The Ontology of Systems

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***Abstract*— Systems analysis comprehends systems in terms of an ontology that relates any system, its elements, and its environment in terms of their functional, structural, and behavioral relations. At the heart of systems ontology is "design", the combination of two interactive loops: one loop relating the system to its environment, the other loop relating the system to its parts. For systems analysis, *e.g.* intelligence analysis of remotely sensed facilities in denied territory, 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 exposition presents the interactive loops of design in systems ontology, treating analysis of Soviet national missile defenses as an example of successful application of systems ontology.**

***Index Terms*—Ballistic missile defense, cold war, intelligence analysis, ontology, systems methodology**

I. Introduction to Systems

The analysis of design in systems ontology leans heavily on the modern concept of a system, especially the definitions of "system" due to Bertalanffy and Ackoff.

Bertalanffy (1969, pp. 55-56) defined systems as follows: "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's subsequent restatement suppresses explicit mention of the relations among elements (1981, pp. 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'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 interdependencies unexplained. This leads to abandonment of reductionism, which 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 asserts, particularly the distinction between functions and purposes.

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, either individually or in aggregation. Systems analysis exploits these two ontological 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 ontological razors for winnowing candidate functions and candidate purposes in systems analysis.

II. Design in Systems Ontology

A. Definitions of "Design"

"Design" as a verb is a rational or economic act of requirements transformation. In 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.

Engineering design develops efficient applications of resources to satisfy needs. The economic or rational aspect of design, combined with functional allocation in design, distinguishes designs from other arrangements of parts for a collective purpose by the economy of means to an end so that nothing is invoked other than what is functionally justified.

In keeping with the definition of designing as an inherently rational or economic activity, "design" as a noun is the rationale for the requirements transformations understood in the structural, functional, and process relationships between the system, its environment, and its parts or elements.

The outputs of engineering design are product and production specifications in sufficient detail to eliminate interpretation in the production process, rather than any cognitive basis for requirements transformations. "Design" as a noun is not the outcome of "design" as a verb; schematics and specifications are not designs but rather summaries 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. 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.* a surface-to-air (SAM) missile complex, and apprehending 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 ontological (specific to the relations among elements), and specifically an analytical rationality (comprehensibility) rather than an etiological rationality. The cause of rationality in design is not the rationality of any designer, but rather the environmental, technical, and economic constraints within which the system is realized. Failing to appreciate this distinction, by insisting on the rationality of causal agents, leads to a characteristic failure of analysis discussed in section IV.b below.

B. Function and Purpose

Functions are not arbitrary properties of system elements; they must be among those properties that are essential to the element as an element, in light of the essence of systems (the interdependence of behaviors of systems and elements). This distinguishes the intercept function of an anti-ballistic-missile (ABM) in a national missile defense (NMD) system from its non-functional trans-sonic boom. Claiming that the sonic boom is non-functional is to claim that there is no system that can be fully analyzed in terms of the ontology of systems, whose design leads to the ascription of any function or purpose to the sonic boom of an ABM. Any well-formed system comprising the ABM will avoid such ascriptions; any putative system whose analysis entails such ascriptions for the sonic boom of the ABM will fail to converge on a design, as discussed in section IV.a below.

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 as a system. For instance, if a function of a search radar in a ballistic-missile defense (BMD) system is cueing targeting radars, and if re-entry vehicle (RV) destruction is the purpose served by that function, then this entails (1) that RV destruction is an emergent property of the BMD system, (2) that the search radar is an element of that system, and (3) that the search radar does not cue targeting radars apart from its belonging to a BMD 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, if a function of a search radar in a BMD system is to cue targeting radars, and if RV destruction is a purpose of the BMD system, then that does not entail that cueing targeting radars is a purpose of the search radar (*i.e.* an end served by functions of elements of the radar such as the antenna, transceiver, beam-former, power supply *etc.*), nor does it entail that RV destruction is a function of the BMD system in the national defense architecture. Both of these hypotheses are, in practice, reliable starting points for iterative systems analysis, but they are not necessary consequences of search radar function or BMD system purpose.

C. Analogy of Engineering and Analysis

Design in systems ontology is the combination of two interactive loops, one addressing the relationship of the system to its environment, the other addressing the relationship of the system 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. Analysis mirrors the structure of engineering even when analysis is conducted without access to system designers, because of the ontological commitments of scientific realism regarding systems: systems being what they are, they must be analyzed (and designed, if designed at all) in terms of the underlying reality of systems, which involves the two loops of design.

Viewed from the perspective of any 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.

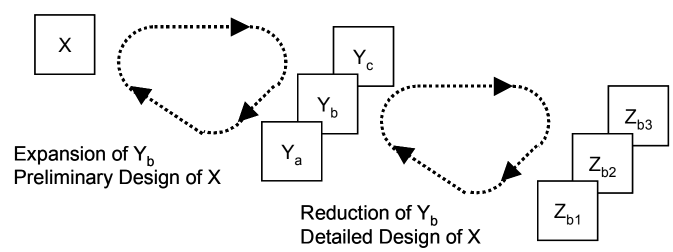

Fig. 1. Nested design loops of systems methodology

The relationship between the systems engineering design of X and the systems analysis of one of its elements Y_b is illustrated in figure 1 above for a system X consisting of elements Y_i, each of which in turn consists of sub-elements Z_{ij}. 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}.

Figure 1 offers an opportunity to distinguish functions from purposes using Bertalanffy's definition of a 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 ontology 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.

D. Relating Structure, Function, and Process

As summarized by Gharajedaghi (1999, pp. 112-113), the design approach to systems analysis iteratively examines structure, function, and process to develop understanding in terms of design. In the ontology of systems, process and structure co-produce function in the context of environment, so that inquiry necessarily becomes iterative because of the cyclic graph ontology of systems. Structure, function, and process are each co-produced by the others, as well as co-producing each other. Therefore, developing new understanding of each necessarily modifies 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 this 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 systems. Following Churchman (1971, 1979), systems analysis uses the same ontological 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.

III. Analysis of Soviet National Missile Defense

Sparked by a 1953 joint letter of seven Marshals recommending national missile defense (NMD), the Soviet Politburo approved their first plan for NMD in 1954. This plan, implemented in stages, adapted the SA-1 SAM in an ABM role, and developed the Sary Shagan missile test range as well as 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 this 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 BMD 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 were based on the ontology of systems. 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 ABM treaty, and the diplomatic community imposed a change in the nature of evidence required 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 ontological razor of rational economy of means, 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 core questions, all potentially answerable from available intelligence methods:

[1] Were the SA-5 and the SA-10 interceptors dual-function 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. An 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 1960sera analysis). The inference was based only 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. This is consistent with function and purpose being matters of ontology, matters of the nature and relationships among things as they are, rather than being dependent upon the intentions of causal agents, or otherwise contingent upon causal history.

All four core questions address issues of function or purpose through 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 a characteristic of systems analysis of artificial systems: an ontological analysis often develops functional ascriptions which contradict the claims of authorities, a characteristic amply documented in Ackoff's many writings on his analyses of government and UN agencies, corporations, charities, *etc.*

IV. Failures of the Analysis of Soviet NMD

A. *Failures of Systems Analysis*

The various failures of systems analysis of Soviet NMD described by Lee 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 problem of correct delimitation of a system in systems analysis remains difficult, and inspiration remains part of the solution (Zandi, 2000; Churchman, 1971, 1979).

It is important to note in the case of Soviet NMD that the consequence of initial failure to properly distinguish and delimit the systems was not a conclusive faulty analysis, but rather it was failure of the ontological analysis to converge. This is characteristic of ontological systems analysis, that rather than confidently reaching erroneous conclusions from false premises, it dissolves into a muddle when its underlying premises are incorrect.

B. *Other Failures of Analysis*

Other failures after the analysis of the 1960s reflect departures from analysis methods of systems ontology, rather than failure of systems analysis to understand Soviet NMD. For instance, the mistaken projection by western experts of mutually assured destruction (MAD, with its implicit disavowal of NMD), upon the Soviet leadership as the Soviet national nuclear strategy stemmed from the non-systems-ontology assumption of rationality on the part of system designers (as "rational" nuclear policy was then understood in the west), rather than the weaker systems ontology assumption of rationality of design relations among elements of a system. This kind of strong assumption may not be an error in other fields (*e.g.* it is a core assumption of the diplomatic theory of *realpolitik*), but it is unwarranted in systems analysis, and in this specific case it turned out to be materially false.

A related error committed in mis-analyzing Soviet NMD was the inference from high presumed cost and low presumed effectiveness of NMD to the conclusion that the Soviets weren't deploying NMD, because doing so would be uneconomical, or because NMD just wouldn't work. This is an example of misplacing the economy inherent in systems from the relationship of elements (an ontological matter) to the decisions and motives of owners, or making the unwarranted assumption that a systems must work to have designs. For these and other reasons systems analysis emphasizes understanding the design without attempting to understand either the designer or the beneficiary, without even assuming that any designer or beneficiary exists. Only the manifest relationships of system elements are understood rationally; understanding the designer or the motives that lead to existence of the design are not part of the ontological analysis.

V. Conclusion

Design in systems ontology consists of two interactive loops, one relating the design object to its environment, the other relating the design object and its elements. The analysis of any system's design develops information, knowledge, and understanding of the system and its elements presuming that rational and economic relations among system elements determine structure, function, and process in the context of environment. This method is capable of discerning functions and purposes that are not apparent from structures alone, or from analogy with structures of known function.

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