing the optimum roles and missions for each member of the partnership will constitute the essence of the task of moving systems engineering ahead by the introduction of artificial intelligence.

A principal question in extending the systems engineer's computer aids will be how to integrate them with computer-aided design, computer-aided manufacturing, and computer-controlled test. Perhaps computer-aided systems engineering should be looked upon as the function that furnishes the integrating program. As systems become more complex, systems integration and test will rise in importance in the system's development.

The second major trend is the increase in the complexity of systems being routinely developed. We should anticipate the use of the techniques of systems engineering on an even wider range of problems than any of the past. Consider, for example, the engineering problem of how best to develop the vast information network needed in the future. The national U.S. system (and, even more, that of the entire world) will merge the technologies of communication and computation. As the pervasive network comes into being it will dwarf the current telephone system. It will involve hundreds of millions of terminals and will furnish two-way, wideband information flow between people at home and work and during travel. Another example is the design of a practical arms-control system. This would constitute an information and control system involving observation, judgment, and alerting.

At least in a philosophical way, the general system theory of von Bertalanffy [1] has contributed to the realization that many processes not normally thought of as such are in fact systems. Many standout, unhandled, central problems of society that are not best categorized as engineering problems nevertheless need and deserve a systems approach. An optimistic thought for the future is that the engineering discipline known as systems engineering will contribute to the solution of some of these problems.

Take, for instance, the achievement of true national security. To be secure, the United States needs many things: economic strength, social stability, high morale and patriotism, an understanding of potential enemies, skill in formulating foreign policy and negotiating with other nations, a broad industrial infrastructure, assured availability of resources for the anticipated duration of possible wars, an effective organization for setting security strategies, and adequate military forces. A solid defense posture requires integrating and balancing these diverse items, a difficult but necessary systems task.

One component, adequate military strength, not only must be well matched to the other components of security, but it has its own rather varied set of subrequirements. For instance, one of these is weaponry and it includes weapons based on recent and complex technology as well as military hardware that is more mundane, simpler, and less technologically advanced. To guarantee a sufficient quality and quantity of the high-technology weapons alone, the United States needs science and engineering skills in depth. Over the long term, this requires a continuing national program that plants the seeds for and cultivates the expert human resources behind technological advance and makes sure that an array of technological projects specifically geared to military needs are constantly being started and carried forward. Thus, from policy to actions, national security is a many-dimensioned systems problem and should be recognized and tackled as such.

Another example of a broad systems problem is government regulation to limit the impairment by technical operations of safety, health, and the environment. Decision-making on technological operations can hardly be sound unless it includes the steady examining of alternatives. There is no such thing as zero risk, so to seek it can only generate an expensive bureaucracy with no chance of succeeding. Comparing imperfect options and balancing their risks and gains, both in arriving at rules and policing their application, is key. If a regulation is overly severe, it is not necessarily an error on the safe side, because it could also have a negative impact on productivity and employment. It could hurt America's ability to compete in the world market. It could lower return on investment, raise prices, discourage new investment, and decrease average income. People who are made poorer because a weakened economy suspends their employment suffer from health problems just as surely as do normally healthy citizens whom we do not protect from health hazards. A systems approach is necessary to trade off the many effects before selecting the appropriate action.

The tradeoff between improving the environment and increasing the energy supply is typical. If coal use is expanded, then energy supply will be enhanced, but safety, health, and environmental protection hazards will increase. Letting the economy slow down because of an energy supply or cost problem is bad. Allowing more pollution and accidents is also bad. Balancing the positives and negatives is mandatory. However, in unrelated acts, the government first imposed drastic controls on coal use; then, to cut air pollution, it mandated that utilities using coal change over to oil and gas. A little later, reacting to OPEC actions, it decreed greater use of coal. Meanwhile, with no one in charge of comparing alternatives and balancing the positives and negatives, the government set a low ceiling price on natural gas. This simultaneously increased demand and discouraged further exploration. The ceiling price was kept on even though double-digit inflation arrived and greatly increased the mismatch. The government energy policy preached conservation but encouraged dissipation (by keeping conventional fuel prices low). Then, having made development of new domestic energy sources through private investment less attractive, it started government-funded programs to pursue new energy alternatives. Such regulation is often self-contradictory and violates common sense when it fails to consider the inevitable impact of individual rulings on the rest of the economy—the systems problem.

These examples illustrate the need for a systems approach to major problems of society. The fundamental concepts of systems engineering, even if not all of its specific tools, would improve the handling of such problems in the future [2].

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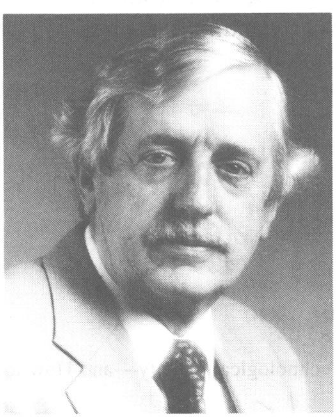

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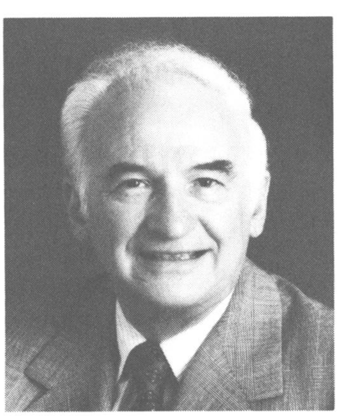

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