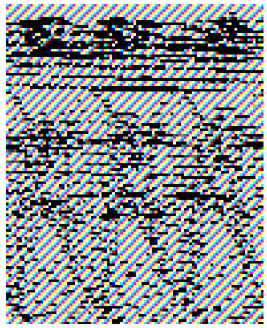

# Beyond the Industrial Web

## *Economic Synergies and Targeting Methodologies*

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## Disclaimer

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# *Abstract*

Economies are complex systems composed of a number of infrastructure elements. These elements, such as electrical grids, petroleum, oil, and lubricants (POL) distribution networks, and telecommunications systems, are interconnected in a myriad of ways. As a result of this connectivity, an attack on one infrastructure element influences the others to varying degrees. When targeting an economy, an air planner must account for this connectivity and the downstream effects that naturally occur. Historically, however, air planners have overlooked the interrelated nature of a nation's infrastructure and employed reductionist targeting techniques. Typically, they split an economy into individual target sets. Then, they select targets in each set in isolation from other targets, without anticipating the holistic effect of air bombardment. This is an inappropriate technique for targeting, as it overlooks the complex behaviors and characteristics of economies.

In this thesis, we propose a new manner of targeting economies—a holistic approach that accounts for the linkages between infrastructure elements and their resultant synergies. We first establish a theoretical foundation for targeting based on complexity science. This discipline examines the nature of complex, interconnected systems such as economies. Next, we demonstrate that economies are indeed highly interconnected systems. These linkages cannot be ignored in the targeting process. Finally, we tentatively propose a computer algorithm capable of targeting multiple, interacting infrastructure elements. The technique employs a genetic algorithm coupled to standard industrial analysis programs. When implemented, this computer technique should dramatically improve the effectiveness of economic targeting.

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I alone am responsible for any technical errors or inadequacies in this report.

## Chapter 1

# Looking Beyond The Web

*Science today stands on something of a divide. For two centuries it has been exploring systems that are either intrinsically simple or that are capable of being analyzed into simple components. The fact that such a dogma as "vary the factors one at a time" could be accepted for a century, shows that scientists were largely concerned in investigating such systems as allowed this method; for this method is often fundamentally impossible in the complex systems.*

—Ross W. Ashby
*An Introduction to Cybernetics*

Since the dawn of powered flight, air planners have recognized that economies are complex, interconnected systems. As early as 1911, French Lieutenant Poutrin wrote in Revue Générale de l'Aéronautique Militaire that German aerial attacks on key ministries, transportation networks, and communication centers in Paris would shut down essential public services, thus preventing the country from mobilizing.[1] However, the notion of economies as intertwined entities took on particular meaning at the Air Corps Tactical School (ACTS) in the 1930s, with the development of the "industrial web" theory by the ACTS "bomber mafia."[2] Since modern theorists have likewise recognized the importance of connections between economic sectors, we would logically expect air planners to identify and exploit the linkages present in modern economies.[3] Paradoxically, however, most economic targeting has proceeded as though the interconnections between elements of an economy were of secondary importance.

In practice, air planners have behaved much as Ashby's scientists. They have dissected economies into their component parts and targeted each part in isolation. During World War II, the industrial web theory influenced planners to search for bottlenecks—those critical industries upon which significant portions of an enemy war economy relied.[4] But once such industries were pinpointed, the planning tended to focus on destroying individual target sets rather than attacking key points in different sets.[5] Consequently, when one system failed to yield the desired results, the priorities shifted to another target.[6] Planners "sought, partly and inescapably through trial and error, to find good target systems."[7] Even though they only partially succeeded, this reductionist approach survives today. During the Persian Gulf War, for example, planners did not perform detailed systems analyses that highlighted the intertwined nature of the Iraqi economy.[8] As in prior conflicts, airmen recognized the complex interconnections of the Iraqi economy, but did not fully exploit them in the planning process.

Targeting science today stands on something of a divide. We have reached the point where we can retire the old reductionist targeting methods. Rather than separating the different sectors of an economy and targeting each one in isolation, we can now approach targeting from a synergistic or holistic viewpoint. Economies are complex systems and must be targeted as such. The purpose of this research is to move us across the targeting divide, from the old reductionist ways to newer holistic methods.

## Objectives and Scope

The focus of this study is economic targeting. It has two principal objectives. First, it will demonstrate that economies are complex systems that do not readily submit to reductionist analyses. This point has important ramifications. As noted above, planners following the traditional approach first separate the economy into its principal *infrastructure elements*, such as electricity, petroleum, oil, and lubricants (POL), telecommunications, and transportation. Next, they examine each element *in isolation from the other elements* and select appropriate targets. This approach ignores the linkages that exist between infrastructure elements, and that they cannot be deduced from individual analysis.[9]

If the traditional method is inappropriate, how should a planner approach economic targeting? This question lies at the heart of the second objective of the study. It develops a new technique for analyzing economies that preserves their complex nature. The technique draws from several recent developments in computer technology as well as standard industrial analyses. The result is a proposed computer tool capable of performing targeting analyses on the interconnected elements of an economy. This computer algorithm should help overcome the current dearth of economic modeling and simulation tools available for targeting.[10]

Several limitations apply to this study. First, it does not address how economic targeting brings about desired political objectives. The study is strictly limited to examining the ties between target sets, not the political mechanisms triggered by synergistic attacks. Second, the study presumes that our national authorities ordered economic targeting. It does not debate the relative merits and drawbacks of targeting economies. Third, much of the data originates from interviews with US industrial experts. Many of the examples, therefore, apply to the US infrastructure and may not be valid for foreign nations. The usual caveats against mirror imaging strongly apply to this report. However, the computer analysis technique developed below is applicable to *any* economy. Finally, this project is primarily theoretical—it develops a framework for analyzing economies. The "experimental verification" of the theory awaits future research efforts.

## A Convergence of Technologies

Why are we only now beginning to take a hard look at the interrelationships that exist between infrastructure elements? To a large degree, the answer lies in scientific advances. The recent convergence of several technologies provides us with the ability to examine the question in detail. These technologies include stealth, precision guided munitions (PGM), day-night aircraft with improved weather capabilities, and computer algorithms and hardware.

During WWII, sequential air operations were the general rule. Air planners selected target sets and attacked them in series. To a large degree, aircraft limitations and weather were responsible for this mode of operation. High bombing circular error of probability (CEP) meant that huge numbers of aircraft had to mass together in order to mathematically assure mission success.[11] Consequently, the number of targets that could be attacked simultaneously was severely limited. Relatively low bomb loads (by today's standards) also drove up the number of bombers required for a mission. Distant targets, which required more fuel and smaller bomb payloads, exasperated the problem. Finally, the weather constrained the number of bombing days per month.[12] These factors strictly limited the number of targets that could be attacked simultaneously or within a short time period. As a result, planners sought bottleneck targets that could be attacked sequentially.[13] Out of necessity, synergies created by near simultaneous attacks in different target sets were pushed aside in favor of seemingly lucrative bottlenecks.

Fifty years later, technological revolutions allowed a radically different form of air war during the Persian Gulf War. PGMs decreased the number of sorties required to destroy targets by orders of magnitude.[14] Increased payloads further reduced the aircraft requirements per target. Stealth and cruise missiles contributed as well; targets in highly defended areas were suddenly vulnerable to attack. Day-night operations were possible due to improvements in sensors and aircraft. In sum, technological advances allowed a fundamental shift in operations: parallel and hyperwarfare were born. Instead of serial attacks against bottleneck targets, planners during the Gulf War attacked significant numbers of targets in different sets simultaneously. The goal was strategic paralysis, a condition in which the Iraqi authorities were unable to react to Coalition actions. Consequently, conditions were right for the air planners to seek synergistic effects during operations. Unfortunately, a crucial element was missing: the capability to perform nodal analyses of infrastructure elements.[15]

Today, the final piece of technology is appearing that will allow a major shift in the way planners target economies. Engineering and nodal analyses are beginning to appear in military writings.[16] Even so, an analysis of a single element, such as POL or telecommunications, is simply an improved version of the reductionist approach. What is still required is a method that allows analyses of multiple economic elements that preserves the complex interconnections between them. The development of such analysis tools will allow a further revolution in operations: we will be able to leap across Ashby's divide.

Concentrating on synergistic effects in analyses will do far more than just lead to elegant target sets. Rather, it will allow a fundamental shift in operations. Consider for the moment a conflict in which the number of available aircraft or munitions is severely restricted. In this type of conflict, every sortie must count and every bomb must hit a significant target. "Rules-of-thumb" or "back-of-the-envelope" techniques are inadequate to determine the appropriate targets. Furthermore, reductionist analyses of isolated target sets, even if performed with tools such as load-flow programs, will not produce the best target sets—in fact, inappropriate targets may result. We will examine these propositions in detail in the ensuing chapters.

## Thesis Organization

Chapter 2 provides the theoretical framework for targeting studies. This framework draws heavily from dynamical systems analysis, or complexity theory as it is more popularly known. Complexity theory deals with the behaviors of complex, interconnected systems. As we shall see, economies are examples of the type of systems that complexity theory treats.

In chapter 3, we move from abstract theory to a concrete discussion of the complex nature of economies. The chapter begins with a discussion of centers of gravity. Determining whether a given infrastructure element is a center of gravity is a crucial step in planning. Next, the chapter looks at a detailed notional economy that contains four elements (an electrical grid, natural gas networks, oil distribution networks, and a telecommunication system). The example illustrates the complex nature of economies, and highlights the inadequacies of reductionist targeting.

Chapter 4 then explores computer techniques applicable to targeting complex economies. It begins with a discussion of targeting philosophies, then presents several computer algorithms that a planner could employ in a targeting program, and examines at length a proposed computer program that produces target sets for complex economies. The program uses standard industrial analysis programs (such as a load-flow program) to model the effects of an attack on given infrastructure elements. However, it preserves the complex linkages between the different elements. In this respect, the program represents a considerable step forward in targeting.

Chapter 5 contains several tables that list typical linkages between the electrical, POL, telecommunications, and transportation elements. The tables provide a final, compelling argument for the holistic analysis techniques advanced in this study.

Chapter 6 recapitulates the general points made earlier and recommends additional research.

## Notes

1. Lee Kennett, *The First Air War: 1914–1918* (New York: Free Press, 1991), 44.

2. Led by Harold Lee George and Don Wilson, a handful of ACTS faculty members developed and refined the "industrial web" theory of air bombardment. The instructors believed that economies were intricate, interconnected entities that rested on certain basic industries (transportation, steel, iron ore, and electrical power). Destroying one or more of the threads in the web would unravel the economic and social fabrics of the nation. The subsequent collapse of national morale and loss of the economic means of waging war would bring about the capitulation of the enemy nation. Robert T. Finney, *History of the Air Corps Tactical School 1920–1940* (Washington, D.C.: Center for Air Force History, 1992), 67–68.

3. Col John A. Warden III, "Strategic Warfare: The Enemy as a System," unpublished manuscript, 3 January 1993, 5–13. Note figure 2, which depicts the direct and indirect effects of attacks.

4. In a memorandum to Lt Gen Henry H. Arnold dated 8 March 1943, the Committee of Operations Analysts (COA) wrote, "In the determination of target priorities, there should be considered (a) the indispensability of the product to the enemy war economy; (b) the enemy position as to current production, capacity for production and stocks on hand; (c) the enemy requirements for the product for various degrees of activity; (d) the possibilities of substitution for the product; (e) the number, distribution and vulnerability of vital installations; (f) the recuperative possibilities of the industry; and (g) the time lag between the destruction of installations and the desired effect upon the enemy war effort." In short, the planners looked for vulnerable bottleneck industries with few workarounds. Guido R. Perera, *History of the Organization and Operations of the Committee of Operations Analysts, 16 November 1942–October 1944*, vol. 2, tab 22, USAF Historical Research Agency (hereafter cited as HRA) file 118.01. The Economic Objectives Unit followed similar guidelines during target selection. Carl Kaysen, "Note on Some Historic Principles of Target Selection," RAND, RM-189, 15 July 1949.

5. This point becomes apparent upon examining the two US air war plans, AWPD/1 and AWPD/42. The plans go into great detail on each target set, but very rarely consider the synergistic impact of disrupting one target set and not another. See AWPD/1, *Munitions Requirements of the Army Air Forces to Defeat Our Potential Enemies*, 12 August 1941, HRA file 145.82-1; and AWPD/42, *Requirements for Air Ascendancy, 1942*, HRA file 145.82-42.

6. The changes in the target set priorities between AWPD/1, AWPD/42, and the Combined Bomber Offensive bears out this point. An illuminating comparison can be found in Haywood S. Hansell, Jr., *The Air Plan That Defeated Hitler* (Atlanta: Higgins-McArthur/Longino & Porter, Inc., 1972), 163.

7. Bernard Brodie, *Strategy in the Missile Age* (Princeton: Princeton University Press, 1959), 115.

8. Col John A. Warden III, commandant, Air Command and Staff College (ACSC), interview with author, 28 March 1994. In particular, the Checkmate planners looked for target sets that would cut across all rings of Colonel Warden's Five Rings model, thus affecting the entire Iraqi system. For details on the Five Rings model, see Warden, "Strategic Warfare," 5–13; and Col John A. Warden III, "Employing Air Power in the Twenty-first Century," in *The Future of Air Power in the Aftermath of the Gulf War*, edited by Richard H. Shultz, Jr., and Robert L. Pfaltzgraff, Jr. (Maxwell AFB, Ala.: Air University Press, July 1992), 62–69.

9. Interestingly, a considerable number of reductionist studies of economies were undertaken during the last year or two at Air Command and Staff College, the School of Advanced Airpower Studies (SAAS), and elsewhere. See, for example, Maj Bruce M. DeBlois et al., "Dropping the Electric Grid: An Option for the Military Planner," unpublished research report (Maxwell AFB, Ala.: ACSC, 1994); Maj Thomas E. Griffith, Jr., *Strategic Attack of National Electrical Systems*, thesis (Maxwell AFB, Ala.: SAAS, 1993); David A. Shlapak, "Electrical Power as a Target System," Project AIR FORCE, RAND Memorandum PM-187-AF, December 1993; Maj Edward J. Felker, "Does the Air Force Practice Its Doctrine? A Limited and Focused Air Campaign Concept," unpublished thesis (Fort Leavenworth, Kans.: Command and General Staff College, 1991); Maj Mark W. Graper et al., "Petroleum as a Center of Gravity," in *Air Campaign Course 1993: Research Projects*, edited by Dr Richard Muller, Lt Col Larry Weaver,

and Lt Col Albert Mitchum (Maxwell AFB, Ala.: ACSC, 1993); Maj Scott E. Wuesthoff, *The Utility of Targeting the Petroleum-Based Sector of a Nation's Economic Infrastructure,* thesis (Maxwell AFB, Ala.: SAAS, 1992); Maj Paul DiJulio et al., "Communications-Computer Systems: Critical Centers of Gravity," in *Air Campaign Course 1993: Research Projects;* and Maj Gerald R. Hust, *Taking Down Telecommunications*, thesis (Maxwell AFB, Ala.: SAAS, 1993).

10. Warden interview; Brad Godfrey, Sandia National Laboratories (hereafter cited as Sandia), interview with author, 6 April 1994. Colonel Warden cited the lack of analysis tools as a significant shortcoming during the Persian Gulf War.

11. Postwar studies of the bombing accuracies in Europe revealed that on average only 20% of the bombs dropped fell within 1,000 feet of the aimpoint. In February 1945, the bombing accuracy peaked at 70%. *The United States Strategic Bombing Survey, Summary Report (European War*), 30 September 1945 (reprinted edition, Maxwell AFB, Ala.: Air University Press, October 1987), 13.

12. Poor weather hampered both the Allies and Germans. For a detailed discussion of the impact of weather on operations, see Stephen L. McFarland and Wesley Phillips Newton, *To Command the Sky: The Battle for Air Superiority over Germany, 1942–1944* (Washington, D.C.: Smithsonian Institute Press, 1991), 79, 132, 158–59, 170, 172, 183, 185–86, 196–98.

13. Philosophically, the planners were disposed toward serial operations aimed at the total destruction of given targets. ACTS taught that once a target was selected, it should be attacked until destroyed. Finney, 63. During WWII, the COA adhered to the same notion. Writing to General Arnold, the committee noted, "It is better to cause a high degree of destruction in a few really essential industries or services than to cause a small degree of destruction in many industries. Results are cumulative and the plan once adopted should be adhered to with relentless determination." Perera, vol. 2, tab 22.

14. Richard P. Hallion, *Storm Over Iraq: Air Power and the Gulf War* (Washington, D.C.: Smithsonian Institute Press, 1992), 283–84. In particular, note chap. 6, tables 2 and 3. Hallion states that ". . . small formations of strike aircraft could achieve the same destructive results with unguided bombs that had taken hundreds and even thousands of aircraft in World War II."

15. Warden interview.

16. DeBlois et al. advocate the use of load-flow programs to analyze electrical grids. Electrical utilities use these computer programs to analyze their networks, plan for future growth and expansion, develop contingency plans, and so forth. We will examine load-flow programs in greater detail in the following chapters.

## Chapter 2

# Complexity Theory and Economic Targeting

Economies are vital, dynamic entities that constantly react to the influences of their environments. A typical economy consists of different *infrastructure elements*, such as electrical power grids, transportation networks, POL distribution systems, and communications systems. These elements intertwine in a myriad of nonlinear linkages and feedback loops. Examining each element in greater detail yields a hierarchy of parts, or key nodes and linkages. To understand how these nodes and linkages function, we must turn to dynamical systems analysis, or complexity theory as it is popularly known.[1]

Dynamic systems analysis seeks to explain how time-dependent systems operate. It encompasses complexity and chaos theories. Complex dynamic systems such as economies can exhibit a rich variety of behaviors, including many that are counterintuitive. An essential truth of complexity theory is that such systems must be analyzed from a holistic rather than reductionist point of view. In recent years, several papers have appeared examining warfare in light of chaos theory.[2] However, analysis of economies for war-fighting purposes goes beyond the bounds of chaos theory; the proper framework actually lies within complexity theory.

As a result, this chapter explores complexity theory and economic targeting. More specifically, it examines three premises. First, economies are complex systems. We can employ complexity theory to understand economic infrastructures and their behaviors. Second, given that economies are complex systems, air planners must account for their dynamics when targeting them. Finally, and perhaps most importantly, the reductionist methodology followed in traditional economic targeting is invalid. A planner must instead approach the problem from a synergistic viewpoint. These three contentions will become clear as we further explore the nature and the behavior of complex systems.

## Complex Systems Defined

Dynamic systems analysis has its roots deep in modern mathematics. Although some of it traces back to the work of the French mathematician Henri Poincaré in the early 1900s, the field has grown enormously during the past 15 to 20 years. Computers are largely responsible for the recent growth, since they have allowed scientists and mathematicians to study the temporal dynamics of complex, nonlinear systems. Today, complexity theory encompasses a wide variety of disciplines ranging from physics, chemistry, and biology to sociology, cultural anthropology, and economics.[3]

A *complex system* is a large collection of interacting parts or entities. In the language of complexity theory, the parts are commonly referred to as *agents*. These interacting parts create the environment in which they exist. Further, by constantly acting and reacting with one another, the parts continually perturb and modify their environment. For example, in a chemical system, the physical interactions between the reagents form linkages. As the chemical reactions consume the reagents and create new products, the environment each molecule "sees" changes. The interaction rules for the agents can be quite simple. Even so, systems with simple interaction rules frequently give rise to extremely intricate behaviors.[4] In sum, collections of interacting agents form the basis of complex systems.

Complex systems often contain hierarchical structures. Figure 1 sketches the concept. Separate groups of agents form within the system. Each group is in its own right an agent, and interacts with the other groups. In general, the form of the agents, environment, and interaction rules vary at each hierarchical level. A government bureaucracy illustrates the principle. Offices interact to form divisions, divisions cluster to create agencies, and agencies work with one another to create the overall governmental structure.

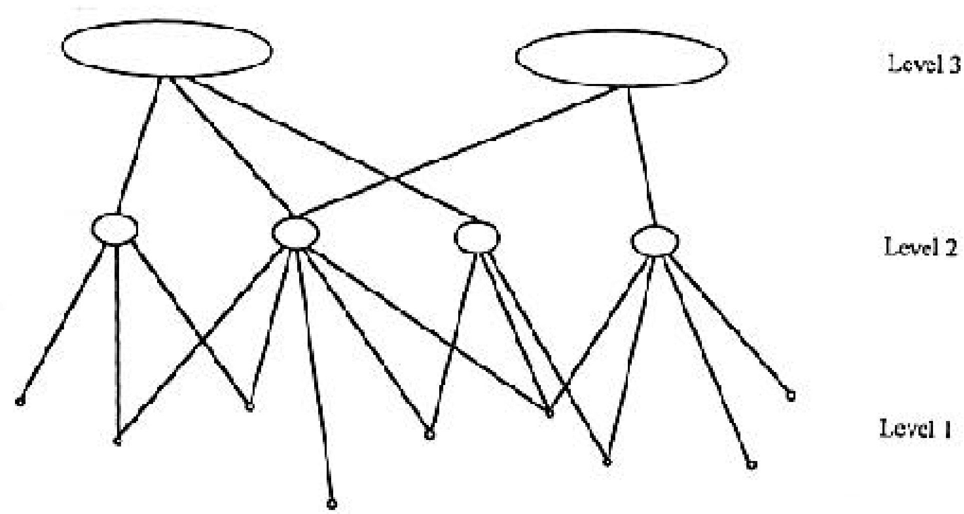



**Figure 1. The Hierarchical Structure of Complex Systems**

Agents and their linkages can be characterized in three ways. First, we can broadly classify the couplings between the agents as tight and loose.[5] Tight coupling refers to agents that are strongly dependent upon one another. Disturbances in the system may be highly correlated to each other when the system is tightly coupled. Time-dependent processes, with little give or slack, characterize tightly coupled systems. Additionally, disturbances tend to propagate throughout a tightly coupled system. A natural gas-fired electrical generator and the gas pipeline system form a tightly coupled pair.[6] The generator provides the electricity for the compressor stations along the pipeline, which in turn assure a constant supply of fuel to the generators. Since gas generators generally have no local storage, this particular system is very tightly coupled. Generator disturbances will directly affect the pipeline and vice versa. Loose coupling, on the other hand, implies that the agents are relatively independent of each other. Events in the system are usually either weakly correlated or independent. Give and slack exists in the system, since the processes are not nearly as time dependent as in a tightly coupled system. A coal-fired electrical generator and the diesel-powered railroad network supplying its coal are weakly coupled. Coal-fired generators often have 90-day supplies of coal available. Consequently, short term disturbances in the rail supply rarely affect power generation. Tight and loose coupling, then, refers to the degree of dependencies between the agents.

Second, the couplings between the agents may be further classified as linear or nonlinear. These terms describe the mathematical forms of the linkages. A linear linkage satisfies two conditions. First, it obeys the law of proportionality. If an input $x$ to some linkage results in an output $y$, then linearity requires that an input of $ax$ produces an output of $ay$, where $a$ is some arbitrary constant. Second, the linkage must allow the superposition or additivity of inputs. That is, if the inputs $x_1$ and $x_2$ give rise to outputs $y_1$ and $y_2$, respectively, then the input $(x_1 + x_2)$ yields $(y_1 + y_2)$. Nonlinear linkages do not display proportionality or superposition. Slight changes in the inputs may result in disproportionately large differences in the outputs or vice versa, depending upon the mathematical relationships between the inputs and the outputs. In a nonlinear system, the whole is not necessarily equal to the sum of the parts. Clearly, linear linkages are simpler to understand and model than nonlinear linkages.

Lastly, agents or collections of agents may carry out sequential or branching processes.[7] This refers to the manner in which the agents carry out their processes. Sequential processes, as the name implies, proceed in series: event A occurs before event B which occurs before event C. The process occurs in steps, much like an assembly line. Most systems designed by man are sequential. Branching operations, however, have a more involved structure: they contain feedback loops, branches and bifurcations, and jumps from one linear sequence to another. The consequences of perturbations in a branching operation are much less clear or comprehensible than in a sequential operation. Communication systems contain this type of branching, as calls can be routed in a myriad of directions, through many different switching stations. The German war economy during WWII is a further example of a branching process.[8] Production was characterized by a geographic division of labor and supplies, linked by the Reichsbahn. As industry dispersed in response to the Allied bombing attacks, the number of supply and subassembly paths between facilities proliferated. Consequently, the economic processes became intrinsically more intricate in the manner denoted above.

In summary, complex systems consist of large collections of interacting agents. Hierarchies of agents may be present, each with its own particular dynamics. Agents are tightly or loosely coupled to one another, depending upon their degrees of interdependency. Furthermore, the linkages themselves are either linear or more typically nonlinear. Finally, the agents can carry out sequential or branching operations. With this abstract background on the nature of complex systems, let us turn now to their characteristics and behaviors.

## Characteristics of Complex Systems

Complex adaptive systems appear in a wide variety of settings. Examples readily arise in the scientific and engineering disciplines. However, we also find complex behavior within the social and human sciences. Cultural, social, and political systems all display attributes of complexity.[9] An economy is an "example par excellence" of a complex adaptive system.[10] A considerable body of research has been amassed relating to complexity in economies.[11] Herein lies the motivation behind this section: targeting complex adaptive systems requires an understanding of their dynamics.

Despite their diversity, complex systems share certain fundamental behaviors. These include *emergent behavior, adaptive self-organization, evolution to the edge of chaos,* and the *ability to process information.* Unfortunately, valid mathematical laws do not exist that describe the conditions under which these behaviors appear.[12] Nevertheless, they are general patterns that arise in a wide variety of systems. The following subsections examine each of these properties in detail. Interestingly, many of the system properties commonly discussed in military circles, such as Graham T. Allison's organizational and political models,[13] economic substitution,[14] and John R. Boyd's observe-orient-decide-act (OODA) loop,[15] arise naturally as a result of complex behavior.

### Emergent Behavior

Emergent behavior is an important distinguishing characteristic of complex systems.[16] The interactions of the agents may lead to emerging global properties that are strikingly different from the behaviors of the individual agents. These properties cannot be predicted from prior knowledge of the agents.[17] The global properties in turn affect the environment that each agent "sees," influencing its behavior. A synergistic, feedback loop is thus created—the interactions between agents determine the emerging global properties which in turn influence the agents. Figure 2 diagrams the process. Furthermore, emergent structures of agents can arise through their mutual competition and rivalries.[18] Each structure exhibits its own emergent behavior, and in turn influences the global behavior of the system. The emergence of coherent, global behavior in a large collection of agents is one of the hallmarks of complex behavior.[19]

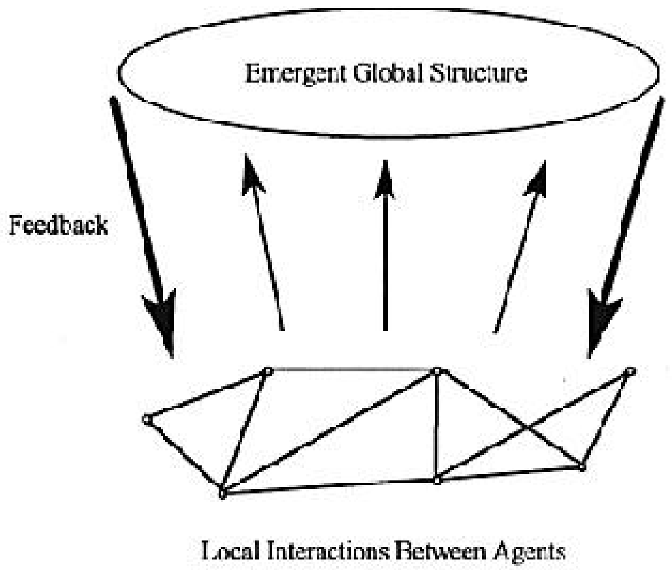



**Figure 2. Local Interactions Lead to Emergent Global Behavior[20]**

Emergent behavior implies that reductionist analysis methods have limits when applied to complex systems.[21] The traditional scientific method is the embodiment of the reductionist philosophy. The researcher decomposes a system into progressively smaller and smaller parts. His analysis centers on the properties of the pieces, rather than the dynamics of the entire system. Particle physics, the study of the basic building blocks of matter, is perhaps the ultimate limit of this philosophy. However, by focusing on the parts instead of the system as a whole, the emergent properties are lost. The blurring of the global behavior occurs because the emergent properties are functions of the *interactions* between agents and their effects. Although important, the properties of the agents do not exclusively determine the global system properties. As P. W. Anderson notes:

> The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe. In fact, the more the elementary particle physicists tell us about the nature of the fundamental laws, the less relevance they seem to have to the very real problems of the rest of science, much less to those of society.[22]

An analysis of complex systems requires a holistic or constructionist approach rather than a reductionist one. Consider for the moment a complex system composed of hierarchies of agents. The structures and the rules of behavior change with each level of organization. New emergent behaviors appear for each layer in the hierarchy. To understand the global properties of the system, one must move progressively higher and higher in the organization, incorporating the interactions between each level of agents in the analysis. Allison's Governmental (Bureaucratic) Politics Model III illustrates these principles quite well. He describes this model as:

> [T]he Governmental (or Bureaucratic) Politics Model sees no unitary actor but rather many actors as players—players who focus not on a single strategic issue but on many diverse intranational problems as well; players who act in terms of no consistent set of strategic objectives but rather according to various conceptions of national, organizational, and personal goals; players who make government decisions not by a single, rational choice but by the pulling and hauling that is politics.[23]

According to this model, the global emergent properties (the strategic decisions) of the government come about not because of the personal, organizational, and national goals of the agents (players), but rather because of the interactions (political maneuvering) between the agents within the governmental hierarchy. An a priori knowledge of the agents does not suffice in comprehending the emergent decisions of a government. A holistic, rather than reductionist, methodology that includes the interactions between agents and various hierarchical levels is necessary to understand global dynamics.

The reductionist philosophy likewise fails to properly analyze economic infrastructure elements for targeting purposes. It wrongly perceives economic structures as isolated entities. Rather, they are intertwined in complex, nonlinear ways and continuously interact with and influence each other. The usual method of targeting the elements in isolation overlooks the synergistic effects and the emergent properties of the economy. An appropriate targeting philosophy must incorporate these interactions and examine the global properties of the system. The overall effects of an attack can only be determined in this manner.

This point is crucial in an armed conflict, as "*war is . . . an act of force to compel our enemy to do our will.*"[24] The target(s) and timing of an attack should be designed to trigger a mechanism that precipitates a desired political outcome.[25] If the synergies and emergent properties of the enemy economic system are not considered during the planning process, then the specific results of an air attack cannot be adequately assessed. As a result, the inputs to the mechanism blur or become indeterminate. In the worst case, the connection between the attacks and the desired political outcomes break; in the best case, the level of fog and friction in the targets-timing-mechanism-political outcome paradigm rises. Incorporation of synergies and emergent behaviors in targeting analyses will not assure that the air attacks produce the desired political outcomes. However, it will provide the planner with a clearer view of the effects of air attacks and hopefully reduce the level of uncertainty associated with targeting.

Emergent behavior is a hallmark of complex systems. It demands that analyses proceed from a synergistic rather than reductionist viewpoint. The implications for targeting are clear: interactions between target sets must enter the decision-making process if the global effects of air attacks are to be determined.

## Adaptive Self-Organization

Adaptive self-organization is the second fundamental characteristic of complex systems.[26] As Stuart A. Kauffman notes, "contrary to our deepest intuitions, massively disordered systems can spontaneously ‘crystallize’ a very high degree of order.”[27] This appears to be an innate property of complex systems. Self-organization arises as the system reacts and adapts to its externally imposed environment. Such order occurs in a wide variety of systems, including for example convective fluids, chemical reactions, certain animal species, and societies.[28] Although the specific mechanisms of self-organization are difficult to determine, some valuable insights come from considering the Second Law of Thermodynamics and the concept of “attractors.”

At first glance, self-organization appears to be in direct conflict with the Second Law. The law states that for isolated systems *that cannot interact with their environment,* entropy will remain constant or increase in time.[29] The increase in entropy is commonly interpreted to mean that the isolated system will become increasingly disordered, since higher entropy levels are associated with an increased number of states or configurations in which the system can exist.[30] This interpretation has been incorrectly applied to nation-states and military systems.[31] A more detailed examination of the Second Law helps clear up the discrepancy.

For a system of weak or noninteracting particles, the implications of the Second Law are fairly clear. If such systems are isolated (i.e., they cannot exchange energy, matter, etc., with their environments), then the usual interpretation of the law holds. For nonisolated systems, the situation changes considerably.[32] In this case, exchanges with the environment take place. The internal entropy of the system will still increase or remain constant in time. However, entropy can now be exchanged with the environment. The flux of entropy may be such that the overall entropy of the system decreases. For the noninteracting particles, this decrease in entropy is often associated with a decrease in the accessible states, or an increase in order.

The situation is much less clear for nonisolated systems of strongly interacting particles or agents. In the presence of nonequilibrium constraints, the system can evolve toward multiple ordered states via phase transitions.[33] Kauffman notes that “the second law really states that any system will tend to the maximum disorder possible, *within* the *constraints* due to the dynamics of the system.”[34] In sum, for nonisolated systems, whether weakly or strongly interacting, there is no conflict with the Second Law. Systems can move toward states of higher order under the influence of exchanges with the environment and external, nonequilibrium constraints.[35]

Attractors provide a further means of visualizing the increases in order.[36] Every system has an associated *phase space.* In the simplest terms, the phase space is the set of all possible states in which the system may exist.[37] The dynamics and external constraints imposed on the system will generally limit it to certain regions of phase space. These regions are called *attractors*. An undisturbed system remains within the confines of its attractor. In general, the attractors contain only a fraction of the total volume of phase space. In this sense, then, attractors represent an increase in order of the system: the system is not free to wander through all regions of phase space.[38]

Attractors themselves are dynamic. The environment of the system is not necessarily static. It may change in time, for example, if some of the constraints are altered. As the environment changes, the attractors shift. The system correspondingly modifies its behavior, as it is constrained to its attractors.

Attractors are not just abstract notions that apply to systems from physics and mechanics. Attractors exist for all dynamic systems, whether they are immune systems, neural networks, bodily organs, communities, or ecosystems.[39] Economies self-organize around their attractors, as they are complex dynamic systems. The attractors define the types and limits of behavior that the system can exhibit. In short, attractors may be thought of as imposing order upon the complex systems.

What is the applicability of adaptive self-organization to warfare, and in particular, to economic targeting? Since economies are complex entities, the ties are direct. Two examples, one abstract and the other concrete, will help illustrate the connections between adaptive self-organization and warfare.

The abstract example draws from Carl von Clausewitz's notion of a reactive enemy. In discussing the differences between warfare and the arts and sciences, Clausewitz states:

> The essential difference is that war is not an exercise of the will directed at inanimate matter, as is the case with the mechanical arts, or at matter which is animate but passive and yielding, as is the case with the human mind and emotions in the fine arts. In war, the will is directed at an animate object that *reacts*.[40]

Furthermore, the two parties in the conflict mutually interact and affect one another:

> War, however, is not the action of a living force upon a lifeless mass (total nonresistance would be no war at all) but always the collision of two living forces. The ultimate aim of waging war, as formulated here, must be taken as applying to both sides. Once again, there is interaction.[41]

Clausewitz implies later that interactions occur not only between the combatants, but also in the processes of war itself.[42] He portrays war as an interactive undertaking in which each adversary reacts to changes in himself originating in enemy actions, and changes in the environment arising from the actions of both combatants.

These concepts parallel the notions of adaptation to environmental changes and self-organization. The conflict changes the environment in which the combatants exist. The environmental shifts modify the phase space and the attractors of the adversaries. In order to survive, the adversaries must adapt to the changes. An adversary who cannot adapt or whose attractors shift too radically will end up broken and defeated on the battlefield.

Wartime economic substitutions and workarounds provide a second, more concrete connection between adaptation theories and warfare. Economies are organic and adjust to the disruptions of war, in manners consistent with Clausewitzs observations. An examination of the WWII wartime economies and Iraq in the aftermath of the Persian Gulf War reveals several possible adjustments:

elimination of excessive or luxurious uses of items;

diversion of resources and the means of production from nonessential to militarily essential items;

rationing or reduced distribution of essential goods and services;

substitution of different raw materials for scarce ones required in manufacturing;

increasing the number of shifts per day;

operation of equipment in hazardous manners that would normally not be employed in peacetime;

removal of cost reducing practices that hinder the production rate (practices that reduce the costs of fuel, coal, electricity, water, etc.); and

dispersal of critical industries and other measures to reduce the vulnerability to attack.[43]

Although the direct and indirect costs of these adjustments may be high, wartime necessity can justify their implementation. Furthermore, Moncur Olson, Jr., makes three observations about the degree of substitution that an economy can make.[44] First, when a small portion of any industry is destroyed, the economy can adjust to make up the relatively small shortfalls. Items are shifted from nonessential uses to the critical needs. As a result, he argues that an economy can weather small losses to even a large number of industries (such as those created by the British area bombing of Germany). Second, if a large part of an industry is destroyed, the economy has a much more difficult time making up the losses.[45] Finally, an economy can accommodate the loss of most of any industry provided the industry is small enough. The small, critical industry upon which the entire economy hinges simply does not exist. These ideas closely track with some of the concepts of phase spaces and attractors.

If small perturbations occur in a system, the attractors shift by relatively small amounts.[46] If the shifts are not too great, the system transitions to the modified attractors. This particular case roughly corresponds to Olson's first and third points. Economic adaptation accommodates relatively small disturbances. However, if the perturbations are large, the qualitative nature of the phase space may change. Alternatively, a large disturbance could so modify the attractors that the system shifts to a different attractor altogether. In either case, the behavior of the system changes markedly. Olson's second observation corresponds to this case. The changes in the attractors thus qualitatively explain the modifications observed in the economies.[47]

Adaptive self-organization is the second characteristic of complex systems. The systems tend to crystallize into some ordered state, from which the emergent behaviors become apparent. The exact origins of the order are uncertain. Economic systems are subject to self-organization, and display many of its properties. In particular, the adjustments of economies under the duress of war are manifestations of the dynamics of adaptive self-organization.

## Evolution to the Edge of Chaos

Dynamic systems occupy a "universe" composed of three regimes.[48] The first is an ordered, stable region. Perturbations to the systems tend to die out rapidly, creating only local damage to the system. Additionally, information does not flow readily between the agents. In the second regime, chaotic behavior is the rule. Disturbances propagate rapidly throughout the system, often leading to destructive effects. The final regime is the boundary between the stable and chaotic regions. Known as the complex regime, it is a phase transition region between the stable and chaotic regions. According to Kauffman, systems poised in this boundary regime are optimized to evolve, adapt, and process information about their environments.[49] Disturbances propagate

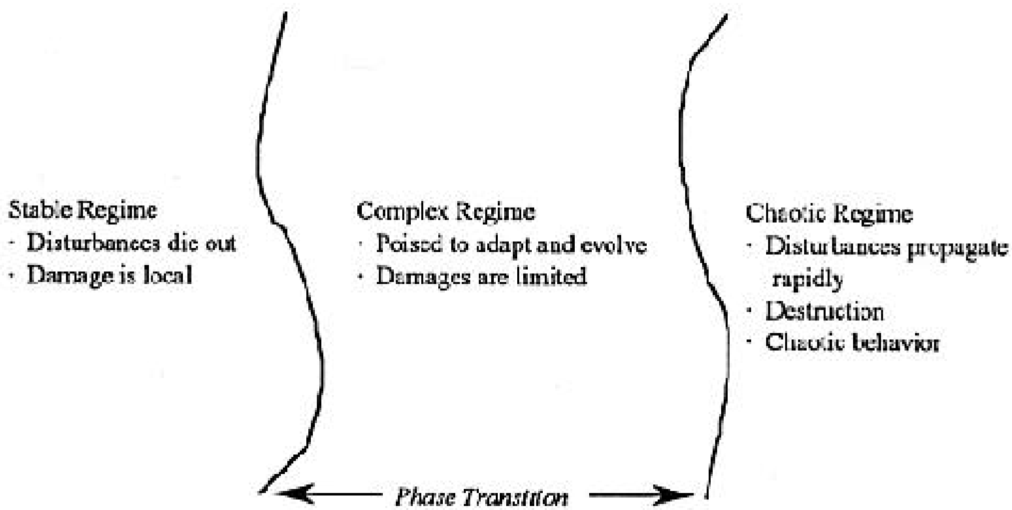



**Figure 3. The Three Regimes of Dynamic Systems**

throughout the system, yet damages are limited, allowing further system evolution. Figure 3 shows the relationship between these three regimes.

As complex systems evolve, they appear to move toward the edge of the chaotic regime.[50] As time progresses, they generally increase in complexity. Competition and environmental disturbances force the systems to discover new "functions" that allow them to perform new tasks and better survive in a competitive world. These phenomena parallel natural selection. The same type of growth in complexity occurs in man-made objects, such as jet engines, microprocessors and microelectronics, and software. Social, economic, and bureaucratic structures display similar evolution patterns as well.

In the case of bureaucratic structures, Allison's Organization Process Model II illustrates the evolution toward the edge of chaos.[51] The essence of this model is that a government (or by implication, an organization) is "a loose conglomeration of semi-feudal, loosely allied organizations . . . Governmental behavior can therefore be understood, according to [this] model, less as deliberate choices and more as outputs of large organizations functioning according to standard patterns of behavior."[52] According to this model, a government approaches a problem by first factoring it into manageable pieces. It distributes the pieces to the appropriate agencies for resolution. The agencies solve their parts of the problem by applying standard operating procedures (SOP). Normally, the agencies have repertoires of SOPs from which to choose. An agency will usually choose the first solution to the problem that it finds in its repertoire, rather than looking for the best solution. Thus, the individual solutions generally are *satisfying* rather then *optimizing.* The overall solution to the problem is a conglomeration of individual solutions, tailored by governmental leaders.[53] Problem resolution is essentially the output of organizational routines.

Occasionally, a problem confronts an agency for which no SOP is applicable. Then, the agency uses a simple-minded procedure to develop an applicable solution. The agency searches its existing routines for one that can be adapted to the problem at hand. It is more likely to adapt an existing SOP than generate an entirely new procedure. Nevertheless, the agency learns from the experience and adds the new SOP to the repertoire. The evolutionary growth is slow and incremental, although major disasters may precipitate large organizational changes.

In many respects, the Model II evolutionary growth parallels that of a complex system.[54] The system has a set of internal "models" or analogies that drive its behavior. The models are used to interpret the environment and guide the system's reactions. The models are not static; they are modified to accommodate new situations. Feedback about the performances of the models further tunes them. The models are the counterparts of Allison's SOPs; both fulfill the same role in problem resolution and system evolution.

By extension, the same processes occur in an economy during a conflict. Destruction of materiel, the means of production and distribution, and other infrastructure elements pose significant problems that the economic system must overcome. The damage inflicted by the adversary drives the system away from the edge of chaos and toward either the chaotic or stable regions. The system attempts to return to the complex region by invoking a set of emergency SOPs, such as those detailed by Olson and William M. Arkin or employed by Albert Speer. Although not evolution per se, the movement back toward the edge of chaos is an attempt to limit or overcome the damages and return to the status quo.

Evolution toward the edge of chaos is a natural behavior of complex systems. Allison's organizational process models closely tracks the major themes of this evolution. There appear to be similarities between the reactions of economies to wartime destruction and the dynamics of organizations and complex systems. Although only advanced here as a hypothesis to explain the actions of an economy under the pressures of war, the use of complexity theory to frame the problem merits further examination.

### Information Processing

In general terms, complex systems possess the ability to process information.[55] The systems sense their environments and collect information about surrounding conditions. They then respond to this information by using a set of internal models to guide their actions. The systems may also encode data about new situations for use at a later date. This characteristic is closely related to the adaptation that occurs near the edge of chaos.

Information processing is similar to Boyds OODA loop.[56] In his model, a system observes some event of interest, decides how to resolve a problem posed by the event, and finally acts upon its decision. This process frequently arises during military operations, where the commander's objective is to "get inside the enemy's OODA loop." He does this by simultaneously destroying the enemys capability to sense, process, and act on information while preserving his own ability to do so. Once reaching this point, the commander can force the enemy to constantly react rather than take the initiative. Both the friendly and enemy sides cycle through the OODA process; the friendly objective is to do so more rapidly than the adversary. In doing so, the enemy's actions lose coherence with the changing environment.

In an exceptionally close paraphrase of Boyd's theory, Kauffman describes how information is processed by complex systems:

> But it is also plausible that systems poised at the boundary of chaos have the proper structure to interact with and internally represent other entities of their environment . . . organisms sense, classify, and act upon their worlds. In a phrase, organisms have internal models of their worlds which compress information and allow action . . . Such action requires that the world be sufficiently stable that the organism is able to adapt to it. Were worlds chaotic on the time scale of practical action, organisms would be hard pressed to cope.[57]

By sensing, classifying, and acting upon their worlds, organisms cycle through Boyd's OODA loop. Chaos on the time scale of practical action implies that some organisms are unable to assimilate environmental conditions fast enough. Here, the environmental conditions change within a single period of an organism's OODA loop, precluding it from acting coherently. In essence, the environment has "gotten within the organism's OODA loop." The correspondence between Boyd's model and the information processing capabilities of complex systems is striking.

Information processing is the final major characteristic that complex systems possess. It relates to the system's ability to sense its environment and act in a manner consistent with a set of internal models. The frameworks erected by complexity theory, Allison's organizational processes model, and Boyd's OODA loop possess a remarkable degree of consistency with respect to information processing.

## Summary

In this chapter, we have explored the nature of complex systems. These systems are large collections of interacting agents. The agents may be tightly or loosely coupled to one another via linear or nonlinear linkages. The interactions between the agents define and influence the environment in which they exist. Complex systems are not simply abstract creations of mathematicians and scientists; real world examples abound in such diverse fields as physics, chemistry, biology, sociology, anthropology, and most importantly for this study, economics.

Further, complex systems display several virtually universal characteristics. First, the local interactions of agents give rise to emergent, global behavior. This behavior cannot be predicted a priori, even given perfect knowledge of the individual agents. Consequently, reductionist analyses tend to miss the important macroscopic features of systems while concentrating on the microscopic ones. The analyst must use holistic or constructionist approaches to determine emergent, global behavior. Second, systems tend to adapt to their environments and self-organize. Instead of tending toward maximum disorder as do weakly interacting isolated systems, complex systems spontaneously crystallize into highly ordered states. Third, systems evolve toward the edge of chaos and increase in complexity as time passes. They "learn" from their environments and add new functions to cope with previously unknown conditions. In doing so, they increase their complexity and adapt along the edge of chaos. Finally, systems exhibit the ability to process information. Simply put, they can sense their environment and react to it based on internalized models. Information processing is closely related to a system's ability to learn near the edge of chaos. Although these properties may appear to be associated with living organisms only, they apply to complex systems in general, ranging from the man-made to the organic to the sociological and cultural.

Since an economy is perhaps the "example par excellence" of complex systems, economic targeting should take into consideration the above characteristics. In particular, planners must bear in mind that reductionist approaches to targeting will miss the global properties of economies—and consequently, the global effects of an attack. A holistic approach, in which the synergies between target sets are properly included, is the correct one to follow. Other considerations that play into (economic) targeting, such as Olson's theories of substitution and Allison's models of organizational dynamics, fall naturally under the framework of complexity theory. In short, economies are complex, adaptive systems and they should be targeted as such.

In the next chapter, we will look at four economic infrastructure elements from a nonreductive viewpoint. The elements are national electric grids, natural gas distribution networks, oil distribution networks, and telecommunication systems. Of particular interest are the ties between each of these elements. Although limiting the study to only four elements is in its own right reductionist, it is a first step in demonstrating the types of synergies that can be expected within economic structures. It is furthermore a step away from the traditional method of targeting each element in isolation.

**Notes**

1. An interesting philosophical introduction to complexity science may be found in John L. Casti, *Complexification: Explaining a Paradoxical World Through the Science of Surprise* (New York: HarperCollins Publishers, Inc., 1994), 269–78.

2. These works include Alan Beyerchen, "Clausewitz, Nonlinearity, and the Unpredictability of War," *International Security*, vol. 17, no. 3 (Winter 1992/93): 59–90; Maj Eileen

Bjorkman et al., "Chaos Primer," in *Air Campaign Course 1993: Research Projects*, ed. by Dr Richard Muller, Lt Col Larry Weaver, and Lt Col Albert Mitchum (Maxwell AFB, Ala.: ACSC, 1993); Siegfried Grossmann and Gottfried Mayer-Kress, "Chaos in the International Arms Race," *Nature*, vol. 337, no. 6209 (23 February 1989): 701–4; Steven R. Mann, "Chaos Theory and Strategic Thought," *Parameters*, vol. 12, no. 2 (Autumn 1992): 54–68; and Lt Col Pat A. Pentland, "Center of Gravity Analysis and Chaos Theory or How Societies Form, Function, and Fail," unpublished thesis (Maxwell AFB, Ala.: Air War College, 1993).

3. Several books have recently appeared that survey the field. The most accessible are Casti; Roger Lewin, *Complexity: Life at the Edge of Chaos* (New York: Macmillan Publishing Company, 1992); and M. Mitchell Waldrop, *Complexity: The Emerging Science at the Edge of Order and Chaos* (New York: Simon & Schuster, 1992). A more theoretical work dealing with the mathematical aspects of complexity theory is Grégoire Nicolis and Ilya Prigogine's *Exploring Complexity: An Introduction* (New York: W. H. Freeman and Co., 1989). Finally, biological aspects of complexity and self-organization may be found in Stuart A. Kauffman, *The Origins of Order: Self-Organization and Selection in Evolution* (New York: Oxford University Press, 1993). In particular, chap. 5 of Kauffman's work takes an in-depth look at complexity.

4. Chaotic systems provide an excellent illustration. The equations leading to chaos can be surprisingly simple. For example, the logistics map is an idealized model describing how animal populations change in time. Given some population $x_n$ at time $t_n$, the population $x_{n+1}$ at time $t_{n+1}$ is given by:

$$x_{n+1} = rx_n(1 - x_n)$$

where $r$ is a constant. This model is simple in form, yet possesses very rich dynamics. A second example is Lorenz's model of a fluid system (the Rayleigh-Benard instability). His model consists of three coupled, nonlinear, first order differential equations. Like the logistics equation, this simple system displays a wide variety of dynamic behaviors, including chaos. For details on these chaotic systems, see Edward Ott, *Chaos in Dynamical Systems* (Cambridge, Mass.: Cambridge University Press, 1993), 31–44, 57–59.

5. Charles Perrow, *Normal Accidents: Living with High-Risk Technologies* (New York: Basic Books, Inc., 1984), 89–100.

6. Edwin (Bud) L. Averill, senior electrical engineer, Production Engineering, Public Service Company of Oklahoma, interview with author, Tulsa, Okla., 26 January 1994. Note that foreign systems may operate in different manners.

7. Perrow, 72–89. We shall use the terms *sequential* and *branching* in lieu of Perrow's labels linear and complex, respectively, to avoid confusion with the previous definitions of linearity and complexity.

8. Alfred C. Mierzejewski, *The Collapse of the German War Economy, 1944–1945* (Chapel Hill: University of North Carolina Press, 1988), chap. 2.

9. Waldrop, 145.

10. Ibid.

11. A sampling of some of the popular writings on complexity in economies includes W. Brian Arthur, "Why Do Things Become More Complex?" *Scientific American*, vol. 268, no. 5 (May 1993): 144; W. Brian Arthur, "Pandora's Marketplace," *New Scientist* (Supplement), vol. 137, no. 1859 (6 February 1993): S6–S8; W. Brian Arthur, "Positive Feedbacks in the Economy," *Scientific American*, vol. 262, no. 2 (February 1990): 92–99; Lewin (1992), 10; and Waldrop, chap. 1. Perrow's work on "normal accidents" is essentially an analysis of many economic and technological systems from the vantage point of complexity theory, although he does not couch it as such.

12. Ian Stewart, "A New Order," *New Scientist* (Supplement), vol. 137, no. 1859 (6 February 1993): S2–S3.

13. Graham T. Allison, *Essence of Decision: Explaining the Cuban Missile Crisis* (HarperCollins Publishers, 1971).

14. First Lt Mancur Olson, Jr., "The Economics of Target Selection for the Combined Bomber Offensive," *RUSI Journal*, vol. 107 (November 1962): 308–14; and Mancur Olson, Jr., *The Economics of the Wartime Shortage: A History of British Food Supplies in the Napoleonic War and in World Wars I and II* (Durham: Duke University Press, 1963).

15. John R. Boyd, "A Discourse on Winning and Losing," unpublished briefing and essays, Air University Library, document no. MU 43947 (August 1987). Boyd introduces his concept on p. 5 of chap. 1, "Patterns of Conflict," and develops it with historical examples.

16. Lewin (1992), 12–13, 47.

17. James P. Crutchfield et al., "Chaos," *Scientific American*, vol. 255, no. 6 (December 1986): 46–57.

18. Waldrop, 88.

19. Nicolis and Prigogine, 13.

20. Adapted from Lewin (1992), fig. 1, 13.

21. Crutchfield et al., 56; Murray Gell-Mann, quoted by Roger Lewin, "The Right Connections," *New Scientist* (Supplement), vol. 137, no. 1859 (6 February 1993): S4–S5; Casti, chap. 5, "The Irreducible," 171–211.

22. P. W. Anderson, "More Is Different," *Science,* vol. 177, no. 4047 (4 August 1972): 393–96.

23. Allison, 144.

24. Carl von Clausewitz, *On War*, ed. and trans. by Michael Howard and Peter Paret (Princeton: Princeton University Press, 1976), 75, emphasis in original.

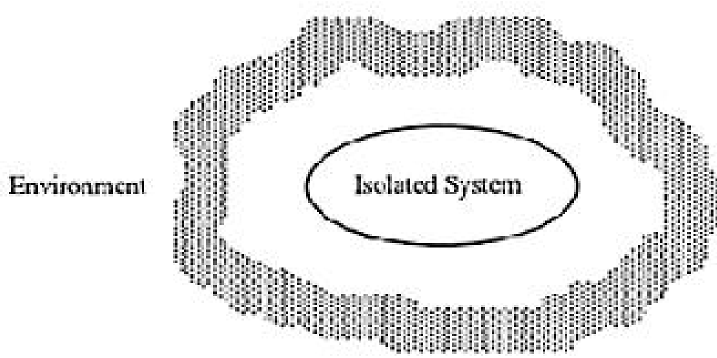
25. For example, Douhet argues that a massive, time-compressed attack against an enemy population will shatter civilian morale and destroy the social structure of the nation. As a result, the civilians will revolt against the government and its policies that led to war. The uprising will eventually force changes in governmental policies that the aggressor desires. Here, the attacks (time compressed, against civilians) trigger a mechanism (civilian revolt against the government) that obtains the desired political outcome (change in governmental policies). Giulio Douhet, *The Command of the Air*, trans. by Dino Ferrari (Washington, D.C.: Office of Air Force History, 1983), 20, 51, 57–61, 125–27.

26. Kauffman (1993), chap. 5; Stuart A. Kauffman, "Antichaos and Adaptation," *Scientific American*, vol. 265, no. 2 (August 1991): 78–84; Nicolis and Prigogine, especially chap. 1; Per Bak and Kan Chen, "Self-Organized Criticality," *Scientific American*, vol. 264, no. 1 (January 1991): 46–53.

27. Kauffman (1993), 173.

28. See chap. 1 of Nicolis and Prigogine for specific—and widely varied—examples.

29. An isolated system is one that does not exchange energy or matter with its environment; no fluxes arise between the system and its surroundings. Pictorially, the isolated system is as follows:




The system sits as though in its own shell. For the isolated system, the Second Law may be expressed as:

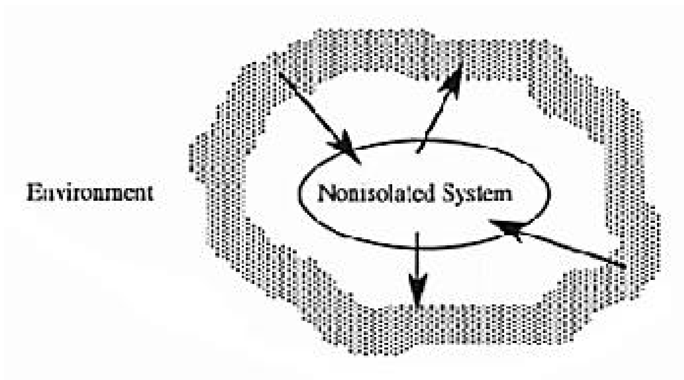
$$\frac{dS}{dt} \geq 0$$

where $S$ is the entropy. Note that the entropy of the system either increases or remains the same in time, but never decreases.

30. Ibid., 61–65.

31. Col John A. Warden III, “Strategic Warfare: The Enemy as a System,” unpublished manuscript, 3 January 1993, 9–10.

32. A nonisolated system has interactions with its environment, leading to fluxes (matter, energy, etc.) between the system and the environment. Pictorially, this situation now looks like this:




The entropy $S$ of the system now consists of two components: the internal entropy $S_i$ due to the processes in the system itself, and the external entropy $S_e$ due to the fluxes between the system and the environment. The Second Law now becomes:

$$\frac{dS}{dt} = \frac{dS_i}{dt} + \frac{dS_e}{dt}$$

As with the isolated system, the change in internal entropy $dS_i$ must be greater than or equal to zero. However, there are no restrictions on the sign of the change of external entropy $dS_e$. For large enough negative values of $dS_e$, the total change in entropy can be driven negative, indicating an overall decrease in entropy of the system. The important point here is that the decrease in entropy occurs because of the entropy fluxes between the system and its environment.

33. Constraints are conditions that are externally imposed upon the system. They can lead to fluxes (exchanges of energy or matter) between the system and its environment. In this case, the system is no longer in a state of equilibrium with the environment. Nicolis and Prigogine, 55–56, 62.

34. Kauffman (1993), 191, emphasis in original.

35. These points are nicely summarized in Pentland, 29–31.

36. Kauffman (1993), 175–181, presents an excellent discussion of phase spaces and attractors. See also David Ruelle, “Les attracteurs étranges,” *La Recherche*, no. 108 (February 1980): 132–144.

37. Two examples from elementary mechanics should clarify the phase space concept. Consider first a particle bouncing around inside a box. The particle is characterized by its position and its momentum. The position and momentum are termed the *phase variables*. In three dimensions, there are three position (spatial) variables ($x, y, z$) and three momenta ($p_x, p_y, p_z$), one for each spatial coordinate. The phase space, then, is a six-dimensional space with an axis for each phase variable. The sextuple ($x, y, z, p_x, p_y, p_z$) describes the points in this phase space. Each point corresponds to a particular position and momentum of the particle in the box. The totality of phase space describes every possible state (position and momentum) of the particle.

As the particle moves in the box, its position and/or momentum change. The point in phase space representing the state of the particle moves as well, tracking each new instantaneous state. In this manner, a curve appears in phase space, representing the evolution of the paricle in the box. This curve is called the *phase trajectory*.

As a second example, consider the pendulum of a grandfather clock. Its motion at some given instant of time is characterized by its velocity and its position (such as its angular displacement from the vertical). The phase variables are therefore the velocity and posistion. The phase space has two dimensions, one for the velocity and the other for the position of the pendulum. As in the case of the particle in the box, the points of phase space are directly related to the state of the pendulum.

38. The attractors for the pendulum in the previous footnote are quite simple in form. If the pendulum is frictionless, the attractor is a circle about the origin of phase space. If there is friction in the pendulum, it will eventually come to rest (zero velocity, zero displacement from the vertical). In this case, the attractor is simply the point at the origin of coordinates in phase space. Notice that these attractors, which represent all possible motions into which the pendulum can settle, dramatically reduce the total volume of phase space. The phase trajectories of a system eventually lead to an attractor.

39. Kauffman (1993), 191.

40. Clausewitz, 149, emphasis in original.

41. Ibid., 77.

42. Beyerchen, 73.

43. Olson (1962), 208–14; and William M. Arkin, Greenpeace, interview with author, 29 April 1994.

44. Olson (1962), 213–14.

45. As Olson notes, the Allied planners correctly recognized this fact during the war. In an 8 May 1943 memorandum to General Arnold, the Committee of Operations Analysts stated, "The Committee has arrived at certain conclusions in regard to target selection. It is better to cause a high degree of destruction in a few really essential industries or services than to cause a small degree of destruction in many industries. Results are cumulative . . . ." Guido R. Perera, *History of the Organization and Operations of the Committee of Operations Analysts*, 16 November–October 1944, vol. 2, tab 22, USAF Historical Research Agency (hereafter cited as HRA), file 118.01.

46. Strictly speaking, we must address the issue of the structural stability of the attractors. An attractor or other phase space feature is said to be structurally stable if perturbations cause relatively small changes in its form. Quantitative changes may occur, but the qualitative features of the phase portrait remain the same. However, if perturbations lead to qualitative changes such as bifurcations, the attractor or phase space feature is said to be structurally unstable. If an economy is operating on a structurally unstable attractor, even small changes of Olson's first or third types may lead to radical shifts in the economy. Structural stability is reminiscent of the phrase "the straw that broke the camel's back." Nicolis and Prigogine, 93–98.

47. Under Albert Speer and in the face of Allied bombing attacks, the German economy increased its armaments production in WWII with a variety of relatively "subtle" efforts rather than a massive reorganization. These efforts included

reallocation of resources within industry;
use of many individual efficiencies that together led to massive savings of all the factors of production;
increased labor productivity;
dissemination of the best methods of increasing production throughout industry;
reduction of the number of models and variants of weapon systems; and
encouragement of management efficiencies by industrial self-responsibility.

See Mierzejewski, 17–19. One may also conjecture that the German economy was operating on a very stable attractor. The large perturbations brought on by the bombings initially caused shifts in the attractor that Speer's subtle efforts were able to compensate for. The ultimate collapse of the economy is indicative of a massive or qualitative change of the attractor.

48. Kauffman (1993), 173; Lewin (1992), 48–55; Nicolis and Prigogine, 8; Larry O'Brien, "Walking at the Edge of Chaos," *AI Expert*, vol. 8, no. 12 (December 1993): 13–15; Stewart, S2–S3; and Waldrop, chap. 6.

49. Kauffman (1993), 173.

50. Lewin (1992), 149; Arthur (May 1993), 144.

51. Allison, chap. 3.

52. Ibid., 67.

53. Notice that the solution is an example of emergent behavior: the interactions of the individual agencies lead to the overall solution of the problem.

54. Waldrop, 145–47.

55. Lewin (1992), 15, 138; Waldrop, 145–47.

56. Boyd, 5.

57. Kauffman (1993), 232. Although Kauffman is discussing biological systems, complex systems in other domains process information in essentially the same manner.

# Chapter 3

# Synergies and Infrastructure Elements

In the previous chapter, we saw that economies are complex systems. However, the text treated the subject in a rather abstract manner, employing the language of complexity theory. For practical purposes, the planner needs to appreciate in more solid terms the synergies that exist between economic infrastructure elements. In this chapter, we address this point.

A recurring theme throughout the chapter will be the shortcomings of the reductionist approach. In the past, air planners have generally followed the reductionist path, primarily due to a lack of suitable analysis tools.[1] Nevertheless, this traditional approach must yield to a synthesis-based methodology.

This chapter explores in detail the interlinked nature of economic infrastructure elements. The goals are to deepen our appreciation of the complex nature of these elements and to demonstrate the pressing requirement for a nonreductionist approach. The chapter first contemplates several issues associated with targeting in general and synergies in particular. The balance of the chapter then examines a simplified infrastructure, composed of an electrical grid, a natural gas pipeline system, an oil pipeline system, and a communications network. The subtle problems posed by targeting interrelated systems should become clear as we study this example.

## Targeting Issues

When examining an enemy economy, a fundamental issue the air planner must address is whether its infrastructure elements are also centers of gravity. The value of the economic targets must be considered in light of political and military strategies and the commander's objectives. A Douhet-style campaign aimed at the enemy population might place a high value on economic elements under certain circumstances. However, a strategy based on isolating enemy leadership may place an entirely different emphasis on an economy.[2] The political objectives and the nature of the conflict are important determinants of centers of gravity.[3]

In addition, an infrastructure element may not be important just in economic terms. Many elements have military as well as societal or economic significance. National railroad systems may provide the bulk of long distance freight shipping capacity for a nation; yet the same railroads, locomotives, and rolling stock may also serve as the primary means of national mobilization. Similar examples can be found in other infrastructure elements. Thus, each element must be examined from a military and economic viewpoint.

Further, the value of each element varies on a country-by-country basis, as well as with the particular contingency. The cultural and societal dimension cannot be overemphasized.[4] For example, American society is highly organized around plentiful energy sources (electricity, oil, coal, etc.). Likewise, energy sources are the driving force behind much of US economic power. Without a continuous, reliable energy supply, the US economic base would be in dire straits. However, in an agrarian society, such as Vietnam in the 1960s, the same elements may be of negligible significance. Societies are individualistic, and each must be regarded as such.

Synergistic effects between different target sets also play into center of gravity considerations. As with any complex system, surface or outward appearances of certain elements may be deceiving. Nonlinear, branching linkages may place greater weights upon certain elements than are initially evident, based upon a cursory examination. As a hypothetical example, we assume that some Country X produces all of its electricity from oil- and gas-fired generators. Furthermore, the gas compressors, oil pumps, controls, valves, and central dispatch station along the pipeline require electricity to function. A feedback loop is present in the electric grid-POL distribution complex. Loss of electricity will affect the pipeline operations. Similarly, a reduction or shutdown of oil and gas flow will impact electrical generation. The analysis must not stop at this simple level of determining synergies; the importance of electricity, oil, and natural gas must be evaluated for the society as a whole. To illustrate this point, we further assume that the society has few requirements for POL. At first glance, POL may have little significance as a center of gravity. However, if the society or military is critically dependent upon the national electric grid, then oil and gas assume greater importance as economic centers of gravity. Bottlenecks and synergies may in themselves be deceiving; they too must be examined from a holistic viewpoint.

In a related vein, the existence of substitutes, workarounds, emergency plans, and repair capabilities may obviate some seemingly promising economic targets. Certain elements may possess extensive contingency plans or backup capabilities.[5] Other elements may be highly redundant and flexible. Such considerations will complicate targeting, and an air planner must consequently factor them into center of gravity analyses as well. An economic infrastructure element may be a valid center of gravity, but it may also be very difficult to destroy in a direct manner.

A network analysis is an important part, then, in evaluating economic centers of gravity and target sets. This is all the more important in light of complexity theory, where emergent behaviors may be more critical than the properties of the individual agents. With these ideas in mind, we turn now to an example that further illustrates the intricacies of complex, interconnected economic systems.

## Dissecting an Economy

In this section, we will investigate the interrelationships that exist in a simple economy. For our purposes, it will consist of four primary infrastructure elements: an electrical grid, a natural gas distribution network, an oil pipeline system, and a communications network. Figure 4 sketches the appropriate elements.

The model economy is purposely simple so that the principal connections within it are clear. The elements themselves are notional, with many of their details omitted. In the electrical system, for example, the generator step-up transformers and distribution network layouts within the cities are deleted for clarity. (Chapter 5 contains more detailed information on electrical grids, POL distribution networks, communications systems, and transportation networks.)

The electrical grid has five main generators. Two generators are gas fired. They connect directly to the gas pipeline and have no local gas storage. The other generators are oil fired. These generation stations stock an average of two months' fuel on site. A dispatch center with a backup site controls the electrical flows throughout the network. The control centers have backup electrical generators with three-week fuel supplies. A satellite communications network transmits data and control information between the elements of the electrical grid. Landline data and voice communications back up the satellite system.[6] Note that Figure 4 only depicts the long-haul transmission system and generators. The notional distribution networks show the grid connections to the other infrastructure elements (such as gas compressors and oil pumps) that require electrical power.

The natural gas pipeline network consists of several main pipelines, numerous spur lines, two gas conditioning plants, and 15 compressor stations. The compressors and related controls are electrically powered. Each compressor station connects directly to the electrical grid. The gas conditioning plants also tie into the electrical grid. A computerized control center with a backup control site runs the pipeline. Data communications between the control centers and compressor stations rely primarily upon satellite communications with landline data and voice backups. A computerized supervisory control and data acquisition (SCADA) system runs the entire pipeline; safe manual operation is not feasible.[7] Both control sites have backup electrical generators, with two-week supplies of fuel.[8]

The oil pipeline system is similar to the gas pipeline network. The system has several main lines, two refineries, 28 pump stations, a centralized dispatch control center, and a backup dispatch control center. The pump stations and refineries require electricity in order to operate. The dispatch control center uses a SCADA system to manage network operations. Satellite communications relay data between the pump stations and the dispatch control center. Landline data and voice communications back up the satellite system. Each control center has a backup electrical generator, with a two-week fuel

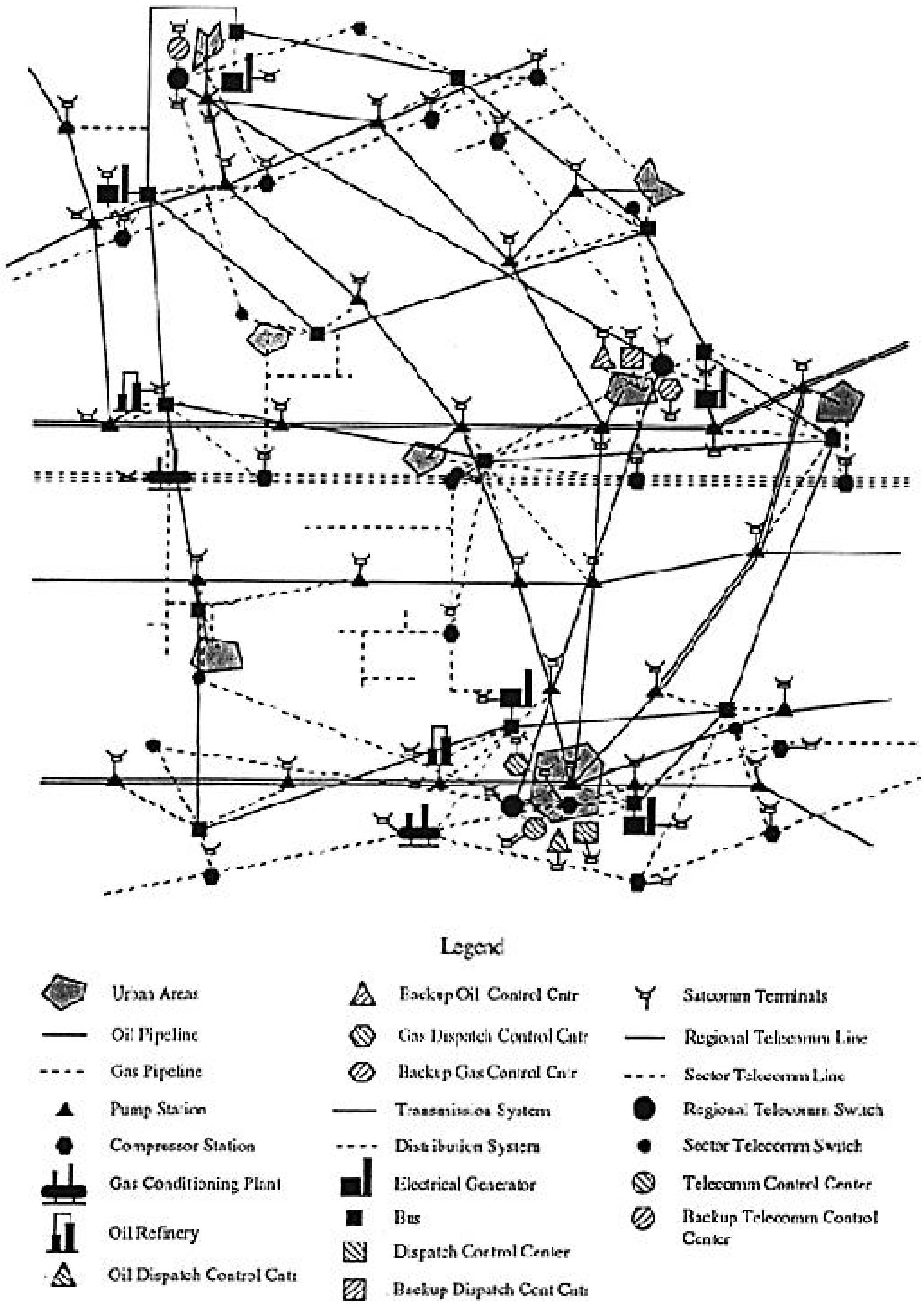



**Figure 4. The Model Economy**

supply. As with the gas pipeline, the network cannot operate safely without its computerized SCADA system.

The communication network ties all of the other systems together. The system consists of a satellite and terrestrial network. It draws power directly from the electrical grid. However, the system has numerous backup generators, each with a two-week supply of fuel. Each major switching station, for example, has a backup generator. A computerized, central control site with a backup site manages all network operations. The network furnishes vital services to the gas and oil pipelines and the electrical grid.[9]

Figure 4 portrays a simplified picture of the real world. The model economy has only four elements; these systems are themselves simplified representations of their real counterparts. Nevertheless, the figure serves to underline the complex, highly interconnected nature of economic infrastructure elements. We shall now examine in detail the nature of this interconnectivity.

### Nodes and Couplings

The systems of the model economy are coupled to one another in intricate manners. Table 1 lists several representative couplings between the elements. Tight coupling is characterized as having no slack, give, or buffering—it is highly time dependent. Loose coupling, on the other hand, has some degree of slack or give. It is not as time dependent as tight coupling. Note that tight, moderate, and loose couplings permeate our notional model.

By examining table 1, we see that tight, moderate, and loose couplings permeate the economy. The gas-fired electrical generators—gas pipeline couplings fall under the tight category, as gas is not stored locally at the generators. If the gas pipelines shut down, then the generators drop off-line. There is no slack or buffer in the couplings. On the other hand, if the fuel oil supplies to the oil-fired generators are interrupted for several weeks, the generators can continue operations by drawing down local fuel reserves. In this case, the coupling is loose. The various control centers have moderate couplings to the electrical grid, as each center has a backup generator. As long as the fuel supplies to the backup generators are uninterrupted, the control centers continue to operate indefinitely. Similarly, the control centers are moderately coupled to the communication systems. Each control center relies primarily upon satellite communications with landlines for backups. If either the satellite or terrestrial communication network fails, the control centers will continue to operate. Only the loss of both communication networks will isolate the control centers. In these examples, the coupling degree indicates the time criticality of the linkages and the availability of backup systems.

The couplings listed in table 1 thus link different economic infrastructure elements together. However, by examining the model further, we see that it has a hierarchical structure. The economy is composed of four elements (electricity, natural gas, oil, and communications). Each element is composed of subsystems (the electrical network contains generators, control centers, sub-

**Table 1**

**Typical Couplings Between Elements in the Model Economy**

| Degree of Coupling | Agents |
|---|---|
| Tight | • Satellite terminals—electrical grid<br>• Gas-fired electrical generators—natural gas pipeline<br>• Natural gas pipeline compressors—electrical grid<br>• Oil pipeline pumps—electrical grid |
| Moderate | • Electrical grid dispatch control centers—communications network<br>• Natural gas pipeline dispatch control centers—communications network<br>• Oil pipeline dispatch control centers—communications network<br>• Natural gas pipeline dispatch control centers—electrical grid<br>• Oil pipeline dispatch control centers—electrical grid<br>• Communication system control centers—electrical grid |
| Loose | • Oil-fired electrical generators—oil pipelines |

stations, etc.). Each subsystem is composed of further subsystems (electrical generators have fuel burners, boilers, steam turbines, etc.), and so on. Tight, intermediate, and loose couplings of agents exist *within* and *between* each level of the hierarchy. Consider the electrical grid. The dispatch control centers are moderately coupled to the generators, transformers, and substations. The loss of the control center and its backup would disrupt the operation of the grid. This illustrates that each agent, then, has links to other agents of the same hierarchical level, as well as possible links to agents at other levels. Clearly, the couplings between infrastructure elements of the model economy are complex. What makes them even more so are the hierarchies of couplings.

The couplings examined so far directly link elements (and agents) to each other. This form of coupling is direct, or first order. Indirect, or higher order, couplings are also present in the network. The gas pipeline network, for example, has a direct linkage to the communication network through its SCADA system. An indirect linkage connects the gas lines and communication system through the electrical network: natural gas fuels two generators which in turn provide electricity to the communication system. (Of course, the oil-fired generators also supply electricity to the electrical grid. This further complicates the example.) Additionally, these systems have several feedback loops. A major feedback loop connects gas-fired generators and the gas pipelines. If the gas supplies to the generators are interrupted, the generators drop off-line. However, the generators provide electricity to the pipelines and compressors. In this manner, a feedback loop forms between the two elements. Even in this simple example, the interconnected nature of the agents is intricate.

All four elements have branching rather than sequential topologies. The branching layouts add redundancies to each of the networks. For example, if a given compressor station fails in the natural gas distribution system, the dispatch control center might be able to reroute gas flows through other pipelines. In this manner, the natural gas system adapts to internal changes or component failures. However, a highly interconnected system also tends to propagate perturbations throughout the entire system. Disturbances in one part of the system thus affect all other parts. If one of the five electrical generators fails, the effects will be felt throughout the entire electrical grid.[10] The branching nature of the layouts further complicates the analysis of the four infrastructure elements.

The branching nature, higher order linkages, and feedback loops that comprise the model make it difficult to intuitively analyze the economic elements. Some of the interactions between the elements are hidden, or at least not obvious. Additionally, the higher order linkages and branches are nontrivial. Depending upon the configuration of a network and its environment, the links may have major impacts upon overall system operation. Consequently, the effects of losing or destroying an agent or a link are not clear. What is clear is that even our simple model requires some form of nodal analysis to determine the results of an attack. Furthermore, a reductionist analysis is inadequate to describe the synergistic effects that arise from the couplings. An analysis based on a nonreductive methodology is the only way to proceed.

A "real" economy is vastly more complicated than the simple example of this section. More than four elements will be present, a myriad of interconnections will tie the agents to one another, and the emergent behaviors will preclude a reductionist analysis. "Back of the envelope" calculations or "rules of thumb" may be sufficient to determine an initial, rough target list. However, these methods will fail when refining the target set required to obtain the commander's objectives, or when projecting the overall results of an attack. As this paper will later illustrate, constructionist nodal analyses are necessary for a deeper understanding of the economy and the targeting process.

## Summary

Couplings and synergies abound in an economy. The interconnectivity goes far beyond the bottlenecks and choke points sought by the member of the ACTS faculty and WWII planners. The intertwined nature of an economy leads to emergent behaviors, which in turn demand a holistic approach to targeting. Every nation is a unique entity, and its particular sociocultural character determines how it values its particular economy. These considerations must all factor into the nodal analyses, and ultimately, the master target list and campaign plan.

The notional economy in this chapter demonstrated that systems consisting of only a few interacting agents can be difficult to intuitively comprehend.

Fortunately, a variety of software tools exist that allow a planner to explore the behavior of various economic infrastructure elements. These codes, mated with several recently developed numerical algorithms, hold significant promise as planning tools for the targeteer. We will delve into these possibilities in the next chapter.

**Notes**

1. Col John A. Warden III, Brad Godfrey, and Bill Ling, manager, Strategic Offense Studies Department, interviews with author, 6 April 1994. Interestingly, synergistic modeling that couples POL and electrical networks has been performed in the past by Sandia. Dr Dennis Engi, supervisor, Strategic Technologies Division, Sandia, interview with author, 6 April 1994.

2. Col John A. Warden III, "Employing Air Power in the Twenty-first Century," *The Future of Air Power in the Aftermath of the Gulf War*, ed. by Richard H. Shultz, Jr., and Robert L. Pfaltzgraff, Jr. (Maxwell AFB, Ala.: Air University Press, July 1992), 57–82, (especially, 63–65); Col John A. Warden III, "Strategic Warfare: The Enemy as a System," unpublishsed manuscript, 3 January 1993, 15–16. See also Ernest May, *Lessons of the Past* (Oxford: Oxford University Press, 1976), 125–42; Bruce A. Ross, "The Case for Targeting Leadership in War," *Naval War College Review*, vol. 46, no. 1 (Winter 1994): 73–93.

3. Steven Metz and Lt Col Frederick M. Downey, "Centers of Gravity and Strategic Planning," *Military Review* (April 1988): 23–33.

4. Lt Col Pat A. Pentland, "Center of Gravity Analysis and Chaos Theory or How Societies Form, Function, and Fail," unpublished thesis (Maxwell AFB, Ala.: Air War College, 1993), 20. In particular, chap. 3 analyzes the sociocultural basis of centers of gravity. Pentland notes that "Values, culture, and social groups interact in many permutations and combinations. They form the basis for beginning a systematic center of gravity analysis. This is especially true when looking at the entire spectrum of conflict rather than just conventional operations."

5. The contingency plans of WilTel, one of the largest telecommunications companies in the US, illustrates this point. In the spring of 1992, floods threatened the buildings inside Chicago's Loop. The company brought truck-mounted electrical generators to three of their downtown sites to supplement the existing standby generators. WilTel also sent an additional fuel tanker and generator technicians to the scene. Engineers planned alternate cable routes in case the flooding destroyed existing cables. As a result, WilTel experienced no communications outages due to the disaster. Gil Broyles, assistant to the president, WilTel, interview with author, 27 January 1994; and Gil Broyles, "The First Cut Is the Deepest," *In Perspective: The WilTel Magazine* (Summer 1992): 30–35.

6. Notional data provided by Edwin L. Averill, senior production engineer, Public Service Company of Oklahoma, interview with author, 26 January 1994.

7. Modern oil and gas pipelines are computer controlled with a supervisory control and data acquisition system. SCADA systems allow operators at a central control site "to control and acquire data from remote facilities such as compressors, pressure-regulating stations, control valves and measurement stations. In general, a SCADA system performs functions in sequential control, continuous control, supervisory setpoint control and data acquisitions." Further, SCADA systems are widespread in US pipeline systems, forming the basis of pipeline control and management. The computerization of pipelines has eliminated personnel skilled in operating a pipeline manually, to the degree that pipeline operations are extremely difficult if not impossible without the computers and SCADA system. Andrew Kwok, "Fundamentals of SCADA and Automated Meter Reading," *Pipeline & Gas Journal* (February 1992): 22–28; Kirk Hilbig, shift supervisor, Williams Pipe Line Company, interview with author, 27 January 1994. Further introductory information on SCADA systems can be found in Vernon J. Sterba, "Choosing the Right Technology for Integrated SCADA Communications," *Pipe Line Industry* (May 1992): 25–28; Andy Wike, "Operating Companies Looking at New SCADA Applications–Part 1," *Pipe Line Industry* (May 1992): 25–38; Andy Wike, "Operating Companies Looking at New

SCADA Applications–Part 2," *Pipe Line Industry* (June 1992): 45–49; Arthur K. McCready, "Client/Server Technology in SCADA Systems," *Pipe Line Industry* (June 1992): 30–38; and William Gabris, "SCADA, MIS Systems Served by New Hardware and Software," *Pipe Line Industry* (April 1993): 21–25.

8. Notional data provided by Kirk Hilbig; Roger E. Rinaldi, engineer, Willbros Butler Engineers, Inc., conversations with author, 15–16 July 1993 and 26–29 January 1994; Max Crocker, project manager, Willbros Butler Engineers, Inc., conversations with author, 15–16 July 1993.

9. Notional data provided by Gil Broyles; James S. Wineinger, engineer, Network Development, WilTel Business Networks, interview with author, 27 January 1994.

10. Note, however, that this *does not* imply that perturbations will drive the system towards instability. We need to perform a stability analysis of the system to determine if a given perturbation damps out in time or increases exponentially and leads to a catastrophic change in the system. See Grégoire Nicolis and Ilya Prigogine's *Exploring Complexity: An Introduction* (New York: W. H. Freeman and Co., 1989), appendix I, 243–55, for a detail explanation of stability analyses.

## Chapter 4

# Modeling and Simulation Techniques

Economic infrastructures are complex, interacting systems that continuously react and adapt to their environment. As we have seen, they may be composed of thousands of units, nonlinear linkages, and feedback loops. Consequently, intuitive estimates of the system-wide effects of an attack upon a given unit may contain significant error margins. "Rules of thumb" or "back of the envelope" analyses developed for individual, isolated target systems may be of little use, as they are generally derived from a reductionist rather than holistic view of an economy. In short, understanding and estimating the effects of attacks upon economic infrastructures is not a simple task due to the complex, interactive character of the problem.

Systems analysis techniques can contribute significantly to the understanding of the inner functioning of an economy. A variety of detailed numerical simulations exist that can be adapted to modeling attacks upon various infrastructure elements.[1] These programs require data bases containing information about a particular element. In principle, a planner could numerically simulate the effects of an attack upon an economy provided he or she had a sufficiently detailed data base and the appropriate computer codes. Master attack plans, target lists, and ultimately the air tasking order could be "fine tuned" with the aid of a computer.

At first glance, the use of a computer to determine an attack plan may appear to be risky at best. First, high-fidelity physical models of the economy might be difficult to develop. (High fidelity generally equates to significant amounts of detailed data about the economy or its infrastructure.)[2] An incomplete data base will lead to approximations and possibly inaccuracies in a simulation. Even if the data is available, anchoring the model to a foreign economy may be impossible: one cannot attack a foreign state simply to validate a model.[3] Second, if the infrastructure elements are tightly coupled, the computer models must be capable of analyzing all of the important elements. A reductionist rather than holistic approach would at best only approximate the results of an attack. Finally, by their very nature, modern economies present a considerable number of possible targets. With potentially thousands of targets, the task of computing a target list that accomplishes a particular military objective appears daunting. It also appears to circumvent human intuition, a critical element in war. Political and military constraints further complicate the numerical problem. Nevertheless, these problems are not insurmountable, especially in light of several recent developments in numerical techniques.

Two different computer algorithms developed during the past decade hold promise in overcoming computational problems in targeting. The first computer method, simulated annealing (SA), draws from statistical mechanics. As its name implies, it is patterned after the molecular processes of annealing and freezing. Genetics and natural selection provide the basis for the second numerical technique, the genetic algorithm (GA). Either of these methods could be readily coupled to existing economic models, thus providing powerful new tools for an air planner.

In this chapter, we will explore numerical simulations of economic infrastructures in more detail. The focus is on targeting, while the objective is to propose a new class of numerical tools that aid targeteers in their systems analyses without replacing their human judgment and intuition. In the following section, we will examine two diametrically different targeting philosophies. One philosophy, based on desired outcomes, is clearly superior to an input-based approach, which is narrow and short term in focus. The remainder of the chapter develops numerical algorithms suited to the output-based philosophy. In particular, it presents details on three numerical techniques that are applicable to air targeting. We will pay particular attention to the relative merits and drawbacks of each technique, two of which (SA and GA) are suitable for targeting purposes. We will tie together all of the theoretical and practical aspects of targeting complex economies with a detailed numerical targeting algorithm of our own design. In this algorithm, a GA coupled to load-flow and hydraulic analysis programs provides specific targeting information for electrical grids and POL distribution networks. The couplings between these two networks complicate the targeting problem. The chapter then concludes with a philosophical discussion on the use of computers versus humans in the targeting process.

## Targeting Philosophies

Two general targeting methodologies exist, each approaching the problem from opposite points of view.[4] The first focuses upon *inputs* to the battle; it concentrates mechanically on the number of sorties and the ordnance delivered. The second approach is based upon *outputs*. In this technique, the selected targets flow from the commanders intent and desired objectives. The input approach is easier and is perhaps employed more frequently. However, the output approach directly addresses the commander's desires, and thus is the preferred method.

The input method is a relatively simpler approach to targeting. Given a particular scenario, this technique seeks the answers to *how* and *how many* questions: how should the enemy forces be attacked, and how many targets should be selected?[5] In schematic form, the planner surveys the available targets, and selects some set to attack. If the results of the attack fulfill the commander's objective, the campaign shifts its emphasis to the next objective. If the results do not meet the objective, the planner can either continue the attacks on the initial target set or abandon it in favor of another set. Figure 5 depicts the input method. In a sense, this method approaches the commander's objectives from a backwards direction: the effort is focused on the inputs (the *how* and *how many* questions) with the goal being outputs that

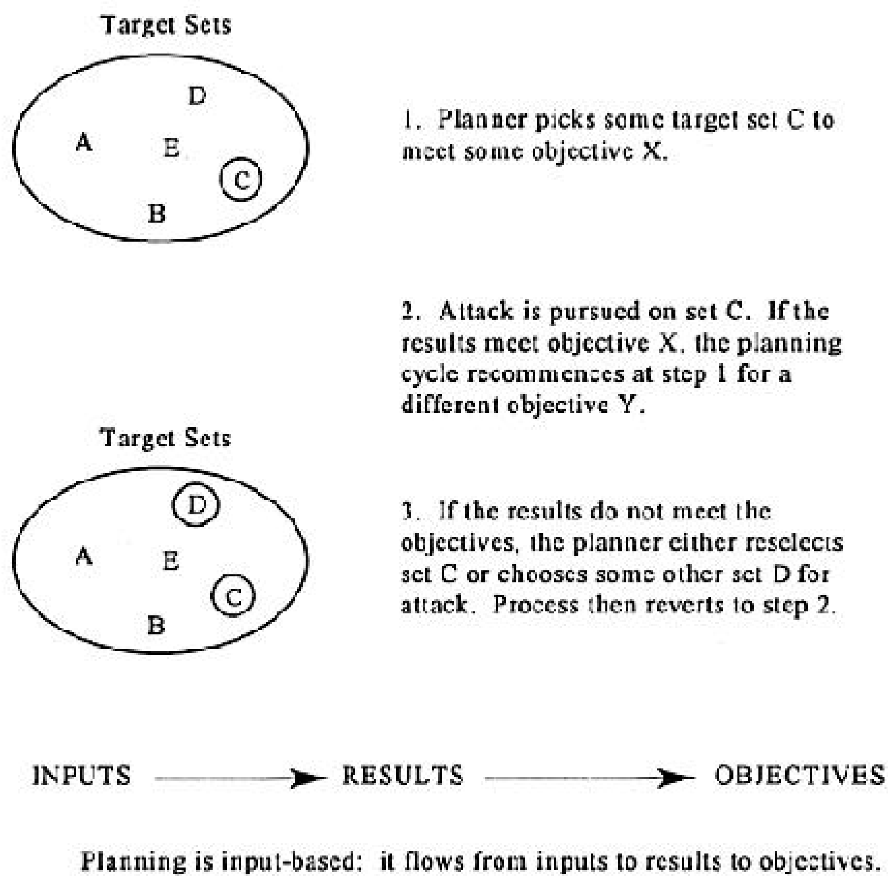



**Figure 5. Simplified View of the Input-based Targeting Process**

support the campaign objectives.

Computer modeling tools can aid the input-based targeting method in a straightforward manner. Given an adequate computer model of the enemy target system, the planner numerically simulates the attack and examines the results. If the results support the commander's objectives, the planner orders the attacks. Otherwise, he uses the simulation to modify the attacks. This approach parallels one type of engineering failure analyses, in which the consequences of the failure of some component or group of parts are determined. The engineer may modify the design or incorporate backup systems depending upon the analysis results. For example, examining a bridge design might reveal that the collapse of a strut would lead to the catastrophic loss of the bridge. The engineer might strengthen the strut or add additional structural members to prevent the collapse of the bridge. Similarly, systems analyses provide important information to the planner, and help him fine-tune his attacks.

The input-based philosophy is limited in its utility, however. It is primarily tactical, as it starts from the *how* and *how many* questions, rather than addressing the larger question of what is accomplished by the attacks.[6] In many cases, it is driven by the immediate battlefield situation, making it a reactive rather than proactive approach. The measures of merit become the numbers of sorties and bombs dropped, rather than what is achieved on the battlefield.[7] Servicing targets becomes the watchword, instead of achieving results. To a large extent, the Army corps commanders pursued this philosophy during Operation Desert Storm. They wanted a fixed number of sorties (inputs) per day in their areas of responsibility.[8] The important measure of merit became the number of sorties flown for battlefield preparation, rather than whether each corps could perform its scheme of maneuver when the ground war began.[9] In sum, this targeting philosophy is narrow in focus and shortsighted in perspective.

The output-based philosophy avoids many of these problems. It essentially flows in the opposite direction of the input-based approach.[10] In this method, the commander's objectives direct certain results—the outputs—that must be accomplished. The desired results then determine the requisite attacks—the inputs. Figure 6 outlines this process. This approach places the primary emphasis on *what* questions: *what* must be achieved in order to meet the com-

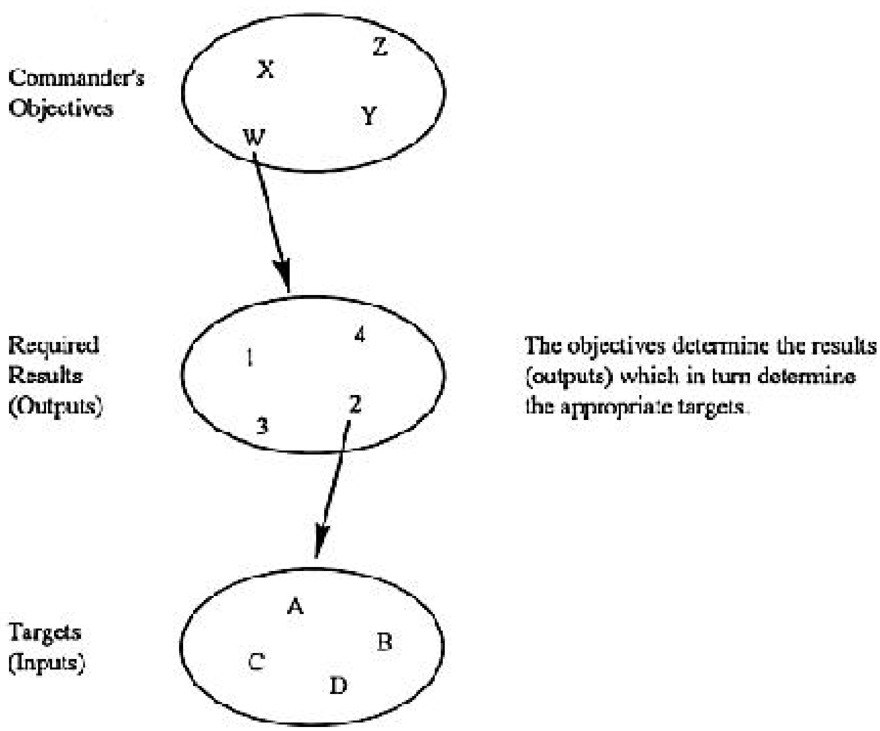



**Figure 6. Simplified View of the Output-based Targeting Process**

manders objectives?[11] The strategic air campaign in Operation Desert Storm was designed with this philosophy, and became one of the major sources of disagreement with the Army corps commanders, who were thinking in terms of the input-based paradigm.[12] This output approach is superior to the input technique, as operational art is now at the forefront rather than tactics.

As with the input-based philosophy, computerized tools can provide invaluable information to the output-oriented planner. As will be shown below, SA and GA algorithms (coupled with system models and data bases) can determine targets that yield the required outputs. The algorithms can be roughly thought of as performing a fault-tree failure analysis: given a desired *system-wide* failure, what components will provide the necessary failure when destroyed? The process is analogous to determining what will cause a bridge to collapse, for example, rather than asking about the effects of destroying a single supporting pier. Clearly, tools that aid the planner in obtaining a desired output are a tremendous boost to the targeting process.

We must note that there is a difference in the way that targets are selected and the manner in which they are attacked. An air force can attack targets in either a serial fashion as in WWII, or in a parallel manner as in the Persian Gulf War. Notice, however, that the target selection procedure for serial or parallel attacks can be either input-based or output-based. The target selection procedure will not automatically determine how the attacks are executed.

In summary, a planner may follow one of two general targeting philosophies. The first is based on inputs, and is limited in scope and utility. The superior method focuses on the commanders objectives and required results. In the following sections, we will develop several computer techniques that will aid the planner in executing this second targeting philosophy.

## Numerical Techniques

Targeting belongs to a class of problems known as combinatorial optimization.[13] In this class, there is some function that must be minimized or maximized. It is alternatively known as the cost, objective, or fitness function.[14] The class differs from the classical minimization and maximization problems in that there are no continuous variables to optimize upon. Rather, the problems contain a large number of *discrete elements* that may be varied. The number of different combinations of the variables is factorially large; hence, an exhaustive search for the best combination for a given cost function is clearly impossible. For example, if the problem has 100 discrete elements that can be in either of two states (100 targets that are either attacked or left unharmed), there are $2^{100} = 1.3 \times 10^{30}$ different combinations or *state configurations*. A random or exhaustive search for even this small problem is impractical. Fortunately, a variety of techniques exist that efficiently determine an acceptable if not optimal solution.

The traveling salesman problem is an example of combinatorial optimization that has been extensively studied. The salesman must visit a number of cities while following the shortest path possible. The cost function is simply the total distance traveled by the salesman. Since he wishes to follow the shortest path possible, the salesman must minimize his cost function. He does this by varying the order in which he visits the cities. Hence, the cities themselves form the discrete elements in this problem; these elements are varied by changing their visitation order in the salesman's itinerary. Furthermore, we can add constraints to the problem. For example, if there are toll bridges in the salesman's region, we can require that the salesman avoid them if possible (in order to pay the minimum toll). The cost function is now the distance the salesman travels *plus* a penalty that is assessed for each toll bridge crossing.[15] The constrained problem now seeks to minimize simultaneously the distance traveled by the salesman and the number of toll bridge crossings.

Targeting is a further example of combinatorial optimization. Here, the cost function indicates how well the targeteer meets the commander's objectives, and includes any constraints, restraints, or rules of engagement (ROE). The individual targets are the discrete variables. Given potentially hundreds of targets, the planner must determine some combination thereof that will produce the desired results and hence the commander's objectives.[16] In general, the final target list should be minimized so that sorties are not wasted on redundant or frivolous strikes. Then, the air planner could use several of the computer algorithms developed to solve combinatorial optimization problems for targeting purposes.

The following subsections examine three numerical algorithms commonly used to solve combinatorial optimization problems. The methods are iterative improvement, SA, and GA. A detailed example which uses a GA to solve a targeting problem appears in the next section. Although any of the three methods could be applied to the targeting problem, SA and GA presently hold the highest potential.

### Iterative Improvement

Iterative improvement is the simplest of the three algorithms.[17] Figure 7 illustrates the technique for the minimization problem. The algorithm starts from an initial set of values for the discrete elements. These initial values are called the *base configuration*. The base configuration can be chosen at random; however, a judicious choice of the base near the minimum will speed convergence.[18] The routine evaluates the cost function for the base configuration. Next, it applies a rearrangement operator to the base configuration and reevaluates the cost function.[19] The routine iterates the procedure until some configuration appears with a lower cost. This new configuration and its cost replaces the current base, and the process starts over. Eventually, the algorithm locates some optimum configuration literally by "walking" through the various rearrangements.

We can use the traveling salesman problem to illustrate the iterative improvement method. For this example, we will assume that there are no constraints (e.g., there are no toll bridges or toll roads to avoid, etc.). The cost function is then the total miles the salesman travels while visiting the cities.

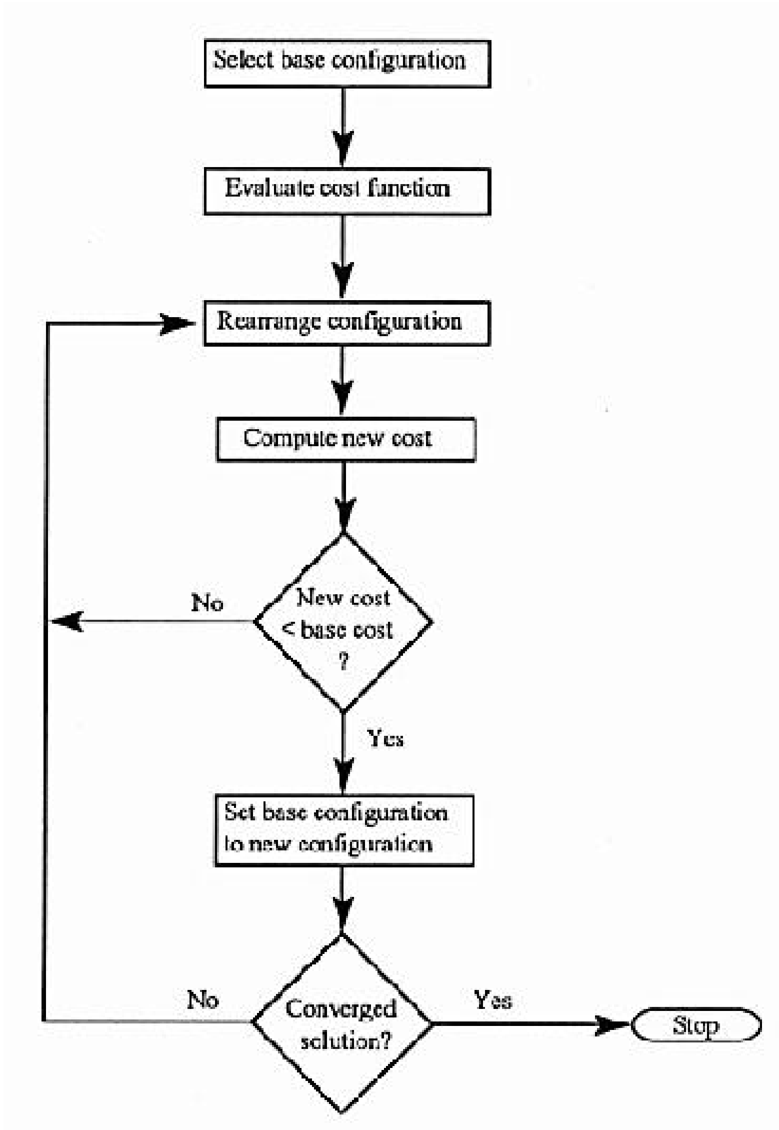



**Figure 7. Outline of the Iterative Improvement Algorithm**

The base configuration is an initial itinerary for the salesman—an initial ordered list of the cities to be visited. A variety of rearrangement operators have been discussed in the literature.[20] One such operator randomly removes a section of the path and replaces it with the order of the cities reversed. Another version removes a path section and inserts it between two other cities. Note that these two rearrangement operators do not completely randomize the order of the cities; some of the past history is retained after each rearrangement. Several different convergence criteria are possible. For example, if the average change of the cost function per iteration drops below some threshold, the routine will stop. Alternatively, if the routine applies the rearrangement operator more than some preset number of times without finding a lower cost configuration, the routine can declare convergence. The routine for the traveling salesman problem follows the flowchart in figure 7.

Iterative improvement suffers from a serious drawback. Many cost functions are multipeaked, resembling a mountainous landscape with many crests and valleys. Figure 8 depicts a multipeaked cost function. A number of *local minima* exist, such as points A and B in the figure. However, only one *global minimum* exists; it is the particular configuration with the overall lowest cost (point C). In the mountain-landscape analogy, the global minimum corresponds to the deepest point in the lowest valley, and the local minima correspond to the floors of the other valleys. The iterative improvement technique tends to lock into a specific valley and determine its minimal value. This point may or may not be the global minimum. For some problems, this valley may contain a sufficient, although not best solution. Consequently, although the iterative improvement scheme can locate local minima, it may not solve the particular problem at hand. For the traveling salesman problem, suppose that the dotted line in figure 8 represents the highest acceptable cost. Then, point A is unacceptable whereas B

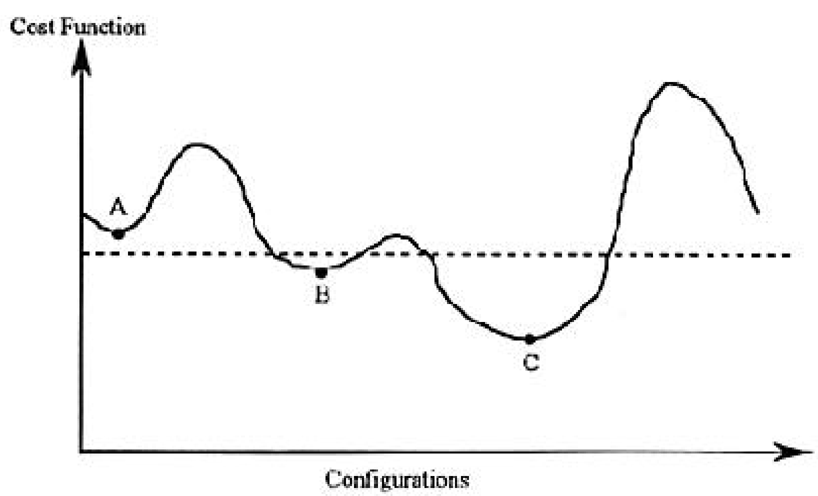



**Figure 8. A Multipeaked Cost Function. Points A and B are local minima; point C is the global minimum.**

and C are viable solutions. If the cost function is extremely rugged with many peaks and valleys, the iterative improvement technique will be useless unless it starts from an extremely good initial base configuration.

Several modifications to iterative improvement have been implemented.[21] For example, the algorithm itself can be iterated over a range of initial configurations until it locates some “best” local minimum. Nevertheless, if the cost function is very rugged, even a modified version of the algorithm may not perform well.

In sum, iterative improvement is a simple method capable of converging to a local optimum configuration. It works well if the cost function has a single minimum. However, if several local minima exist, there is no a priori guarantee that the routine will converge to the global or even a near-global optimum.

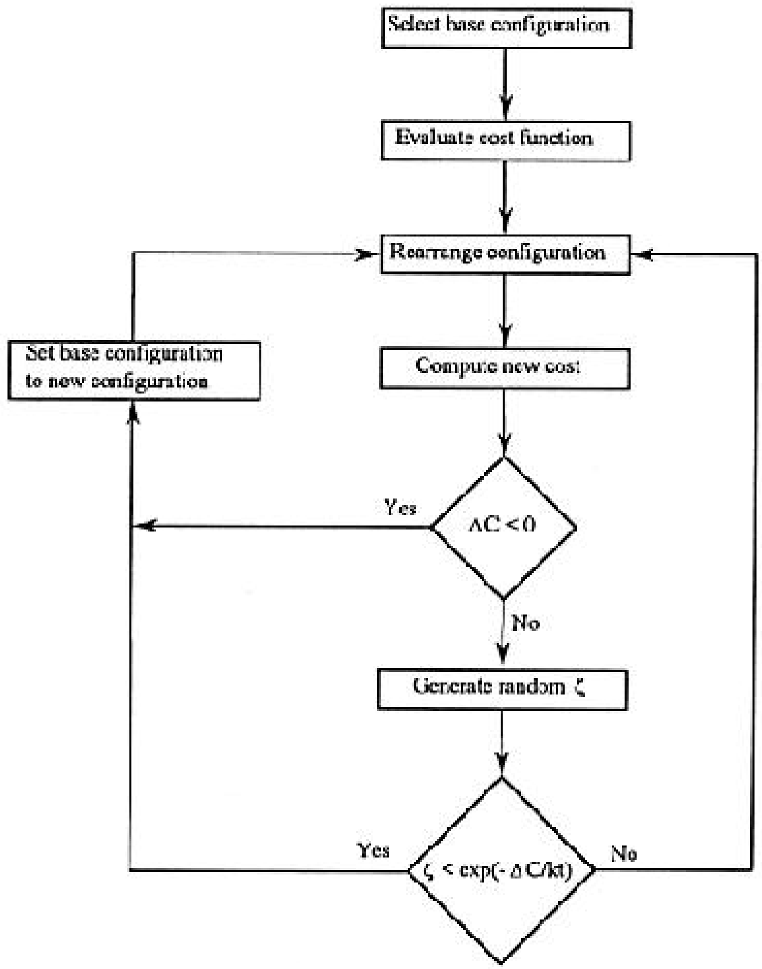
In principle, we can develop a routine based on iterative improvement that solves the targeting problem. The routine would determine a target list that optimizes the cost function. Here, the cost function directly reflects the commander's objectives. (We will delve into this point in-depth in the next section.) However, since iterative improvement locks into a local but not necessarily global optimum, this technique does not hold significant promise for the targeting problem. A local optimum point may be insufficient to meet the commander's requirements; it may in fact be worse than a solution generated "by hand." Therefore, we must look to other methods that can locate global (or near-global) optima for the targeting process.

### Simulated Annealing

Simulated annealing was first proposed by S. Kirkpatrick et al. in 1983.[22] Since then, it has undergone rapid development.[23] SA has successfully solved a number of problems, including the traveling salesman problem. William H. Press et al. examine the traveling salesman problem in detail, and provide a heavily documented FORTRAN source code for the problem with river crossing constraints.[24] SA is an interesting technique that is analogous to annealing and freezing processes.

SA has its roots deep in statistical physics. The principal algorithm, termed the *Metropolis method*, was developed in 1953 for calculations of the material properties of collections of interacting molecules.[25] Kirkpatrick and coworkers modified the Metropolis method in the first published description of SA. To understand the physical basis of the algorithm, consider a collection of molecules in a liquid. If the temperature decreases, the molecules slow down and begin to freeze or crystallize. While doing so, the molecules seek an arrangement with the minimum energy.[26] Since the molecules are in constant motion just above the freezing point, the system can "explore" its entire configuration space and search out the minimum energy configuration.[27] If the system is cooled slowly enough, the system selects and freezes itself into this arrangement. In other words, the system has optimized (minimized) its energy state. SA works in an almost identical fashion to optimize the cost function.

SA is essentially a version of the iterative improvement method that borrows the Metropolis algorithm. Figure 9 is a simplified flowchart of the SA algorithm for the minimization problem we just described. The method starts with a random initial base configuration at an initial "temperature" $T$. The algorithm computes the cost of the base configuration. The procedure applies a rearrangement operator to the configuration, and calculates the cost of the new configuration. If the change in cost $\Delta C < 0$ (the new configuration has a lower cost), the algorithm accepts the new configuration and its cost as the base. However, if $\Delta C > 0$, the new configuration is accepted with a Boltzmannian probability. That is, the algorithm selects a random number $\zeta$ between 0 and 1. The algorithm accepts the new configuration and its cost as its base if $\zeta$ $e^{-\Delta C/kT}$ where $k$ is the Boltzmann constant, even though the new base cost is greater than the original. Otherwise, the routine retains the original base configuration. The algorithm applies the rearrangement operator to the configuration, and a new iteration begins. In this manner, the algorithm explores a range of states in the configuration space, as in the annealing process.




Notes: 1. ΔC = new cost - old cost
2 $0 \leq z \leq 1$
3. The process is iterated a set number of times. The temperature $T$ is then lowered, and the cycle recommences.

**Figure 9. Outline of the Simulated Annealing Algorithm**

The ability to accept higher cost configurations is an important advantage of SA over iterative improvement. As noted above, iterative improvement routines will often lock into local minima. By accepting positive $\Delta C$ values, the SA routine can hop out of a local minimum and continue the search for the global minimum. This feature considerably increases the power of SA over iterative improvement.

The temperature $T$ plays a crucial role in the algorithm. $T$ is actually a control parameter, but it is analogous to the temperature in freezing and annealing processes. The SA method initially starts at a relatively high temperature $T$. Here, the routine can accept relatively large positive values of $\Delta C$.[28] It will not get trapped in valleys as does the iterative improvement technique. In this manner, it is free to explore large regions of the configuration space as it searches for the global minimum. This is precisely what our collection of molecules does in its liquid phase: it tests a large variety of arrangements as it searches for the minimum energy state. Upon discovering some promising region of configuration space, the algorithm decreases the temperature. As $T$ decreases, progressively smaller positive values of $\Delta C$ are accepted with a high probability. In this stage, the algorithm tends to lock into a valley with either a near global or the actual global minimum. Additional reductions in $T$ force the algorithm to seek the valley floor. Convergence to the solution occurs when further reductions in $T$ result in insignificant reductions of the cost function. Essentially, the algorithm mimics the behavior of molecules undergoing a phase transition. In sum, varying the control parameter $T$ is analogous to varying the temperature of our collection of molecules.

The initial value of $T$ and the schedule for lowering it are critical to the performance of the algorithm. If $T$ decreases too rapidly, the algorithm may lock into a region with a local but not global optimum. This is similar to rapidly freezing a liquid, which results in a glassy solid rather than a minimum-energy crystal. On the other hand, lowering $T$ too slowly wastes computer time. Determining a good initial value of $T$ and an appropriate schedule requires insight into the problem and/or trial-and-error experimentation.[29]

SA has several additional advantages and disadvantages. On the positive side, the algorithm readily adapts to parallel processing. For a given $T$, a parallel version can analyze a number of configurations simultaneously. SA uses its past configuration history to improve the search for the global optimum, since the rearrangement operator does not completely randomize the test configurations. On the negative side, the temperature variation schedule is crucial to the proper operation of the algorithm. Numerical experimentation is probably necessary to determine good initial values of $T$ and temperature schedules.[30]

At this juncture, SA annealing appears to have promise for the targeting problem. Since SA does not lock into the first valley (and thus local minimum) that it locates, it is more robust than iterative improvement. Since the cost function for the targeting problem is likely to be quite rugged (especially if the economic infrastructure elements are very complex), the robustness of SA is a definite advantage. We shall explore this aspect in more detail in the example of the next section.

### Genetic Algorithms

Practical genetic algorithms date back to 1975, when John Holland of the University of Michigan developed classifier routines that “evolved” solutions to optimization problems.[31] As with SA, GAs have enjoyed almost explosive growth in recent years in both theoretical and practical terms.[32] The method is particularly suited to applications in which there is no simple relationship between the system configuration and the cost function or where the solution literally must be discovered rather than calculated.[33]

GAs belong to a subclass of artificial intelligence known as artificial life. In the GA literature, the cost function is called the fitness function or fitness landscape. In the natural world, the fitness function of an organism is a measure of its ability to survive in a given environment. Reproduction, exchange of genetic material, mutations, and natural selection change the genetic code of successive generations of the organism, either improving their positions on the fitness landscape or not. A GA uses the same basic processes to evolve optimal solutions to problems inside a computer. Like its organic counterparts, the GA creates "generations" of solutions that progressively move toward the global maximum of the fitness function. In solving the problem, the GA mimics naturally occurring biological processes—hence its inclusion in the artificial life class of algorithms.

A principal element of a GA is the gene string or *genotype*. The simplest and most general genotype occurs in the binary combinatorial optimization problem. Here, there are $n$ discrete elements or variables, such as $n$ potential targets. Let $a_i$ represent the $i^{th}$ element. Since the elements are binary, they can take only one of two values, 0 or 1 (on or off, attacked or not attacked, etc.). Concatenating the elements in a string yields a binary variable $a_1a_2a_3 \ldots a_n$. Thus, every value of $a_1a_2a_3 \ldots a_n$ corresponds to a point in the configuration space. For example, 0111001011 and 1101010011 are two points in the configuration space of an $n = 10$ binary problem. In an analogy with the biological case, the string $a_1a_2a_3 \ldots a_n$ represents a chromosome (genotype), each bit position of the genotype corresponds to a gene, and each gene represents the state of a particular discrete element. Consequently, the genotype represents all of the possible system configurations.

A second key element of the GA is the fitness function. As noted above, the fitness function is merely the cost function. In essence, the fitness function is the embodiment of the problem at hand. As with iterative improvement and SA, care must be taken when designing a fitness function. In the targeting problem, the value of the fitness function denotes how well a given targeting solution (an individual) meets the commanders requirements. If a solution comes close to satisfying needs, the fitness of the solution is high. On the other hand, a low fitness solution fails to meet the requirements. Clearly, the fitness function will change for every targeting scenario. In all scenarios, the GA will attempt to "evolve" high fitness targeting solutions.

The operation of a GA parallels the biological processes of selection, reproduction, and genetics. Figure 10 outlines the procedure. The algorithm begins by creating an initial population of *individuals*. That is, the routine generates m values of $a_1a_2a_3 \ldots a_n$, where $m$ is some integer. Each individual is a trial solution to the optimization problem. The values may be randomly chosen, although this is not required. Any insight into the problem that is used when assigning initial values to the $m$ individuals will probably help convergence.

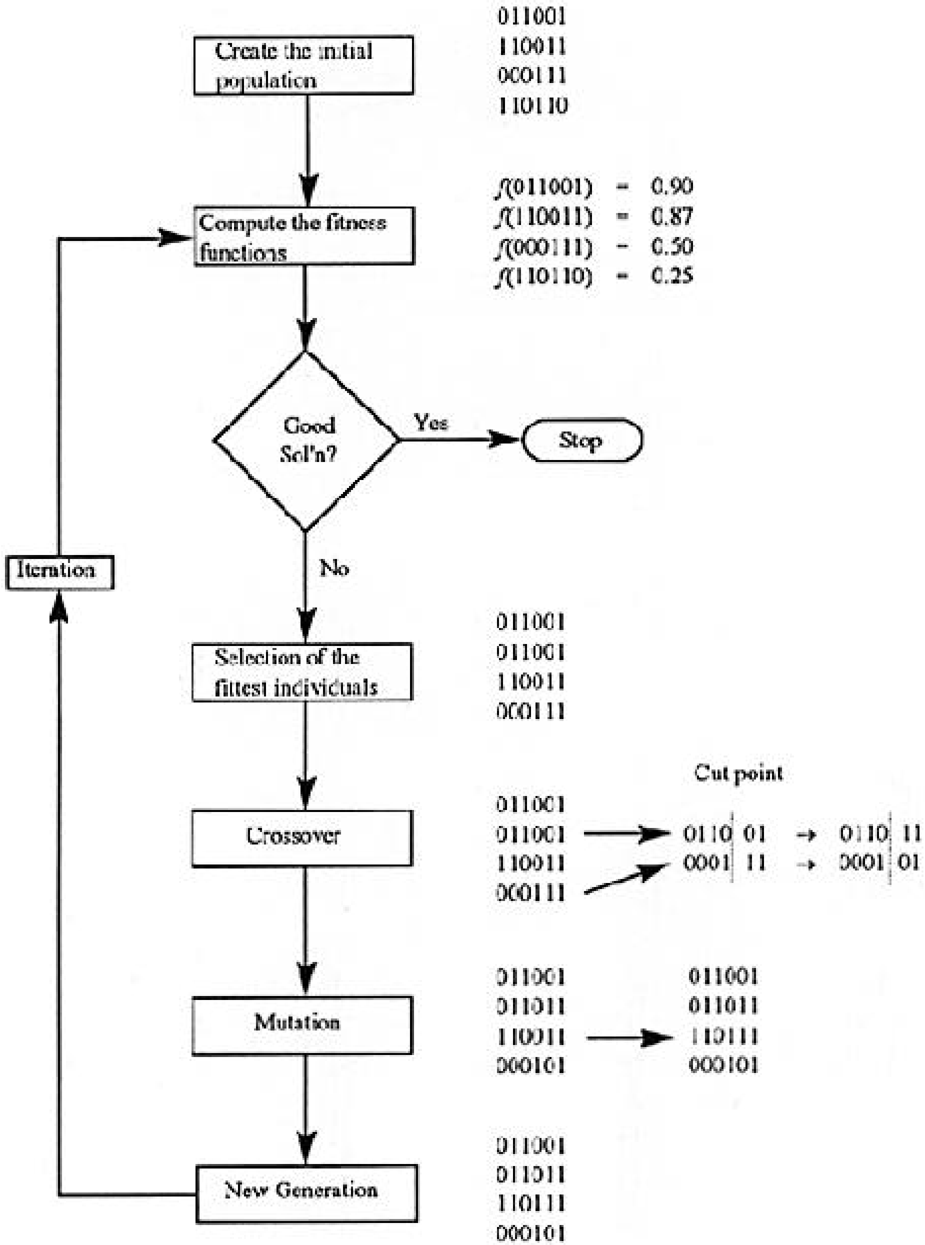



**Figure 10. Outline of a Genetic Algorithm. (The values given in the figure are notional.) The routine generates an initial population of *m* = 4 individuals. Next, it calculates the fitness *f* of each individual. If the generation contains a converged solution, the routine terminates. Otherwise, it continues with the reproduction step. The routine selects the three fittest individuals for reproduction. Note that it makes two copies of 011001, and eliminates 110110. The algorithm chooses the second and fourth individuals for cross-over, swapping their genetic material to the right of the cut point. Finally, the third individual undergoes a mutation by flipping its fourth bit. The algorithm iterates using the new generation as its starting point.**

Once the program has created the population, it is ready to pass to the reproduction step. As the name implies, the reproduction step creates the next generation of individuals. First, the routine evaluates the fitness function for each individual. The fitnesses determine whether an individual survives to the next generation or dies out. Low fitness individuals have a low probability of survival; selection may preclude their replication in the next generation. On the other hand, high fitness individuals are more likely to survive. In fact, the routine may create multiple copies of high fitness individuals in the next generation. In this manner, selection probabilistically eliminates low fitness individuals and ensures that those with the highest fitness form the basis of the next generation. The average fitness of the successive generation is generally higher than that of the previous one.

Following reproduction and selection, the algorithm performs two crucial operations. The first is crossover, in which two individuals swap blocks of genetic material.[34] In the simplest form, the routine arbitrarily selects two individuals for crossover. Next, a point in the genotype is randomly chosen, and all genes following this point are exchanged between the two individuals. This operation adds diversity to the population, and also ensures that the best gene combinations are preserved in successive generations. In the second operation, a mutation operator selects an individual at large and then randomly chooses and flips one of its bits. As a result, the operator prevents the algorithm from becoming stuck in some local optimum of the fitness function. Crossover and mutation are important steps that maintain the diversity of the population as well as allowing the algorithm to sample large regions of the configuration space.

The above description sketches a highly simplified picture of the main steps of a GA.[35] Researchers have modified this simple routine in many ways, adapting it to a variety of problems. The key concept is that a properly operating GA converges to a high-average-fitness population after a sufficient number of generations. The high fitness individuals represent points in configuration space that are close to the optimal solution of the fitness function. In figure 10, after some number of generations, the GA would determine values of the sextuple $(a_1, a_2, \ldots, a_6)$ that produce high fitness values. In this manner, the properly designed and tuned GA "evolves" a solution to the problem represented by the fitness function.

As with any numerical routine, GAs have their particular advantages and disadvantages. The positive aspects include relative robustness and applicability to a wide range of problems. GAs readily adapt to parallel processing. In fact, the algorithm is inherently parallel; even on serial computers a number of solutions are processed in parallel due to the nature of the algorithm.[36] One of the principal drawbacks is the tuning requirements. A GA has a considerable number of parameters, such as the number $m$ of individuals in the population, the selection probabilities, and the crossover and mutation rates. Often, successful convergence of a numerical routine depends upon the choice of such parameters. As with SA, the designer frequently has to vary the parameters in order to obtain a well-behaved, convergent GA. This may require trial-and-error tuning of the GA for each targeting scenario as well as the use of any insight into the problem. Computer time requirements are another drawback to GAs, as the routine must evaluate the fitness function of each individual during each generation.[37] Many of the unanswered questions about GAs are the subjects of current theoretical and simulation projects.

On the whole, GAs appear to be promising for output-based targeting. Targeting itself adapts well to the GA, as it is an example of binary combinatorial optimization. Furthermore, the complex nature of economies will lead to emergent and often counterintuitive behavior. There may be no simple relationships between the destruction of specific targets in the economy and the global results. Consequently, the overall effects of attacking the economy cannot be adequately guessed a priori. From this viewpoint, the GA is particularly suited for the targeting problem and merits further exploration. The following section examines this proposition further, outlining in detail a GA that determines the optimal targets for an electrical grid coupled to a POL distribution network.

## Targeting Economic Sectors€
## A Proposed Numerical Simulation€

GAs and SA have potential for computerized routines that aid the output-based targeting process. To illustrate their potential, we will now develop in detail a notional computerized targeting routine. The program uses a GA coupled to load-flow and hydraulic analyses of an electrical grid and POL network, respectively. In principle, the program could use an SA driver routine instead of a GA. Note that the program described below has not yet been coded and tested; however, an air planner could adapt existing computer tools to create a targeting program based on the example.

### Problem Description

The problem centers on the notional electrical and POL networks of some hypothetical country.[38] Following the output-based targeting philosophy, the friendly commander has decided that certain sectors of the electrical grid and POL networks must be destroyed. Their elimination will hamper enemy efforts: integrated air defense systems and communication networks will suffer from power outages, electrified rail transportation for mobilization will shut down, motorized transportation will be hindered from the loss of POL resources, and so forth. The adversary can use backup electrical power generation and stockpiles of POL to overcome some of the immediate losses of economic resources. However, we are also interested in the synergistic effects that arise from the couplings between the networks.

In more concrete terms, we assume that the commander has decided that the electricity and POL pipelines must be shut down in the eastern half of the adversary nation. To facilitate reconstruction efforts after the conflict, those elements targeted for destruction must be reparable within six months. This restriction eliminates certain potential targets, such as generators and their step-up transformers. Furthermore, we assume that the ROEs constrain the attack sorties to the eastern third of the nation.

The problem thus poses objectives as well as several constraints. The fitness function must include all of these considerations. Before turning to the GA and its implementation, a description of the electrical grid and POL network analysis programs is in order.

## Electrical Grid Load-Flow Analysis

The electrical power industry has developed a variety of computer tools for analyzing electrical grids. The type of study most applicable to targeting is the load-flow analysis.[39] The main inputs to the studies include line impedances and normal operating conditions. The primary outputs of load-flow studies are the real and reactive power flows through the grid and the bus voltages and phase angles.[40] Table 2 lists typical program inputs.

A typical contingency analysis employs a load-flow program to determine the effects of the loss of one or more grid elements. By direct analogy, a planner could estimate the effects of air attacks upon certain components of an electrical network with a load-flow program. By selectively eliminating

**Table 2**

**Typical Load-Flow Analysis Inputs**

| Grid Component | Required Data |
|---|---|
| Power Lines | • ID numbers of the buses to which the lines connect<br>• Line resistance and reactance<br>• Total line charging |
| Transformers | • ID numbers of the buses to which the transformers are connected<br>• Transformer resistance and reactance<br>• Total charging |
| Buses | • Buse names and ID numbers<br>• Bus type (swing or regulated)<br>• Bus-voltage magnitudes<br>• Bus phase angles<br>• Desired generation in megawatts and megavars<br>• Upper and lower limits of megavar generation<br>• Load in megawatts and megavars<br>• Total magavars of static capacitors and reactors on the bus |
| All | • Emergency power ratings |

**Source:** Adapted from William D. Stevenson, Jr., *Elements of Power System Analysis*, 3d ed. (New York: McGraw-Hill, 1976), 207–8.

components from a grid data base, the planner would simulate the effects of the attack. Any grid components that exceed their emergency power ratings would in practice drop off the grid due to open breakers and other protective circuitry. If the load-flow program displays the components exceeding their emergency ratings as well as the targeted elements, the planner can directly observe the effects of the attack.[41] This type of analysis yields important first-order information for targeting an electrical grid.[42]

## POL Network Hydraulic Analysis

To assess the effects of the attacks on the POL network, we must perform a hydraulic analysis. The pipeline industry uses hydraulic analyses to design pipeline systems.[43] Given the network layout and the geographic elevations along the pipeline, a hydraulic analysis computes fluid flow rates through the system. Table

**Table 3**

**Typical Hydraulic Analysis Inputs**

| Network Component | Required Data |
|---|---|
| Terrain Geography | • Geographic elevations along the entire pipeline network |
| Network Layout | • Locations and layouts of pipes, pumps, fittings, etc. |
| Pipes | • Diameters<br>• Wall friction head losses<br>• Type of construction material (i.e., steel or iron)<br>• Safe and maximum working pressures |
| Fittings | • Head losses |
| Pump (Compressor) Stations | • Number of available pumps (compressors)—number of pumps (compressors) in use<br>• Net available head (pressure) per pump (compressor)—normal and emergency values<br>• Pumping rates (i.e., barrels per hour or cubic feet per hour)—normal and emergency values<br>• Suction pressures<br>• Pump (compressor) power source (i.e., electric motor or diesel engine) |
| Fluid or Gas | • Types of fluids (gases) normally pumped through the system<br>• Specific gravities (fluids)<br>• Pressures and temperatures (gases) |

**Sources:** Reuben M. Olson, *Essentials of Engineering Fluid Mechanics,* 3d ed. (New York: Intext Educational Publishers, 1973), 335–81; US Army TM 5-343, *Military Petroleum Pipeline Systems,* Revision C-1 (Headquarters, Department of the Army, 1973), 6-1 to 6-30. *Head* is a measure of pressure; it is equal to the pressure divided by the specific weight of the fluid.

3 lists typical inputs for a hydraulic analysis. In particular, the key input required by the analysis is the elevation data along the entire length of the pipeline.

For the air planner, this analysis indicates the extent to which air attacks would reduce POL flow rates in the network. As with a load-flow analysis, the planner selectively eliminates pipeline elements from the network data base. These elements represent the attacked targets. As components of the pipeline are destroyed, the pipeline operators will reroute the POL flows through undamaged sections. The analysis of the postattack pipeline network indicates the new flow routes and rates that the damaged system can safely sustain. Thus, the planner directly observes the effects of his planned strikes in the outputs of the hydraulic analysis. It provides invaluable information for developing air attacks against a POL network.

### The Data Base

Tables 2 and 3 indicate the types of physical information required by load-flow and hydraulic analysis programs. Before a planner can analyze any network, he or she must have a data base containing the required inputs to the programs. The data base is an extremely important part of the simulation. The more detailed the data base information, the closer the simulation results will match reality. There is a balance point, however, at which the amount of data base detail is sufficient for the planner. The amount of intelligence required to obtain higher detail may not be justified by marginal improvements in the accuracy of the results. Determining the balance point requires physical insight into the systems being modeled. In any case, successful use of the targeting routine relies upon the existence of an adequately detailed data base.

By examining the two tables further, we note that a significant amount of the data requires geographic information. For example, the elevations along the pipelines are essential inputs to the hydraulic analysis. Transmission lines link geographically separated buses; hence, they form a tie between two spatial points. More importantly, displaying the results of the load-flow and hydraulic analyses on a map requires the geographic location of each item in the data base. This form of geographic display is crucial to the commander's situational awareness of the impacts of a proposed attack. The requirements for geographic data motivate us to employ a Geographic Information System (GIS) and geographic data base.

GIS is a computer technology that links objects in a data base via their geographic coordinates.[44] It is much more, though, than a set of map coordinates appended to each data base object. The power of GIS lies in its ability to perform *spatial queries* of the data base. That is, a user may pose questions based upon geography to the GIS. For our example, such questions include:

> What infrastructure elements require electrical power within a 50-mile radius of a given electrical generator?
>
> Which customers will lose their oil supply with the destruction of a given section of POL pipeline?

Which electrical generators do not lie in the restricted flight zone, and what happens to the POL network if they are destroyed?

Furthermore, a GIS capability allows us to model and simulate different elements by using the geographically linked data base objects. This is precisely what our load-flow and hydraulic analyses perform. In short, a GIS is an enabling technology which we should employ with our data base.

Although data base development might at first appear to be overwhelming, there are considerations that may simplify the task to some degree. First, much of the data necessary to develop the initial network topologies is commercially available. For example, commercial data bases exist that give general network layouts for the worldwide oil industry.[45] Second, in some industries, there are few suppliers of critical heavy equipment. Consequently, some equipment may be standardized to a certain degree. (Electrical generators, for example, are manufactured by only one-half dozen firms worldwide.)[46] Finally, developing nations are following the US lead in some infrastructure technologies. The telecommunications networks of some nations are based upon those in the US—their equipment and protocols parallel those used in the US in some instances.[47] Nevertheless, the development and maintenance of adequately detailed data bases is a large project that cannot be neglected.[48]

## The Genotype

Our notional targeting problem is an example of binary combinatorial optimization. The electrical grid and POL network consist of $n$ components (lines, buses, transformers, generators, pipeline segments, compressor and pump stations, etc.), where $n$ is some large integer. Each component can be in one of two states: targeted (and assumed destroyed during an attack) or untargeted.[49] If the variable $a_i$ is the state of the $i^{th}$ component, then it takes one of two values, 0 for untargeted (undamaged) and 1 for targeted (destroyed). The state of the entire electrical grid and POL network is then represented by the genotype $a_1a_2a_3 \ldots a_n$. The genotype takes the particularly simple form of a binary variable.

The genotype will be long if the number of components $n$ is large. However, if the number of targets that can be attacked is limited (by total available aircraft, munitions, etc.) and is much less than $n$, then the genotype will be sparse. Compression of the genotype information will reduce the storage requirements, especially if the population size $m$ is large. For example, in a very sparse genotype, it is only necessary to store a set of pointers that indicate which components are targeted, rather than storing information about each component.

## The Fitness Function

The fitness function $f$ is arguably the most important part of the routine. It is the embodiment of the targeting problem, and as such must incorporate the commanders objectives and all constraints and restraints. As mentioned above, considerable care must go into its development.

Each electrical grid and POL network component has an associated set of rewards and penalties. In keeping with the commander's desires, every electrical grid and POL network component in the eastern half of the country that shuts down as a result of the attack accrues a positive reward. Likewise, every eastern transmission line or pipeline that is still operational after the attack incurs a negative penalty. Any targeted facilities in the western two-thirds of the nation will also incur a negative penalty. Note that there is no penalty for components still running in the western half of the nation. Some components may be weighted more heavily than others, depending upon the commander's wishes. For example, if the commander determines that destroying the electrical grid is more important

**Table 4**

**Fitness Function Rewards and Penalties**

| Variable | Type | Weight | Description |
|---|---|---|---|
| $r_i$ | reward | 100 | Electrical grid component in the eastern region that is shut down |
| $s_i$ | reward | 50 | POL component in the eastern region that is shut down |
| $t_i$ | penalty | –80 | Electrical grid component in the eastern region that is running |
| $u_i$ | penalty | –40 | POL component in the eastern region that is running |
| $v_i$ | penalty | –25 | Attacked component has a repair time >6 months |
| $w_i$ | penalty | –100 | Attacked component is in the restricted flight zone |

NOTE: The weights listed in the table are hypothetical and would vary from one scenario to the next. We can glean an understanding of the commander's intentions from their magnitudes. For example, shutting down the electrical grid is more important than turning off the flow of oil, as the rewards and penalties for electrical components are twice those of the POL components. Similarly, respecting the restricted flying zone is significantly more important than not attacking components with repair times greater than six months.

than shutting off the POL flow, the electrical grid rewards would be correspondingly higher than those for the POL network. Note that the values of the penalties and rewards may require tuning to improve the convergence of the GA. However, any tuning of the parameters must be in consonance with the commander's desires. Furthermore, any change in the commander's desires will force changes in the weights. Table 4 lists the rewards and penalties for our particular problem.

Each component, then, has an associated set of weights. The weights form a vector; for this example, the weight vector is ($r_i$, $s_i$, $t_i$, $u_i$, $v_i$, $w_i$). Using the weights from the table, a destroyed electrical grid component on the eastern border of the country with a repair time of two years (such as a generator step-up transformer) would have (100, 0, 0, 0, –25, 0) as its vector. A destroyed pump station with a four-month repair time located in the restricted flight zone but in the eastern half of the country would be characterized by (0, 50, 0, 0, 0, –100). If the same pump station is unattacked but nevertheless shut down, its vector becomes (0, 50, 0, 0, 0, 0). Similarly, every component in the data base has a weight vector.

The fitness function is given by the sum of the rewards and penalties over all grid elements:

$$\{f = \sum_{i=1}^{n} (r_i = s_i + t_i + u_i + v_i + w_i)$$

The maximum value $f_{max}$ is simply the sum of the rewards ($r_i + s_i$), which occurs when all components in the eastern half of the country are down, and no constraints have been violated. With this particular fitness function, the program must attempt to find a target set that maximizes $f$. A reasonable criteria that a good solution must satisfy is $f = \alpha f_{max}$, where $\alpha$ is somewhat less than 1.

## Program Logic

The program employs a genetic algorithm to evolve targeting solutions that meet the commander's requirements. Figure 11 is a block diagram of the program logic. The program follows the general flow of a GA. The synergies are incorporated during the load-flow and hydraulic analyses. The manner in which the synergies are incorporated merits deeper discussion.

The nodal analysis begins after the routine generates the population. Each individual in the population pool is, in essence, an attack plan. The value of the genotype indicates which components are attacked or bypassed. The program uses an iterative technique to determine the synergistic results of the attack. First, the routine simulates the attack by "removing" any targeted components from the data base. The result is a "postattack" data base used in the ensuing nodal analyses. This data base reflects the state of the economy after the attack.

Second, the routine performs separate nodal analyses of the two elements. In this step, the program analyzes each element *in isolation* from the other. In essence, the program calculates the effects of the damage on each element without regard for any synergistic couplings. The analyses determine the components that shut down due to the attacks. Any such electrical grid or POL pipeline component is removed from the postattack data base. The data base now contains only those components that are still functioning *in the isolated economic elements.*

Third, the routine reconciles the effects of the couplings between the two elements. For example, if electricity is lost to a substation that feeds a pipeline pump, the pump ceases to function. Although the pump was not directly attacked, the loss of electricity causes the pump failure. The routine then removes the pump from the postattack data base. Similarly, if the natural gas pipeline feeding a gas-fired electrical generator shuts down, the electrical generator drops off-line. The program reflects the loss of the generator by removing it from the postattack data base. At this point, the program has removed any components that either were destroyed in the attack, "failed" during the isolated nodal analyses, or shut down due to synergistic couplings.

Fourth, the program repeats the nodal analysis-reconciliation steps. We noted above that the routine removed components from the data base during

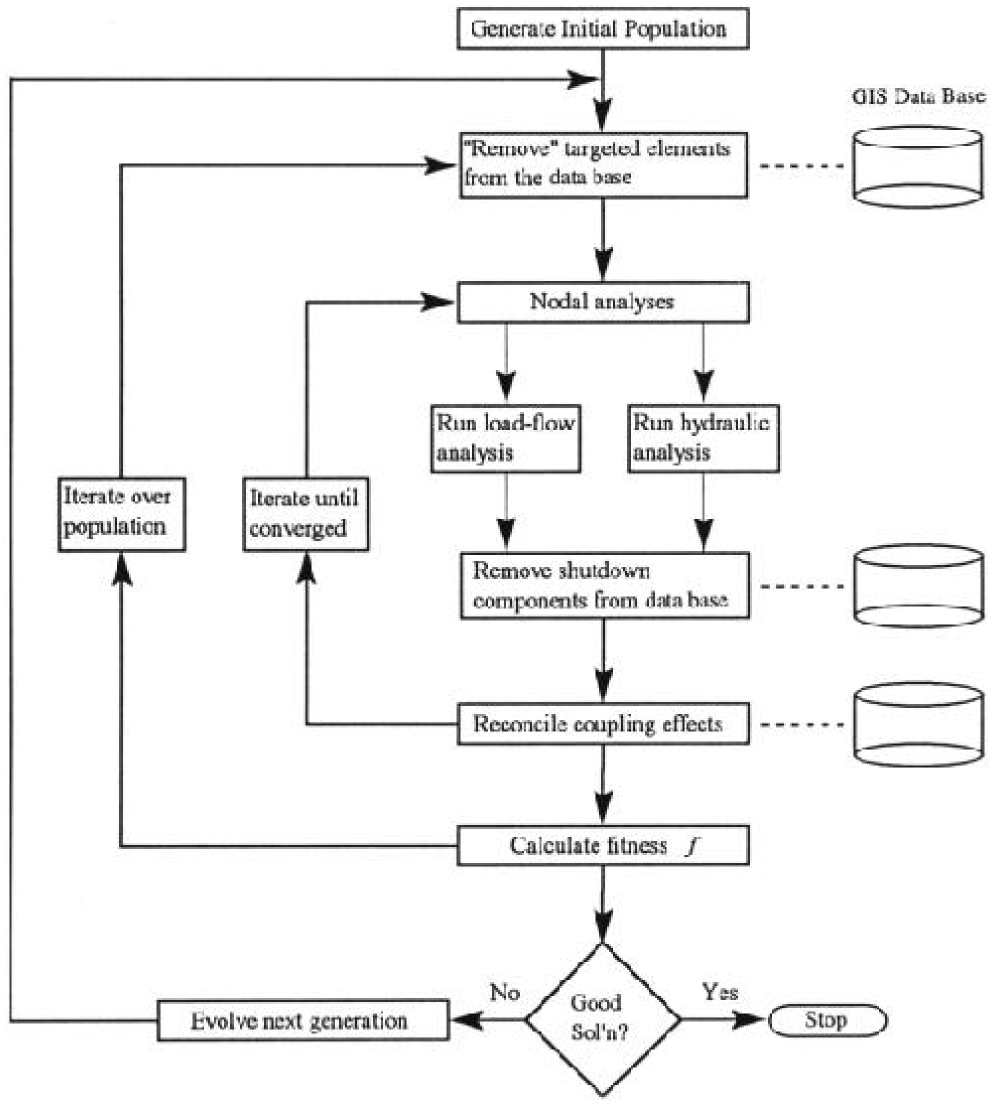



**Figure 11. Simplified Flowchart for the Targeting Program**

the nodal analysis and reconciliation steps. The program must now include these losses in assessing the results of the attacks. Therefore, it iterates the nodal analysis-reconciliation steps. In essence, the program calculates the cascading failures within and between the two elements of the model during this step.

Eventually, the routine will converge to a postattack data base that undergoes no further changes. This data base represents the final operating state of the model after the attacks. It includes the results of the synergistic couplings and cascading failures. The last nodal analysis yields the final state to which the coupled economic elements deteriorate.[50] The GA evaluates the fitness of this final state.

The preceding steps describe the nodal analysis performed on a single individual in the population pool. The GA repeats the analysis for the other $m - 1$ individuals in the population. The result is a set of fitness values that indicate how well the targeting solutions represented by the $m$ individuals meet the commander's desires. The GA then determines the next population iteration in the manner described in the previous section.

### Discussion

This section has taken a top-level view of one form of a targeting program. Numerous modifications to the proposed program are possible: use of SA instead of a GA as the main driver routine, different fitness functions, different stopping criteria, and so forth. Indeed, a considerable amount of numerical experimentation might be required to determine the driver routine with the best convergence properties, reasonable fitness functions, the required level of data base detail, and so forth. In any case, at this juncture, there appears to be several plausible approaches to solving the output-based targeting problem numerically with readily available modeling tools.

This particular example has focused on an electrical grid coupled to a POL network. Although the example contains only two coupled elements, it is a step up from the traditional reductionist approach. We have seen that systems do not exist in isolation and must not be treated as such. This becomes particularly important if the coupling between different systems is tight. The addition of other infrastructure elements may require a reformulation of the fitness function, changes in the fitness function weights, increases in the data base size and genotype length, and more computations to determine the results of the attacks. In principle, the extension of our model to include other target sets is straightforward, with a program logic parallel to that described in this section. This type of multiple system simulation and planning tool would be extremely valuable to the planner.

## Philosophical Aspects of Computer-based Targeting

A philosophical dimension of computer-based targeting is the wisdom of turning the targeting function over to a machine. Basic Air Force doctrine states that "war is not an engineering project and must not be treated as such."[51] However, in this instance, the machine is augmenting the commander—it is not replacing his judgment and intuition.

In any targeting problem, the planner must analyze his opponent. If a physical system such as a POL distribution network is the object of the attack, an engineering analysis is clearly called for. Whether done by a human or machine is immaterial; a well-designed program follows the same engineering analysis steps as a human with pencil and paper. The advantage of the machine is that it can examine more attack options at a much faster rate, and quite possibly find solutions that the analyst would miss. Furthermore, since infrastructure targets are complex, dynamical systems, their behavior under attack might be counterintuitive. What the planner might dismiss as an unreasonable system behavior might be the actual dynamical response to the attack. A program would not have the same reaction to strange dynamic behavior. In short, the computer performs the same analysis as its human counterpart, but at a faster rate, covering more options, and remaining unbiased by unusual results.

In all cases, the commander makes the final decision to execute, modify, or discard the proposed attack. The computer is simply a tool, neither designed nor destined to replace the human element. The commander is the final authority and must remain so, as war is truly a human enterprise.[52]

## Summary

In this chapter, we have explored modeling and simulation tools applicable to the targeting problem. Two general approaches to targeting are possible. One is input-based, concerned more with the *how* and *how many* questions. It is tactical in focus, and of limited scope and utility. The more appropriate methodology is output-based, where the emphasis is placed on *what* must be done to obtain the commanders objectives. This approach brings operational art to the forefront. It is the preferred approach to the targeting problem.

A variety of modeling and systems analysis tools exist that can be adapted to targeting. Under the approximation that each target on the list is destroyed in the attack, targeting becomes a binary combinatorial optimization problem. Two recently developed techniques, simulated annealing and genetic algorithms, appear applicable to numerical targeting programs. A GA formed the basis of a proposed targeting program described in this chapter, although SA could probably be used as well. Until such programs are developed and tested, the better algorithm choice will remain uncertain.

Numerical simulations and automated targeting programs do not remain far in the future. The tools exist today to develop such programs. In light of the recent Desert Storm experiences, we would be wise to do so.[53]

### Notes

1. For example, the electric power industry routinely uses a variety of commercially available programs to simulate the operation of their grids. Load-flow programs compute the power flow through the grid, and stability programs analyze the instantaneous behavior of the network. For more details, see William D. Stevenson, Jr., *Elements of Power System Analysis*, 3d edition (New York: McGraw-Hill, Inc., 1975). TRANSNET is a data base accessible from INTERNET. Developed and maintained by Sandia National Laboratories, it contains several

transportation route and flow models that are available for public use. ithink™ by High Performance Systems is a computer package capable of modeling transport-type problems. It can readily model POL distribution networks, for example. Another similar but more capable tool is SLAM (Simulation Language for Alternative Modeling), by Pritsker and Associates.

2. Electrical utilities, for example, routinely perform numerical simulations of their grids that encompass thousands of buses, lines, and transformers. Stevenson, 207. On a smaller scale, the Plantation Pipe Line Company operates 57 pumping stations and delivery terminals, as well as hundreds of miles of pipe in the southeastern US, from Louisiana to Virginia. Public Service Brochure, Plantation Pipe Line Company (1993). The Explorer Pipeline Company, in turn, operates 1,400 miles of pipeline stretching from Louisiana to Indiana, 20 pump stations, 88 storage tanks, and six terminal stations. Company brochure, Explorer Pipeline Company (September 1992).

3. However, disasters, strikes, and other major perturbations could be used to anchor the model to the enemy economy. If data relating to infrastructure degradation or failure is available, simulations of the perturbation might provide important tuning information for modeling.

4. Col John A. Warden III, commandant, ACSC, interview with author, 28 March 1994.

5. Maj Edward Felker, "Does the Air Force Practice Its Doctrine? A Limited and Focused Air Campaign Concept," unpublished thesis (Fort Leavenworth, Kans.: Command and General Staff College, 1991), chap. 5.

6. Ibid., 123.

7. Ibid., 124.

8. Lt Col Rick Lewis, "JFACC Problems Associated with Battlefield Preparation in Desert Storm," to be published in the *Airpower Journal.*

9. Ibid.

10. Warden interview.

11. Felker, 122.

12. Warden interview.

13. William H. Press et al., *Numerical Recipes: The Art of Scientific Computing (Fortran Version)* (Cambridge, Mass.: Cambridge University Press, 1989), 326; S. Kirkpatrick et al., "Optimization by Simulated Annealing," *Science*, vol. 220, no. 4598 (13 May 1983): 671–80.

14. Note that maximizing a cost function is mathematically the same as minimizing the negative of the function. In the following, the iterative improvement and SA routines are presented as cost function minimizers, whereas the GA is given as a maximization algorithm. However, the three methods can be used in either minimization or maximization programs, depending upon the formulation of the cost function.

15. The penalty is an important variable in the constrained problem. If the penalty is very high, then reducing the number of bridge crossings becomes more important than minimizing the distance traveled. Hence, the salesman may travel incredible distances while keeping the number of bridge crossings to the absolute minimum. However, if the penalty is relatively small, then minimizing the distance traveled becomes more important than limiting the bridge crossings. The solution may then have a considerable number of bridge crossings while strictly limiting the distance traveled. The solution is therefore dependent upon the penalty assessed for each bridge crossing; care must be taken when choosing the value of the penalty.

16. Lewis, 6. Before the end of Operation Desert Storm, the Master Target List contained over 460 targets. This does not include the targets on the deputy CINC's Target List, which contained targets in Kuwait for battlefield preparation.

17. See Kirkpatrick et al., 672, for a detailed discussion of iterative improvement.

18. In some problems, we may have information about the location of the minimum value. We can use this information to pick a base configuration near the minimum configuration. Convergence to the minimum solution will usually speed up, as the base configuration is in the vicinity of the minimum. In some instances, the routine will fail to converge if it starts from poorly chosen initial values. Properly chosen starting values are important in any class of optimization problem.

19. The rearrangement operator simply perturbs the current base case. It does not necessarily generate a completely random configuration. In this manner, the algorithm maintains a history of its previous tests.

20. Shen Lin, “Computer Solutions of the Traveling Salesman Problem,” *The Bell System Technical Journal*, vol. 44, no. 10 (December 1965): 2245–69.

21. David H. Ackley, “An Empirical Study of Bit Vector Function Optimization,” in *Genetic Algorithms and Simulated Annealing*, ed. by Lawrence Davis (Los Altos, Calif.: Morgan Kaufmann Publishers, Inc., 1987), 170–204. Ackley proposes several variations to the iterative improvement technique, and compares their operation on a variety of cost functions.

22. Kirkpatrick et al. is the first publication of the SA technique.

23. For several implementations and examples of its use, see D. Abramson, “Constructing School Timetables Using Simulated Annealing: Sequential and Parallel Algorithms,” *Management Science*, vol. 37, no. 1 (January 1991): 98–113; Ackley, 170–204; Atanu Basu and L. Neil Frazer, “Rapid Determination of the Critical Temperature in Simulated Annealing Inversion,” *Science*, vol. 249, no. 4975 (21 September 1990): 1409–12; Lawrence Davis and Martha Steenstrup, “Genetic Algorithms and Simulated Annealing: An Overview,” in *Genetic Algorithms and Simulated Annealing*, ed. by Lawrence Davis (Los Altos, Calif.: Morgan Kaufmann Publishers, Inc., 1987), 1–11; S. Kirkpatrick et al.; Scott Kirkpatrick, “Optimization by Simulated Annealing: Quantitative Studies,” *Journal of Statistical Physics*, vol. 34, nos. 5/6 (1984): 975–86; and Mario P. Vecchi and Scott Kirkpatrick, “Global Wiring by Simulated Annealing,” *IEEE Transactions on Computer-Aided Design*, vol. CAD-2, no. 4 (October 1983): 215–222.

24. Press et al., 326–34.

25. Nicholas Metropolis et al., “Equation of State Calculations by Fast Computing Machines,” The Journal of Chemical Physics, vol. 21, no. 6 (June 1953): 1087–92.

26. In general, systems at thermodynamic equilibrium will seek the lowest energy state possible. The reason comes from statistical thermodynamics. Consider some small system $A$ in thermal equilibrium with a heat reservoir $A'$. $A$ can occupy a variety of states (configurations), depending on its energy. In particular, we are interested in the probability that $A$ occupies some state $r$ with energy $E_r$. This probability $P_r$ is given by the Boltzmann distribution:

$$P_r = \frac{e^{-Er/kT}}{\sum_r e^{-E_r/kT}}$$

where $T$ is the temperature and $k = 1.38054 \times 10^{-16}$ ergs deg$^{-1}$ is the Boltzmann constant. For a fixed temperature $T$, the probability that $A$ is in a high energy state decreases exponentially. Hence, $A$ is most likely found in a lower energy state. This leads to the common statement that systems in thermal equilibrium seek the lowest energy state possible (the most probable state). Nevertheless, there is a finite probability that $A$ will be found in any of its possible states, regardless of the energy. For further details and a derivation of the Boltzmann distribution, see F. Reif, *Fundamentals of Statistical and Thermal Physics* (New York: McGraw-Hill Book Co., 1965), 202–06.

27. The configuration space is the set of all possible molecular arrangements. Due to interactions between the molecules, some arrangements will have lower energies than others. These molecular arrangements are preferred as the system cools and freezes.

28. The important point to note here is the ratio $\Delta C/kT$. For large values of $kT$, $\Delta C$ can take on relatively large positive values before the Boltzmann probability drops to negligible levels. For example, if $\Delta C = 0.69kT$, the probability that the new arrangement will be accepted is 0.5, even though its cost is higher than the current base. For $\Delta C = kT$, the probability of accepting the new configuration drops to 0.37. Thus, the higher the value of $T$ (and thus of $kT$), the greater the probability that a given positive $\Delta C$ will be accepted. In fact, the SA literature discusses using high initial values of $kT$ to “melt” the set of rearrangements. For high $kT$, the odds of accepting a large positive $\Delta C$ are good, and the algorithm acts as though the problem is in the liquid phase.

29. Press et al., 328. The authors discuss temperature schedules, as well as provide an example (FORTRAN source code). See also Basu and Frazer, 1409–12. They discuss methods of determining the critical phase change temperature, at which the configuration “freezes.” Knowledge of this temperature considerably aids the design of the temperature change schedule and the initial choice of $T$.

30. This does not imply that SA is an example of the "Garbage In–Garbage Out" syndrome. Rather, it means that numerical experimentation may be required—an air planner may have to run a SA-based targeting program several times while varying the initial temperatures and schedules in order to obtain convergence. Experimental tuning of algorithms commonly occurs in numerical analysis; this is not a phenomenon unique to SA.

31. For a colorful and highly readable account of the early development of classifier systems and genetic algorithms, see M. Mitchell Waldrop, *Complexity: The Emerging Science at the Edge of Order and Chaos* (New York: Simon & Schuster, 1992), chap. 5.

32. The current literature on genetic algorithms is vast. Three excellent introductory references to the subject are Stephanie Forrest, "Genetic Algorithms: Principles of Natural Selection Applied to Computation," *Science,* vol. 261, no. 5123 (13 August 93): 872–78; David E. Goldberg, *Genetic Algorithms in Search, Optimization, and Machine Learning* (Reading: Addison-Wesley Publishing Co., Inc., 1989); and John H. Holland, "Genetic Algorithms," *Scientific American*, vol. 267, no. 1 (July 1992): 66–72. An additional sampling of some of the more readable literature includes Ackley, 170–204; Michael Antonoff, "Genetic Algorithms: Software by Natural Selection," *Popular Science*, vol. 239, no. 4 (October 1991): 70–74; Scott Austin, "Metamorph: A Genetic Algorithmic Tool," *AI Expert*, vol. 5, no. 8 (August 1990): 48–55; Scott Austin, "Genetic Solutions to XOR Problems," *AI Expert*, vol. 5, no. 12 (December 1990): 52–57; Lashon Booker, "Improving Search in Genetic Algorithms," in *Genetic Algorithms and Simulated Annealing*, ed. by Lawrence Davis (Los Altos, Calif.: Morgan Kaufmann Publishers, Inc., 1987), 61–73; Davis and Steenstrup, 1–11; Peter J. Denning, "Genetic Algorithms," *American Scientist*, vol. 80, no. 1 (January–February 1992): 12–14; Chuck Karr, "Applying Genetics to Fuzzy Logic," *AI Expert*, vol. 6, no. 3 (March 1991): 38–43; Chuck Karr, "Genetic Algorithms for Fuzzy Controllers," *AI Expert*, vol. 6, no. 2 (February 1991): 26–33; Scott A. Kennedy, "Five Ways to a Smarter Genetic Algorithm," *AI Expert*, vol. 8, no. 12 (December 1993): 35–38; Alex Lane, "Programming with Genes," *AI Expert*, vol. 8, no. 12 (December 1993): 16–19; Gregory J. E. Rawlins, "Introduction," in *Foundations of Genetic Algorithms,* ed. by Gregory J. E. Rawlins (San Mateo, Calif.: Morgan Kaufmann Publishers, 1991), 1–10; Denny Rock and Joel Hirsh, "Will GAs Breed with Aerospace?" *AI Expert*, vol. 8, no. 12 (December 1993): 29–34; Andy Singleton, "Genetic Programming with C++," *Byte*, vol. 19, no. 2 (February 1994): 171–76; Peter Wayner, "Genetic Algorithms," *Byte*, vol. 16, no. 1 (January 1991): 361–68; and Steve Wilson, "How to Grow a Starship Pilot," *AI Expert*, vol. 8, no. 12 (December 1993): 21–26.

33. Cliff Layton, "When to Use AI Techniques," unpublished briefing slides, presentation to the Oklahoma Artificial Intelligence Special Interest Group.

34. The crossover operation may have been the key breakthrough in the development of practical, operating Gas. Nick Beard, "Evolution and Computers," *New Scientist*, vol. 125, no. 1699 (13 January 1990): 68.

35. The mathematical theory of the GA is beyond the scope of this paper. For a very readable discussion of its theoretical basis, see Goldberg, chap. 2.

36. Ibid., chap. 1.

37. Strictly speaking, individuals that survive to the next generation can carry their fitnesses over with them. The GA will not have to recalculate the fitnesses of these individuals. Nevertheless, the computational requirements will be intense for many generations of large populations.

38. This is an admitted reductionist approach to targeting, as it eliminates the couplings to other economic target sets. We have deliberately chosen this point of view for clarity. Nevertheless, we will preserve and elaborate upon the couplings between the electrical grid and POL networks. An expanded version of this example would include other target sets, such as telecommunications and transportation. In particular, the isolated nodal analysis-reconciliation procedure we propose below is applicable to an expanded model.

39. Stevenson discusses load-flow studies in-depth. In particular, see chap. 8, "Load-Flow Studies," 196–212. The Electrical Engineering and Computer Science Department, College of Engineering, University of Oklahoma, Norman, Okla., graciously provided a copy of their load-flow program (including the FORTRAN source code) and users manual to ACSC in May 1993. The user's manual, *PCLF: Personal Computer Load Flow User Manual* (Norman, Okla.: University of Oklahoma, School of Electrical Engineering and Computer Science, 1986) gives

the background theory of load-flow analyses. This simulation can be currently used to model multiple contingencies and their effects on electrical grids.

40. In general, the current flowing through and the voltage across some component of an electrical grid (such as a transmission line, transformer, etc.) will not be "in phase." That is, plots of the instantaneous current and voltage will not overlap—they will instead be two sinusoidal waves of the same frequency but displaced relative to each other by some *phase angle* $\theta$. This arises due to the inductance or capacitance of the grid.

The power flowing through a component is the product of the voltage and the complex conjugate of the current. If the phase angle $\theta$ is not zero, then the complex power $S$ is given by $S = P + iQ$. (Here, we refer to complex numbers from mathematics, not system complexity.) The real part $P$ is known as the *real power*; it is the average power flowing through the component. $Q$ is the imaginary or *reactive power*. It has an average value of zero as it is alternately positive or negative. Physically, it represents power that alternately flows toward and away from the component. Note that in a purely resistive network, $\theta = 0$ and $Q = 0$. The real power is given in units of watts (or the more practical unit megawatts) and the reactive power is given in vars (or megavars; var stands for voltamperes reactive).

In a similar manner, the voltages across the grid components will generally not be in phase with one another. Thus, overlaid plots of the instantaneous voltages will not "line up." Using standard practice, we arbitrarily pick one component as a reference and set its phase angle to zero. Then, the other components have some phase angle relative to the reference part.

The main outputs of the load-flow program are the real and reactive power flows ($P$ and $Q$) in the grid and the bus voltages and phase angles.

For an excellent introduction to voltages, currents, power flows, and single- and three-phase electrical circuits, see Stevenson, chap. 2, "Basic Concepts," 12–34.

41. Note that this use of the load-flow analysis is actually an example of input-based targeting: the planner selects a group of targets and the program determines the physical results of the attack. The GA routine described below transforms this input-based process into an output-based approach.

42. Edwin (Bud) L. Averill and W. John Light, director, Research & Development, Excel Energy Technologies, Ltd., interviews with author, 27 January 1994.

43.. Russsell Staggs, engineer, Willbros Butler Engineers, Inc., telephone interview with author, 21 April 1994; Roger E. Rinaldi, engineer, Willbros Butler Engineers, Inc., telephone interviews with author, 22–23 May 1994.

44. For an overview of GIS, see "What is a GIS? (And What It Isnt)," *Design Management* (July 1991), 26–28; George B. Korte, "GIS Industry and Software Overview," *P.O.B.*, vol. 18, no. 3 (February–March 1993): 24–32; Gene Bylinsky, "Managing with Electronic Maps," *Fortune*, vol. 119, no. 9 (24 April 1989): 237–54; Steve Ellis and Paul Ginther, "Case History: GIS Developed for Kern River Gas System–Part 1," *Pipe Line Industry* (April 1993): 35–41; Steve Ellis and Paul Ginther, "Case History: GIS Developed for Kern River Gas System–Part 2," *Pipe Line Industry* (May 1993): 45–50.

45. For example, *Oil & Gas Journal* and PennWell Publications produce a significant number of publications that detail virtually every aspect of the global oil industry. PennWell Publications provides the same services for the electrical industry of the US. The product lines include software, data on diskettes, on-line services, surveys, maps, statistical information, and printed material. *Energy Catalog*, PennWell Books, Tulsa, Okla., Winter 1994; Catalog, *Oil & Gas Journal* Energy Database/*Electric Light & Power* Electric Power Database, Tulsa, Okla., Fall/Winter 1993. MAP Search Services publishes oil and gas pipeline and facilities maps for the continental US. They also have electronic maps and digital data bases that include national/state/county boundaries, hydrology, railroads, interstate/US/state highways, ferries, military and civilian airports, and oil and gas pipelines and facilities. Note that their data bases cover two major economic infrastructure elements. Company brochure, MAP Search Services, Durango, Colo., 1994.

46. Averill interview.

47. Gil Broyles, assistant to the president, WilTel, interview with author, 27 January 1994; and James S. Wineinger, engineer, Network Development, WilTel Business Networks, inter-

view with author, 27 January 1994. In no case, however, should a planner mirror image a US system onto a foreign nation.

48. The implications for the intelligence community are clear if the USAF chooses to perform this type of systems analysis and targeting. The intelligence community must develop and maintain data bases required for the infrastructure element simulations. Such detailed information will be time consuming to develop; the time to start collecting the data is now during peacetime rather than after the commencement of hostilities.

49. This particular genotype leaves the issue of "targeted but only damaged" unaddressed. Clearly, in an actual attack, a target might not be completely destroyed—it might only sustain damage or perhaps emerge entirely unscathed. We can approach this important issue from several different angles. First, we can develop a much more sophisticated targeting program. In principle, for each potential targeting solution (each individual in the solution population), the program could allocate weapons against all targets. Using munitions effectivenesses, the program would next compute the probable damages to the targets and the probable effects of these damages. Finally, the program would fold the damages into its economy-wide nodal analysis. This approach requires significant physical data on each potential target, such as construction type, building sizes, etc. In addition, the program must have weapons allocation and munitions effectiveness modules to estimate levels of destruction. This solution represents a significant increase in program and data base complexity.

A second, simpler approach entails randomly assigning degradations to some targeted structures. For example, rather than assuming a targeted electrical generator is destroyed and completely inoperable, the program reduces its power output by some random factor and then performs the load-flow analysis. This approach is significantly simpler than the first approach.

A third, very simple option is a manual version of the first two options. Upon receiving the targeting solution developed by the GA, the planning team "selectively degrades" rather than destroys certain targets. That is, the planners pick certain targets for degradation rather than destruction. The selection is based upon known physical factors (such as hardening of specific targets, point defenses, etc.) or "what if" analyses. (What if a certain pump station is missed? What if the output of an electrical generator is only reduced by 40 percent?) The planners then perform a nodal analysis of the economy with the selectively degraded and destroyed targets. This analysis then indicates the effects of a less-than-perfect attack. This approach suffers in that it is manual and potentially time consuming. However, it allows the planners to use intuition to determine the likely attack failures, rather than the random techniques of the first and second approaches.

50. Of course, this state does not include any workarounds that the targeted nation employs to mitigate the destruction. It simply indicates the degree to which the overall economic system will degrade immediately following the attack.

51. Air Force Manual 1-1, *Basic Aerospace Doctrine of the United States Air Force,* vol. 1 (March 1992), par.1-2a.

52. Ibid., par. 1-2.

53. Warden interview. The planners needed systems analysis tools that did not exist. Such programs would have proven very valuable during the development of the Master Target List.

## Chapter 5

# Synergy Tables

In chapter 3, we developed a simple model of a coupled economy. The economy consisted of four interconnected infrastructure elements: an electrical grid, a natural gas system, an oil distribution system, and a telecommunications network. The example was deliberately simple, so that the interconnections between the elements would be readily apparent. Even so, many of the characteristics of a "real" economy were present: feedback loops, higher order connections, tight and loose couplings, branching processes, and so forth.

This chapter further explores the interconnected nature of economies.[1] It focuses on four elements: electric grids, POL distribution networks, telecommunications systems, and transportation networks. Before examining the interfaces between the elements in the following tables, several notes are required:

1. The tables are not intended to be either checklists or exhaustive summaries. Rather, their purpose is to illustrate the type of synergies that are present in economies and demonstrate their complex, interconnected nature.

2. The majority of the data relates to US systems. Foreign systems may be completely different in structure, organization, and function. Consequently, the data below are only illustrative of the types of synergies that could exist. *They do not reflect the nature of the synergies that will exist in every country.*

3. Each country must be examined individually to determine the relevant synergies. Furthermore, these analyses must take into consideration the sociocultural character of the nation, which will influence the forms, processes, and linkages of the economic infrastructure elements. The planner must avoid mirror imaging US synergies onto foreign nations.

4. The synergies in the tables are generic. Not every power plant is designed and built alike; each pipeline will have its own set of characteristics. As a result, the planner must tailor his analyses to the exact system in question.

5. Many foreign nations lag behind the US technologically. As they upgrade their infrastructures, many use the US as a model, or purchase US equipment.[2] In these cases, there will be direct correlations between the US and foreign infrastructures. Nevertheless, the usual caveats against mirror imaging apply.

6. Only economic rather than military synergies and effects are addressed.

The tables focus on the connections *between* the four target sets. For example, table 5, Electrical Grids, concentrates on how the electrical grid is tied to the POL (fig. 6), telecommunications (fig. 7), and transportation networks (fig. 8). More specifically, the first entry in this table shows how and why natural

**Table 5**

## Electrical Grids

| Infrastructure Elements | Linkages |
|---|---|
| POL | Natural gas-fired generators<br>• The generators require connections to the natural gas pipeline<br>• Gas regulating yards connect the pipeline to the plant<br>• Local storage of the gas is generally nonexistent ("storage is in the pipeline")<br><br>Oil-fired generators<br>• The generators require connections to the oil pipeline<br>• Fuel oil is stored in tanks on site<br>• 1–3 months of fuel is normally stocked at a generator<br><br>Gas turbine generators<br>• May use either natural gas or some other liquid/gas fuel<br>• The generators require connections to the pipelines<br>• Site may have no local fuel storage<br><br>Fuel for backup generators<br>• Electrical generator sites themselves have smaller backup generators for restarts, safely spinning down turbines in an emergency, etc.<br>• Diesel, gasoline, or propane engines may power the backup generators<br>• Dispatch control centers have backup generators to guard against power failures<br>• Backup generators require fuel to operate<br>• Local fuel storage is usually from a few days to a few weeks |
| Communications | Dispatch control centers<br>• Provide system-level control functions<br>• Require communications links to the generators and field sites<br>• Centers are important for balancing power interchanges between areas<br>• Centers are important for "blackout restarts"<br>• Centers will have redundant communication systems (i.e., satcom, fiber optic networks, voice communications, radios)<br>• Backup dispatch centers require comm links to field sites and main dispatch control centers |
| Transportation | Coal-fired generators<br>• Railroads supply the coal to the generators—vulnerabilities include rolling stock, tracks, bridges, etc.<br>• 3-month's coal supplies are typicall kept at sites in open storage areas<br><br>Nuclear generators<br>• Operations involve the shipment of nuclear fuels and waste materials<br>• Fuel is not stockpiled on the generation sites; it is kept in the reactors<br><br>Generators consume additional products ($H_2$, water treatment chemicals, etc.)—the sites rely upon the transportation network for deliveries<br><br>Site Repairs<br>• Transportation network delivers equipment, material, and crews to damaged sites<br>• Transportation modes can be critical in remote, inaccessible areas<br>• For certain equipment, transportation is critical. (For example, generator step-up transformers are large and very heavy; only about 20 railcars exist in the US that can transport these devices. In addition, delivery routes for these transformers must be carefully planned due to the high weights of the devices.)<br><br>Fuel deliveries for backup generators (at generator sites, dispatch control centers, etc.) |

**Table 6**

## POL Distribution Networks

| Infrastructure Elements | Linkages |
|---|---|
| Electrical Grid | Oil fields<br>• Electrical pumps and motors<br>• Electrical controls on the machinery<br>Refineries<br>• Refineries employ electrical control systems, some electrically powered rotating machinery (pumps, compressors, etc.)<br>• Refinery electrical requirements vary from site to site; may be in the range of 10–100 megawatt (MW)<br>• Some refineries use on-site electrical generation; others are directly connected to the electrical grid<br>• Attacking power would shut down the refinery, but the outage duration would vary from one refinery to the next<br>• Refinery could use emergency generators in some cases (i.e., 2–3 MW locomotives)<br>• Power transformers and substations on plant sites are easy to identify and might be very difficult to replace if destroyed<br>Pump and Compressor Stations<br>• Electricity powers pumps, compressors, valves, manifolds, controls, etc. (Note: some sites use diesel or natural gas engines to power the compressors and pumps.)<br>• Sites may have backup generators available<br>• Loss of one or two pumps or compressors will reduce flow rates through a pipeline, but perhaps not cripple it<br>• Pump and compressor stations maintain inventories of critical parts, including those with long lead times<br>Storage Sites<br>• Electricity powers pumps, valves, manifolds, controls, etc.<br>• Workarounds to power loss may be possible, depending upon power requirements and availability of backup generation<br>Distribution (Bulk) Terminals<br>• Terminals typically use electrically operated pumps, valves, manifolds, controls, etc.<br>• Workarounds to power loss may be possible, depending upon power requirements and availability of backup generation<br>Natural Gas Liquid (NGL) Plants<br>• These plants convert natural gas from gas to liquid or vice versa<br>• Require electricity for compressors, coolers, controls, etc.<br>Pipeline Controls<br>• Controls are electromechanical (relays) or solid state<br>• The control network ties together all the elements of the pipeline system<br>• Pipelines rely upon computerized SCADA system for control and management functions<br>SCADA systems used to control all operations<br>SCADA system transmits information between dispatch control centers and remote terminal units (RTU) at pipeline facilities<br>• Manual workarounds to loss of SCADA, electromechanical controls might be extremely difficult to carry out |

**Table 6, continued**

## POL Distribution Networks

| Infrastructure Elements | Linkages |
|---|---|
| Electrical Grid (con't) | Dispatch Control Center<br>• Control centers and backup sites are heavily computerized<br>• Centers rely upon SCADA to control all operations<br>• Backups to power losses include standby generators, alternate control site<br>• Control centers cannot function without electricity; pipelines (in the US) generally cannot function (or function safely) without their computerized controls |
| Communications | Pipeline Controls<br>• SCADA requires continuous communications between the RTUs and the dispatch control centers<br>• Control systems will use satcom and/or landlines for communications between RTUs and control centers<br>• Control systems will have communication backups (i.e., satcom primary system with landline and/or voice backups)<br>• Controls and communications are essential for the safe and efficient operation of a pipeline<br><br>Dispatch Control Center<br>• Linked to remote sites via SCADA and communications systems<br>• Controls and communications are essential for the safe and efficient operation of the pipeline<br><br>Production Control<br>• Communications systems are needed in the day-to-day management operations of the pipeline firms: placements of orders, dispatch control, coordination of repairs, etc. |
| Transportation | Water Transportation of POL Products<br>• Ocean shipment of crude is the primary means that many countries use to obtain their oil. Ocean shipment requires:<br>Port facilities<br>Ocean terminals<br>Oil tankers<br>Offshore unloading sites<br>• Port facilities are vulnerable to attack; such attacks could cripple a country if it imports the majority of its oil<br>• Inland water transport is often used; it requires port facilities, barges, off-loading sites, etc.<br><br>Rail Shipment of POL Products<br>• Relatively small loads shipped via rail (vis-à-vis pipelines)<br>Much NGL is shipped via rail in the eastern US<br>• Importance of rail shipments must be weighed against other transport methods when targeting oil<br><br>Truck Shipments of POL Products<br>• Forms the bulk of the local distribution system<br>• Trucking gets POL products from the “end of the pipeline” to the retail distributors and users (i.e., gasoline stations, aircraft at airports, home heating oil, etc.)<br>• Trucking is the primary means of supplying fuel to backup generators |

**Table 6, continued**

## POL Distribution Networks

| Infrastructure Elements | Linkages |
|---|---|
| Transportation (con't) | Repairs and Inspections<br>• Transportation networks are critical for the delivery of equipment, material, and crews to damaged sites<br>• Pipelines are often sited near transportation networks to facilitate repairs<br>• However, pipelines may also be sited in remote, difficult to reach areas (jungles, deserts, mountains, etc.)<br>• Availability of transportation may be critical in remote areas or for shipment of large equipment<br>Remote repairs may be impossible if adequate transportation does not exist<br>Workarounds to attacks in remote areas may be very difficult due to lack of transportation facilities<br>• Pipelines are inspected at regular intervals for leaks, damage,etc. Inspection means include:<br>Overflight<br>Walking the line<br>• Inspections become more important during a war |

**Table 7**

## Communication Networks

| Infrastructure Elements | Linkages |
|---|---|
| Electrical Grid | Primary source of power for communications and computer equipment<br>• Includes switching sites, points of presence, regeneration stations, etc.<br>• Important sites will generally have backup generators and battery systems<br>Control Centers<br>• Control centers are essential for network operations<br>• Centers are highly computerized<br>• They require electricity for operation<br>• Centers generally have a backup control site and standby generators<br>• Backup control sites are also highly computerized and require electricity to operate |
| POL | Fuels for the backup generators |
| Transportation | Repairs and Inspections of Facilities<br>• Transportation networks are critical for the delivery of equipment, material, and crews to damaged sites<br>• Availability of transportation becomes critical in remote areas or for shipment of large equipment<br>Remote repairs may be impossible if adequate transportation does not exist<br>Workarounds to attacks in remote areas may be very difficult due to lack of transportation facilities<br>• Inspection of lines and facilities<br>Aerial inspections are often used<br>Fuel deliveries to backup generators—relies upon local truck distribution of POL products |

**Table 8**

## Transportation Systems

| Infrastructure Elements | Linkages |
| --- | --- |
| Electrical Grid | Airports—require electrical power for many facilities and systems, such as:<br>• Air traffic control, radars, communication equipment<br>• Runway lighting<br>• Power for support facilities<br><br>Railroads<br>• Primary source of power for some types of rail systems:<br>Electrified railways<br>Subways<br>Streetcars<br>• Electricity is required to operate many of the components of a railway, such as:<br>Signals<br>Switches, marshaling yards<br>Computerized controls<br>Control centers and their backup sites<br><br>Motor traffic (trucking, automobiles, etc.). Electrical power is required for:<br>• Signalization<br>• Fuel pumps at service stations<br><br>Miscellaneous “transportation” modes that require electricity in order to operate include:<br>• Elevators<br>• Escalators |
| POL | The fuel and lubricants for aircraft, diesel locomotives, boats, motor transport, etc.<br><br>The fuel for backup generators at control sites, radar sites, etc. |
| Communications | Operations at centralized control sites depend upon communication networks<br>• Sites include railroad control centers, air traffic control centers, etc.<br>• Integration of operations over large transportation networks demand reliable communications (such as air traffic control)<br><br>Signals control<br>• Railroad signals, especially if they are operated from a centralized control station<br>• Highway and traffic signals<br><br>Railroad switch controls, especially if they are operated from a centralized control station |
| Transportation | Intermodal ties<br>• These ties are the connection points between different means of transportation; they include:<br>Ports: links between water transportation and rail/trucking/pipelines<br>Marshaling yards: links between rail and trucking<br>Airports: links between air and rail/trucking<br>• Note that there are synergies *between* different modes of transportation<br><br>Damage to or destruction of one transportation mode may aggravate overuse problems on other modes, due to substitution |

gas-fired generators are tightly coupled to the natural gas distribution network. There is no attempt in the tables to show the connections *within* a given target set (i.e., the fact that communication control centers rely upon communication networks is not spelled out in table 7). Thus, the tables examine the interfaces between the elements and display the complex intertwined nature of economies. As a natural consequence, the tables further the compelling arguments for holistic rather than reductionist approaches to economic targeting.

## Notes

1. This data is a compilation from the following sources:

Interviews. **Electrical Networks**: Edwin L. Averill, W. John Light. **POL Networks**: G. Alan Petzet, exploration editor, *Oil & Gas Journal*, Tulsa, Okla., 26 January 1994; Kirk Hilbig; Mark D. Beisemeyer, Willbros Butler Engineers, Inc., Tulsa, Okla., 28 January 1994; Andy Martin, Willbros Butler Engineers, Inc., 28 January 1994; Dr Dennis Engi. **Communications**: Gil Broyles, James S. Wineinger. **Transportation**: Dr Stephen C. Roehrig, chief, Advanced Transportation Programs, Sandia, Albuquerque, N.Mex., 9 December 1993, 6 April 1994; Dr Bob Cover, Starbase Laboratory, Sandia, 6 April 1994; William F. Hartman, Special Projects Div 9614, Safeguards Program, Sandia, 6 April 1994; Brad Godfrey; Bill Ling; Keith Almquist, Strategic Studies Department I, Sandia, 6 April 1994; Doug Lawson, Strategic Offense Studies Department, Sandia, 6 April 1994; Jon Caswell, Sandia, 6 April 1994; John Milloy, Sandia, 6 April 1994; Dr Dennis Engi; Len Malczynski, Sandia, 6 April 1994.
Reports and Theses. **General**: Fred C. Iklé, *The Social Impact of Bomb Destruction* (Norman, Okla.: University of Oklahoma Press, 1958). **Electrical Networks**: Maj Bruce DeBlois et al., "Dropping the Electric Grid: An Option for the Military Planner," unpublished research report (Maxwell AFB, Ala.: ACSC, 1994); Maj Thomas E. Griffith, Jr., *Strategic Attack of National Electrical Systems*, thesis (Maxwell AFB, Ala.: SAAS, 1993; David A. Shlapak, "Electrical Power as a Tartet System," Project AIR FORCE, RAND Memorandum PM-187-AF (December 1993. **POL Networks**: Maj Edward J. Felker, "Does the Air Force Practice Its Doctrine: A Limited and Focused Air Campaign Concept," unpublished thesis (Fort Leavenworth, Kans.: Command and General Staff College, 1991; Maj Mark W. Graper et al., "Petroleum as a Center of Gravity," in *Air Campaign Course 1993: Research Projects*, ed. Dr Richard Muller, Lt Col Larry Weaver, and Lt Col Albert Mitchum (Maxwell AFB, Ala.: ACSC, 1993); Bill D. Berger and Kenneth E. Anderson, *Modern Petroleum: A Basic Primer of the Industry*, 2d edition (Tulsa, Okla.: PennWell Books, 1981), chap.10; Maj Scott E. Wuesthoff, *The Utility of Targeting the Petroleum-Bassed Sector of a Nations Economic Infrastructure*, theses (Maxwell AFB, Ala.: SAAS, 1992). **Communications**: Maj Paul DiJulio et al., "Communications-Computer Systems: Critical Centers of Gravity," in *Air Campaign Course 1993: Research Projects*, ed. Dr Richard Muller, Lt Col Larry Weaver, and Lt Col Albert Mitchum (Maxwell AFB, Ala.: ACSC, 1993; Maj Gerald R. Hust, *Taking Down Telecommunications*, thesis (Maxwell AFB, Ala.: SAAS, 1994). Various media information brochures, WilTel, 1992–1993.

2. This is particularly true of the telecommunications industry. Gil Broyles, assistant to the president, WilTel, interview with author, 27 January 1994.

## Chapter 6

# Conclusions

Complex systems abound in the world. They consist of collections of interconnected parts that interact with each other and their environment. We find examples of complex systems in many diverse disciplines, such as physics, chemistry, biology, and sociology. Of particular relevance to this study is that economies are complex systems. A little reflection shows that various economic infrastructure elements (such as electricity, POL, telecommunications, and transportation) are linked to one another. In many ways, each element is dependent upon the other and cannot exist in isolation. Communication systems cannot operate without electricity, POL distribution networks require communications to function properly, and so forth.

All complex systems exhibit several common traits. These characteristics include emergent behavior, adaptive self-organization, evolution toward the edge of chaos, and the ability to process and act upon information. The behavior of a complex system depends critically upon the linkages between its individual components. In fact, system-wide behavior generally cannot be deduced from an analysis of the component parts. Consequently, understanding system behavior requires more than a reductionist analysis of the individual parts—it requires a holistic analysis that incorporates the interactions between the parts. As economies are complex systems, we expect the same to be true of them.

Economies should exhibit the properties of complex systems. They contain various interconnections that act synergistically upon each other. In fact, the overall behavior of an economy may be difficult to predict due to the branching, nonlinear linkages between its elements. Most importantly, perfect knowledge of the various elements in isolation will not be sufficient to understand and predict the overall behavior of the economy. This reductionist approach overlooks the interconnections between elements and their influences upon economic behavior.

Because of the complex nature of economies, air planners require new forms of analyses for targeting. Nodal analyses, such as load-flow and hydraulic studies of electrical grids and POL networks, will greatly aid the planners. However, their utility is limited if the planners perform the analyses on isolated infrastructure elements. Rather, a targeting methodology that incorporates the linkages between the elements is needed.

Such holistic planning tools are at hand today. Indeed, we saw in chapter 4 that simulated annealing or genetic algorithms can form the basis of a complex targeting algorithm. In particular, we examined a genetic algorithm coupled to load-flow and hydraulic analyses that should be capable of analyzing electrical grids linked to POL networks. The particular example preserves the ties between the two elements, and thus avoids the problems of reductionism. Although this new technique was only applied to electrical grids and POL networks, it is in principle extendible to any number of coupled infrastructure elements. Such analysis tools are sorely lacking today—yet the technology exists to begin their development.

## Recommendations

1. This thesis is principally theoretical. It builds a framework for economic targeting upon complexity theory. However, "experimental verification" of the theory is lacking. Not only must we show that synergies and interconnections exist in economies, we must demonstrate that they have significant impacts on how economies function. Natural disasters provide one means of verifying the effects of the couplings. For example, the 17 January 1994 Los Angeles earthquake caused widespread power outages in central and southern California. However, the highly interconnected nature of the electrical grid led to power disruptions as far away as Montana, Washington, Oregon, Idaho, and Utah.[1] Strikes and other disturbances may hold key data as well. Finally, a detailed holistic analysis of wartime economies impacted by aerial bombardment will provide the best evidence for the validity of the theory.[2]

2. The GA load-flow hydraulic analysis program described in chapter 4 has not been written. It currently is a paper concept. If coded and validated, the program would provide an invaluable tool for air planners. Furthermore, a modified version of the code could dramatically increase the realism of warg ames, as the "actual" effects of bombing strikes could be incorporated into the games. The program should be written, validated, and incorporated into Air Force planning processes and war games.

3. Finally, if the military is to pursue nodal analysis, it must possess sufficiently detailed data bases on the infrastructure elements of potential enemies. As noted in the previous chapters, the data bases will require a significant amount of effort to develop and validate. The time to start developing the data bases is now, during peacetime, rather than after the commencement of hostilities with some aggressor. Without adequate data bases, the best nodal analysis tools are useless.

## Final Remarks

Targeting science does indeed stand at the edge of a divide. In light of the complex nature of economies, the old reductionist approaches to targeting must give way to holistic methods. Within reach are nodal analysis tools that will allow planners to make this transition. We need a concerted effort to develop the computer programs and requisite data bases. The payoffs are great: smarter targeting, greater system-wide effects for the same number of weapons, and fewer aircrews and aircraft at risk. As these tools were notably absent in our last major conflict, the Persian Gulf War, we would be sorely remiss to enter the next war without them.

### Notes

1. Stephen Conley, "Quake Darkens the West," *USA Today* (18 January 1994), 1A; and Steve Marshall, "Details on Damage, Delays and the Dead," *USA Today* (18 January 1994), 3A.
2. The best example of this type of analysis is Mierzejewski. An extension of this analysis to include other target sets would provide the necessary verification of the theory. See Alfred C. Mierzejewski, *The Collapse of the German War Economy, 1944–1945* (Chapel Hill: University of North Carolina Press, 1988).

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