Design: Structure, Process, and Function

A Systems Methodology Perspective

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1 Introduction

Systems methodology comprises approaches to systems analysis on the one hand, and systems engineering on the other. Systems analysis develops an understanding of a system, its elements, and its environment that describes their functional, structural, and behavioral aspects. Systems engineering transforms operational user needs into system architectures, performance and functional requirements for system elements, and internal and external interface definitions. The common element of both systems analysis and systems engineering is design.

Design in systems methodology is the combination of two interactive loops, one addressing the relationship of the design object to its environment, the other addressing the relationship of the design object to its parts. For systems analysis, e.g., the medical science of physiology, these loops consider structure, function, and process in the context of environment to develop information (what), knowledge (how), and understanding (why) of the system and elements being studied.

This chapter presents the interactive loops of the design process in systems engineering, and explains the use of analogous interactive loops in systems analysis, considering Harvey's analysis of the function of the human heart and Cold War analysis of Soviet national missile defenses. The core systems analysis insights of Singer, Churchman, Ackoff, and Gharajedaghi are adapted into an exposition that accurately describes both the pioneering scientific work of Harvey and the modern pragmatic work of Cold War military intelligence analysts.

2 Definitions of System, Function, Purpose

2.1 Definitions of "System"

The analysis of design in systems methodology leans heavily on the modern notion of a system, especially the definitions of Bertalanffy and Ackoff.

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Bertalanffy (1969, 55–56): “A system can be defined as a set of elements standing in interrelations. Interrelation means that elements, p, stand in relations, R, so that the behavior of an element p in R is different from its behavior in another relation, R'. If the behaviors in R and R' are not different, there is no interaction, and the elements behave independently with respect to the relations R and R'.”

Ackoff (1981, 15–16; see also 1972; 1974): “A system is a set of two or more elements that satisfies the following three conditions. [1] The behavior of each element has an effect on the behavior of the whole. … [2] The behavior of the elements and their effects on the whole are interdependent. … the way each element behaves and the way it affects the whole depends on how at least one other element behaves. … [3] However subgroups of the elements are formed, each has an effect on the behavior of the whole and none has an independent effect on it.”

Ackoff concludes from his definition that every element of a system has essential properties that belong to it only by virtue of its being an element in the system, and also that every system has essential properties that belong to none of its elements individually or in aggregation. Systems analysis exploits these two conclusions to locate function among the essential properties of an element that it has only in virtue of its being in a system, and to locate the purpose being served by a function among the essential properties of the system that belong to none of its elements. These are critical razors for winnowing candidate functions and candidate purposes.

Ackoff’s and Bertalanffy’s definitions are compatible, but Ackoff’s definition avoids explicitly introducing the relations R as explaining differences in behavior of p, leaving the behaviors unexplained. This leads explicitly to that abandonment of reductionism that is characteristic of systems thinking. Bertalanffy’s definition is important for illuminating why it is that systems have the kinds of irreducibility that are made implicit in Ackoff’s definition: it is the relations of the elements to the system and to one another that give the elements their system-dependent properties on the one hand, and the system its emergent properties on the other. In a nested system-of-systems, Bertalanffy’s definition helps to explain what Ackoff’s definition describes, particularly the distinction between functions and purposes.

2.2 Distinguishing Function from Purpose

Functions are not arbitrary properties of system elements; they must be among those properties that are essential to the element, in light of the definition of a system (interdependence of behaviors of system and elements). This distinguishes the pumping of a heart in a cardiovascular system from its audible thumping.

Similarly, the ends served by the functions of the elements, i.e., the purposes of the system, are among those properties of the whole system that are essential to the system. For instance, if a function of the heart in the cardiovascular system is to pump blood, and circulation of blood is the purpose served by that function, then this entails that circulation of blood is an emergent property of the cardiovascular system, that the heart is an element of that system, and that the heart does not pump blood apart from its belonging to the cardiovascular system.

Functions and purposes are separated by one hierarchical layer in a nested system-of-systems, but purposes at one level are not the same as functions at the next, except by coincidence. So, for instance, that a function of the heart is to pump blood, and that circulation of blood is a purpose of the cardiovascular system, does not entail that pumping blood is a purpose of the heart (i.e., an end served by functions of the heart chambers or cardiac valves), nor does it entail that circulating blood is a function of the cardiovascular system in the human organism, although both hypotheses are, in practice, reliable starting points for iterative analysis.

3 Design in Systems Engineering

3.1 "Design" as a Verb

"Design" as a verb is a rational or economic act of requirements transformation. In systems engineering, requirements are transformed through many stages: from user requirements to system operational requirements through conceptual design, from system operational requirements to element functional requirements through preliminary design, and from element functional requirements to production requirements (specifications, schematics etc.) through detailed design. This process, the concatenation of conceptual design, preliminary design, and detailed design, is shown below in figure 1 (adapted from Blanchard and Fabrycky (1981), MIL-STD-499B (1994), and IEEE Std 1220 (1998)).

The process of engineering design develops efficient applications of resources to satisfy needs. The economic or rational aspect of design, combined with inherent functional allocation in design, distinguishes designs from other arrangements of parts for a collective purpose by a technologically relativistic analogue to Weinberg's criterion of elegance, the economy of means to an end so that nothing is invoked other than what is functionally justified (Weinberg, 1992, 135).

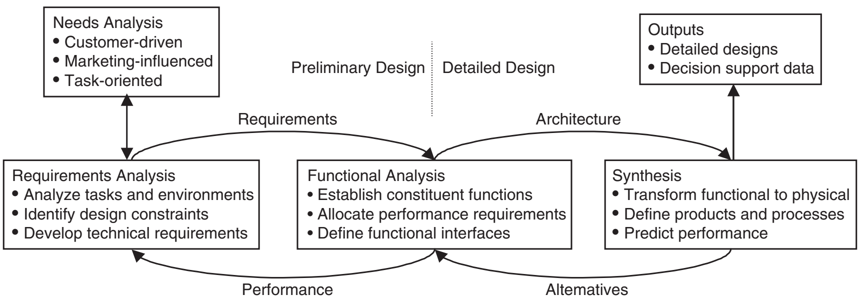

Fig. 1 Design process in systems engineering

The outputs of engineering design are product and production specifications in sufficient detail to eliminate interpretation, variation, or artistic inspiration in the production process. Design results in detailed procedures for processes, detailed algorithms for software, and detailed blueprints for manufacture, without addressing those aspects of production that can be accepted by the engineer as known technique or established art (Aristotelian *technikos*).

Requirements transformation in design is inherently risky: requirements interpreted from one perspective to another cannot be analytically guaranteed to close, e.g., having the elements each meeting their functional requirements in preliminary design does not logically guarantee that the system will meet its operational requirements, etc. This is because requirements transformations are both hierarchical and interpretive: the requirements at each level are expressed in terms natural to the perspective of that level. User needs are expressed in the user's terms with the user's measures of effectiveness, system operational requirements are expressed at the system level, element functional requirements are expressed in discipline-specific functional terms (e.g., electrical, mechanical, control), schematics are expressed in manufacturing and materials terms, etc.

3.2 "Design" as a Noun

In keeping with the definition of designing as an inherently rational or economic activity, "design" as a noun is the rationale, i.e., cognitive analytic basis, for the requirements transformations inherent or implicit in, expressed or embodied in, or imputed to the structural, functional, and process relationships between the system, its environment, and its parts or elements.

"Design" as a noun is not the outcome of "design" as a verb; schematics and specifications are not designs but rather the façades of design, i.e., the interface from design to production, a summary of design sufficient for production. That there is more to a design than is captured in schematics and specifications is evident when designs are protected as proprietary, or delivered from a vendor to a customer in cases of contracting design, or archived for future use. What is included in an archived design, or in a design delivered under a standard contract, or is protected as proprietary when safeguarding designs, includes performance analyses, trade studies, and the development of those alternative system concepts that were evaluated but not, in the end, chosen for production (DAU 2000). In any of these cases what is included in the object called a "design" is the entire rationale for the requirements transformations specified in the design process.

Complementing the distinction between the noun "design" and the products of the activity called "design" is the distinction between comprehending the design of something, e.g., the human heart, and inferring the prior occurrence of an act of design; to acknowledge the design of something is only to judge that the relationships between elements and their capabilities at successive hierarchical levels of nested systems are rational or economical. The rationality of design is an analytical rationality rather than an etiological rationality.

This description of design and designing applies equally to problems of designing simple and complex systems, with the principal distinction being that for systems requiring a great deal of novelty and innovation the process may be nested: what appears to be an element of a system in the design process outlined above may be an un-designed system in its own right, so that specifying its element-level requirements in preliminary design of the super-system may be identical to specifying its operational level requirements in conceptual design of the subsystem.

4 Design in Systems Analysis

4.1 Analogy of Engineering and Analysis

Design in systems methodology is the combination of two interactive loops, one addressing the relationship of the design object to its environment, the other addressing the relationship of the design object to its parts. In systems engineering, the two loops are called preliminary design and detailed design, while in systems analysis they are called expansion and reduction. Viewed from the perspective of an arbitrary element Y_b, a functionally specified constituent of a system X, preliminary design of X and expansion of Y_b both determine the function of Y_b as a contribution to the comprising whole X, while detailed design of X and reduction of Y_b determine the structure of Y_b and how it works.

The relationship between the systems engineering design of X and the systems analysis of one of its elements Y_b is illustrated in figure 2 above for a system X consisting of elements Y_i, each of which in turn consists of sub-elements Z_{ij}. In figure 2, the nesting can continue indefinitely in both directions: X can be an element of some other larger comprising super-system W, and each Z_{ij} can in turn be an object of either design or analysis, so that the preliminary design of X may also be part of the detailed design of W, and the detailed design of X may comprise the preliminary designs of the Y_i and the conceptual designs of the Z_{ij}.

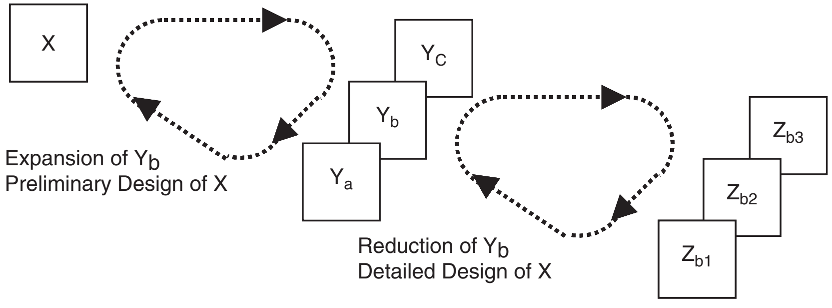

Fig. 2 Nested design loops of systems methodology

Figure 2 offers an opportunity to distinguish functions from purposes using Bertalanffy's definition of system. Consider the relations R_{zb} found among the elements Z_{bj} in the reduction of Y_b, and the relations R_y found among the elements Y_i in the expansion of Y_b. The functions of the elements Z_{bj} serve purposes inherent in Y_b, and the function of Y_b serves a purpose inherent in X. The question to consider is whether the function of Y_b and the purposes inherent in Y_b are identical. Systems analysis answers no, except by coincidence, because the function of Y_b is among those properties that Y_b has in virtue of relations R_y rather than any alternative R'_y, while the purposes inherent in Y_b are among those properties that Y_b has in virtue of relations R_{zb} rather than any alternative R'_{zb}. The function of Y_b and the purposes inherent in Y_b are both at the same hierarchical level, i.e., they are both in Y_b, but they are determined by distinct relations R_y and R_{zb} at adjacent hierarchical levels, and therefore they are not identical, though they may correspond to one another.

4.2 Difference on Function Between Systems Engineering and Analysis

An important difference between design as implemented in systems engineering and as rationalized in systems analysis is in the peripheral role of the concept of function in the former, and its central role in the latter. The difference stems from the difference in relationship between the engineer and his system on the one hand, and the analyst and the object of her inquiry on the other.

The engineer works from concrete customer needs, and is concerned to transform these needs into verifiable requirements at the system and subsystem levels. To the engineer, functional analysis is only a means to requirements, which latter are quantifiable, testable, and verifiable. Once functional requirements are set, they are specific to elements, and compliance can be judged independently.

The analyst works from a concrete system, and is concerned with developing information, knowledge, and understanding. For the analyst, her objectives are descriptive, relative, and functional rather than imperative, absolute, and normative. Functional descriptions are interdependent and relational, and are developed jointly for ensembles of elements.

The relevance of the distinction is illustrated by failure analysis of a system. If the external inputs to the system all conform to specifications, but some external outputs of the system are nonconforming, then the system is a suitable object for failure analysis, in which the analyst, either the designer of the system or a systems analyst, attempts to analyze the failure, attributing failure either to an element of the system or to the system as a whole.

For the design engineer, any element whose output is not in specification while its inputs are all within specifications is nonconforming, regardless of function. Specifications on a system or an element are contingent on inputs, so that an element with nonconforming outputs may be excused if an input is nonconforming. The performance of each element is evaluated against its specifications in isolation. It is possible for all elements of a failing system to be excused on the basis of nonconforming inputs from other elements, e.g., in any case with nonconforming feedback, in which case the failure must be attributed to the system as a whole.

This requirements focus of the design engineer is in sharp contrast to the functional analysis of the systems analyst, who has no prior way of discriminating whether an element has a nonconforming input, or is failing to perform as it should in the context of its input, unless functional ascriptions can be made to the elements and rational requirements inferred from the functions and available means. The systems analyst only makes progress via comprehension of the function of the elements. To the systems analyst, functional description, rather than quantitative specification, is fundamental to analysis of design.

4.3 Structure, Function, and Process

As summarized by Gharajedaghi (1999, 112–113), the design approach to systems analysis iteratively examines structure, function, and process to develop understanding in terms of design. Iteration is necessary because, in the systems approach, process and structure co-produce function in the context of environment. Inquiry then becomes necessarily iterative because structure, function, and process are each co-produced by the others, as well as co-producing each other, so that developing a new understanding of each modifies the understanding of the others in a converging sequence of mutual dependence.

The producer/product relationship is Singer's framework for explanation in the world of complex objects without sufficient causation. In Singer's framework, producers are necessary but not sufficient for their products, in the manner of acorns being necessary but not sufficient for oak trees. Singer (1924; 1959) uses the producer/product relationship to develop a pragmatic theory of choice, purpose, and free will, and extends the relationship in various ways to account for reproducers, co-producers, potential producers, and other analogues for biological and ecological classes (Flower, 1942; Pennypacker, 1942). Systems analysis uses the same framework for developing an objective theory of function and purpose. Function is a joint product of structure and process in the context of a purpose inherent in the essential characteristics of a comprising system.

The key challenge satisfied by the producer/product model of the relationship between structure and function is explaining how a given structure can have multiple functions in the same environment, as is often observed in systems behavior. The answer offered is that a single structure in a single environment can result in multiple functions through multiple processes.

4.4 Distinguishing Systems Analysis from Other Functional Ascriptions

The theory of design presented here defines function in terms of rationalized interlocking producer/product relations among structure, function, and process, so that having a design entails having elements with functions. This design paradigm of systems analysis differs from currently prevalent etiological, welfare, and dispositional analyses of functional ascriptions (McLaughlin, 2001).

In systems analysis, no etiological conclusion is warranted about a system with manifest design, nor is any conclusion warranted regarding whether it, or anything related to it, benefits from its functionality, or even whether the object exhibiting design has the ability to work in the manner implicit in its design. Design in systems analysis is only an objective model for an inquirer developing understanding, i.e., answers to "why?" questions, to complement knowledge and information, i.e., answers to "how?" and "what?" questions.

Systems analysis differs from classical internal teleology on the one hand, and subjective Cummins (1975) functional ascriptions on the other, in attempting an objective analysis of functional characteristics: following Singer (1924; 1959), systems analysis equates functional characteristics of a system with observable behaviors and capacities, and wields rationality and economy as razors for reducing understanding to inter-subjective propositions.

In classical analysis, naturalistic teleology is internal to an entity and causes behavior; thus, although the behavior may be observable, the teleological characteristics are private to their possessor and objects of inference rather than observation to others (McLaughlin, 2001, 16–17). For Cummins, functional ascriptions are instrumental relations relative to a goal, which goal is determined by the analyst's interest and thus is subjective to the analyst, rather than the entity. For Singer, writing in the pragmatic tradition, functional characteristics are identical with their publicly observable phenomena and therefore objectively accessible to observers, with neither the analyst nor the object of analysis (nor the creator, nor the commissioner, nor the user, nor the owner of an artifact) being in a privileged position relative to teleological ascriptions.

That the systems analysis concept of function is distinct from etiological, dispositional, and welfare views, can be shown by considering the example of design failure. Design failure – the universal failure of a type to work properly – is a familiar occurrence in industry, especially during product development. Yet artifact types that are universal failures still have a design, and their elements have functions, even if they do not work, have never worked, and never will work.

For systems analysis, the same can be true of natural organs, since systems analysis does not distinguish between organs and artifacts. That universal failures never work does not prevent systems analysis from comprehending the design of a universally nonworking organ, based on the razors of rationality and economy applied to relations among the elements of the organ and relations among the organs of the comprising organism. This places systems methodology squarely at odds with current philosophical theories of function, since the etiological, dispositional, and welfare views all require that natural organs either work, or historically have worked, or have a disposition or propensity to work, in order to have a function.

For example, the mule, as a reproductive dead end, figures prominently in philosophical analyses of function, where the challenge for philosophy is thought to be explaining how mule hearts can have the function of circulating mule blood even though each mule is genealogically the first of its type, and such pumping and circulation confers no reproductive advantage. What current philosophy passes over in silence are mule gonads, which in systems analysis of mule design have the function of reproduction, even though they are universal failures.

Another noteworthy difference between the design view of function and current philosophical etiological, dispositional, and welfare views is the hierarchical relativism of the design view. In systems analysis, purposes and functions are different and not necessarily linked in a chain to any privileged hierarchical level, e.g., the gene, organism, or species, whose supposed intrinsic goals (survival and reproduction) would anchor the chain of functional ascriptions. In systems methodology, the functions and purposes at any hierarchical level (e.g., cell, tissue, or organ) come from interacting design loops looking only one level up and down the hierarchy of a nested system-of-systems, and no farther.

The design-based theory of function offers a naturalist approach to function analysis that [1] breaks the chains of necessity which currently bind functioning to working, thus offering a richer view of malfunction and failure in both natural and artificial systems, while simultaneously [2] extending scientific relativity to biological hierarchies (genes, cells, organs, etc.), and [3] eliminating the last vestiges of intrinsic teleology in biology (i.e., survival and reproduction as intrinsic goals).

5 Examples of Systems Analysis

5.1 William Harvey and the Human Heart

Harvey, an Aristotelian in the Paduan tradition, sought the unifying process in human organisms that is the essence of life. The Aristotelians of Padua in Harvey's day were in an ongoing dispute with the Galenists (principally in Paris), who denied any singular life process and diffused vitality into separate organs. Harvey undertook a long study of the cardiovascular system to discover the function and working of the heart, with a view to discovering the Aristotelian life process, and in so doing discovered the pumping function of the heart and the fact of circulation of the blood (Boorstin, 1983, Ch. 47; Butterfield, 1957, Ch. 3; Nuland, 1988, Ch. 5).

That Harvey should make two discoveries at once is natural in systems analysis, since function and purpose are related as means and end, and as systems analysis jointly addresses the two interlocking loops of design at hierarchically separate levels. Indeed, given an existing, faulty but internally consistent systems analysis as a starting point, such as Galen's liver-centered physiology of blood, at least two changes have to be made to the existing analysis to reach a new consistent analysis, since structure, function, and process each co-produce the others.

Harvey began with a detailed examination of the musculature of the heart and the vascular walls of the arteries immediately outside the heart, to resolve the systole/diastole controversy. From the exceptional strength and stiffness of the arterial walls, Harvey concluded that the heart pushed blood out to the arteries with considerable violence, and from the manner in which the muscles were connected around the heart, Harvey concluded that they work by contracting the chambers of the heart, rather than by pulling them open, i.e., that the heart does its work during systole rather than diastole. Thus, Harvey's first step was to move from new structural observations to a new understanding of heart process (Harvey, 1628).

Taking up the systolic process, Harvey sought simultaneously to examine the heart and arteries of dying animals, whose heart action was thereby slowed, and concluded that the arterial pulse temporally followed and was caused by the violent contraction of the heart. This was in contradiction to prevailing theories of the "pulsatile faculty" of blood, rhythmic throbbing of *pneuma*, theories of vascular dilation to draw blood from the heart, etc. Harvey completed his description of the systolic process by noting that the process was uniformly directional: the atria (upper chambers of the heart) always contract just prior to the ventricles (lower chambers), implying that the direction of blood flow within the heart was always from the atria down, never from the ventricles up, and therefore always from the ventricles outward. Filling of the heart between beats was only into the atria; at the point of atria overflowing into the ventricles, a new heartbeat occurred. The ventricles were not held forcibly closed between heartbeats; the heart muscle was relaxed yet the ventricles stayed empty.

From this process observation Harvey was able to infer a need for blocking the return of blood to the relaxed ventricles from the arteries once the blood had been expelled, and this lead to discovery of the cardiac valves. Theories popular in Harvey's time involving expansion or dilation of the arteries to hold blood rendered the blocking function of the valves unnecessary, and given Galen's theories of blood moving back and forth a blocking function would have been counterproductive. Since Harvey's method went beyond plausibility to necessity, Harvey could discover a need for cardiac valve existence and function, facts that were not obvious either from examination of the valve structures themselves or from prevailing plausible theories. Harvey's discovery was rooted in going beyond plausible consistency with observations to elegant, necessary functional, explanations.

Harvey's analysis of the systolic process yielded a second, independent inference of function from the passive nature of the heart between beats. Applying the principle of sufficient reason, Harvey determined a need for something to "arouse the somnolent heart", i.e., to trigger a heartbeat. From this Harvey discovered that a function of the atria was to serve as reservoirs, measuring out the time between heartbeats by their passive filling. This inference of atrial function is truly remarkable since artificial pumps, bellows, etc. have no equivalent element. Harvey could not be projecting functional ascriptions by analogy, even though Harvey did value analogy as a source of insight.

From initial observations of arterial structure Harvey determined a process, and from detailed examination of that process he determined required elements with functions, which in turn produced new identification of function-bearing structures, in a sequence of iterative development.

As demonstrated in the cases of cardiac valves and atria, Harvey's systems analysis was capable of discerning functions that were not evident either by direct examination of the structures, or by analogy with other structures of known function.

The rest of Harvey's analysis involved tracing the impact of the systolic process and unidirectional flow of blood through the heart on the traditional explanations of heart, liver, and lung function, showing that food transformed in the liver cannot be the source of all blood, that the pulmonary veins do not carry anything aerial or ethereal (like *pneuma*) from the lungs, that there is no support for the function of the heart being a furnace, and that the blood expelled through the aorta must return to the heart via the venae cavae. This last observation lead to the hypothesis of circulation, which Harvey could not demonstrate but firmly concluded on the basis of the inadequacy of all explanations requiring generation and expiration of blood at the beginning and end of a noncircular flow.

Three striking features of Harvey's analysis arise in contrast to the contemporary Galenic physiology that Harvey was overturning:

1. Harvey never determined the functions of the lungs, liver, or even of blood itself. He refuted legacy functional ascriptions without substituting new ones.
2. Harvey constructed necessary rather than plausible explanations.
3. Harvey ended on an unsolved problem (the hypothesis of "pores" or capillaries).

The first point underscores a characteristic feature of systems analysis: there is no infinite regression of functions, nor even a finite chain of functions leading from every level of hierarchical analysis to some reference level at which an ultimate end, e.g., survival or reproduction, can be defined. Evolutionary biology's coronation of a privileged hierarchical reference level, variously the gene, organism, or species, is inconsistent with systems analysis as done by Harvey.

The second point above stresses that Harvey is everywhere insisting on functional justification of elements, or Weinberg's criterion of elegance. This is particularly evident in Harvey's correction of Fabricius' interpretation of the venuous valves in extremities. Fabricius' descriptive interpretation of their function was that they regulated blood distribution and held pooled blood in the manner of weirs, but Harvey correctly deduced a need for blocking blood flow rather than simply holding blood, and identified the structures as valves rather than weirs. Had Harvey been content with plausible explanations he could have let his mentor's (Fabricius') interpretation of venuous valves stand unchallenged, as it did not contradict any of the rest of Harvey's analysis, but for Harvey function was rooted in necessity rather than plausibility, specifically the requirements of structure and process in a joint producer/product relation with function.

The third point above illustrates that although systems analysis involves no infinite regression and therefore can close, it need not close; it is enough to establish a manifold of relations that cannot be modified without contradiction. In this respect systems analysis is like modern theoretical physics, where the problem of a unified theory remains unsolved yet confidence in quantum mechanics being fully true, and not merely an approximation of truth, remains high, because quantum mechanics seems insusceptible to modification without contradiction (Weinberg, 1992, 88).

5.2 *Soviet National Missile Defense*

Sparked by a 1953 joint letter from seven Soviet Marshals recommending a national missile defense (NMD), the Soviet Politburo approved their first plan for NMD in 1954. This plan, implemented in stages, adapted the SA-1 surface-to-air missile (SAM) in an anti-ballistic-missile (ABM) role, and developed the Sary Shagan missile test range, the Triad targeting radar and the Hen House phased-array radar. Among the achievements of this first Soviet NMD program was the successful 1961 interception of an SS-4 warhead by a modified SA-1 interceptor (called V-1000) at an altitude of 25 kilometers over Sary Shagan, using a conventional explosive warhead. This interception integrated all of the elements of NMD, with a Hen House radar initially acquiring the target at a range in excess of 1000 kilometers and passing targeting data to Triad radars and the interceptor launch site (Lee, 1997).

Following the successful test, operational deployment of missile defense systems began in 1962–63, with simultaneous construction of the Moscow zonal missile defense system, with its characteristic Dog House and Pillbox radars, and the Soviet national system, with its Hen House and Pechora-class large phased array radars (LPAR), most famously the LPAR at Krasnoyarsk.

American intelligence analysis of Soviet missile defense development could only rely on external observations of various kinds, such as operating frequencies and pulse durations collected from Soviet radars, observation of tests at Sary Shagan, and overhead photographs of missile installations. Analyses of this evidence relied on the methods of systems analysis, introduced from industry by US defense secretary, and former Ford Motor Company president, Robert McNamara. During the mid-1960s, while systems analysis of Soviet missile defense failed to understand the significance of many tests conducted at Sary Shagan or the relationship between the Hen House radar network and the Moscow missile defense network, US national intelligence estimates (NIE) nonetheless correctly determined that the Soviets were deploying NMD. These assessments were ultimately challenged in the late 1960s as the USA and the Soviet Union began negotiating what would become the 1972 Anti-Ballistic Missile (ABM) treaty, and diplomacy demanded a change in the nature of evidence for those claiming that the Soviets had deployed NMD (Lee, 1997), since Soviet authorities denied deploying NMD and the treaty forbade it.

The 1960s-era systems analyses of Soviet NMD proceeded from fixing observed Soviet interceptor limitations (especially their slow speed, about 2 kilometers per second, and their languid initial acceleration) as technological design constraints under the razor of economy, and concluding from this that any Soviet NMD would have to operate in battle management mode rather than point defense or perimeter defense mode. With this in mind, the question of whether the Soviets were deploying NMD was analytically reduced to four atomic questions, all potentially answerable from available intelligence methods.

1. Were the SA-5 and SA-10 interceptors dual purpose SAM/ABMs?
2. Were the Hen House and Pechora-class LPAR radars passing target tracking data to missile defenses?
3. Was there a central ABM command authority with a command, control, and communications (C3) system?
4. Did the SAM/ABM missiles have nuclear warheads?

All NIE participants agreed that if the answers to these questions were "yes", and they were, then the Soviets were deploying NMD (Lee, 1997).

Several things are noteworthy about these questions. The overarching feature of systems analysis in this case was that inferences of purpose (NMD) and function (ABM) were being made without any testimony of the system's designers, which would become available in the 1990s, corroborating the analysis. The inference was based only on externally discernible characteristics of the system, on capabilities that NMD systems should have that air defense systems would not, given rational and economic relationships among system elements under the constraints of prevailing Soviet technology.

All four atomic questions address issues of function or purpose though analysis of relations. For instance, the distinction between a SAM and an ABM depends on how the interceptor is integrated with its associated radars, specifically with the function that the interceptors and radars co-produce. Similarly, whether the SA-5 and SA-10 interceptor missiles had nuclear warheads depended on the proximity of nuclear storage facilities to the missile launch sites.

This case also illustrates another characteristic of systems analysis of artificial systems, that the analysis often develops functional ascriptions which contradict the claims of authorities, a characteristic documented in Ackoff's many writings on his analyses of government and UN agencies, corporations, charities, etc.

5.3 Failure of Systems Analysis

The failures of systems analysis described by Lee in the analysis of Soviet NMD are instructive. For instance, the failure to rationalize the sequence of tests at Sary Shagan and the failure to understand the relationship between the Hen House and Dog House radars (in fact there was none) were both due to the same mistake, made by analysts at the beginning of Soviet missile defense deployment in the early 1960s and corrected a few years later: what was in fact two separate systems, with distinct interceptor models, distinct radar models, and distinct areas of responsibility (Moscow on the one hand and the Soviet Union on the other) was analyzed as though it was all one system whose area of responsibility was a topic of contention.

The same kind of mistake, failure correctly to delimit the system, was a contributor to, but not the complete cause of, Galen's errors, e.g., Galen's faulty analysis of the heart, based on a cardiopulmonary rather than a cardiovascular system, concluded that the heart was a furnace receiving *pneuma* through the pulmonary veins. The problem of correct delimitation of a system in systems analysis remains difficult, and inspiration remains part of the solution (Zandi, 2000, amplifying Churchman, 1971; 1979).

It is important to note in the case of Soviet NMD that the consequence of initial failure properly to distinguish and delimit the systems was not a conclusive faulty analysis, but rather failure of the analysis to converge. This is characteristic of systems analysis, that rather than confidently reaching erroneous conclusions from false premises, it dissolves into a muddle when its underlying premises are incorrect. Had Galen insisted on necessary rather than plausible explanations, he might also have failed to converge on explanations of human physiology, instead of reaching conclusions that were detailed, consistent, plausible, and wrong.

6 Conclusion

Systems methodology has been presented as a complementary approach to systems engineering on the one hand, and systems analysis on the other. The element common to both was shown to be design. Design in systems methodology is the combination of two interactive loops, one addressing the relationship between the design object and its environment, the other addressing the relationship between the design object and its elements.

The design approach to analysis considers structure, function, and process in the context of environment to develop information, knowledge, and understanding of the system and elements being studied. In the systems approach, process and structure combine jointly to produce function in the context of environment. This method was shown to be capable of discerning functions and purposes that were not apparent from structures alone, or from analogy with structures of known function.

This chapter has presented the interactive loops of the design process in systems engineering, and the use of analogous interactive loops in systems analysis. The modern systems analysis methodology of Gharajedaghi, Ackoff, and Churchman, built on the foundation of Singer, has been generalized to correspond to Harvey's actual method, and to modern methods of military intelligence analysis of large integrated technical systems.

Systems analysis undermines the purported distinction between natural and artificial systems, separates design from designers, and presents a practically successful account of design function at odds with current philosophical accounts.

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