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Reflections on Opportunities and Challenges for Systems Engineering

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***Abstract*—**This paper summarizes some of the discussions that occurred in a workshop in West Virginia, U.S.A which was sponsored by the National Science Foundation (NSF) in February 2016. The goal of the workshop was to explore the opportunities and challenges for applying systems engineering in large enterprises, and some of the issues that still persist. The main topics of the discussion included challenges with elaboration and abstraction in large systems, interfacing physical and social systems, and the need for axiomatic frameworks for large enterprises. We summarize these main points of discussion drawing parallels with decision making in organizations to instigate research in these discussion areas.

***Keywords*—**Decision analysis, systems engineering, framing, value creation.

I. Introduction: What, How, Why?

THE purpose of this paper is to reflect on the opportunities and challenges that lay ahead in the field of systems engineering, focusing on a workshop that was sponsored by the U.S. National Science Foundation (NSF). The workshop started with a discussion about the "What? How? Why" of systems engineering. There are many definitions of systems engineering, and the purpose here is not to provide a unifying definition, rather a proposed definition that will be considered in this paper: systems engineering is ultimately about deriving value from a given phenomenon within the context of a system of sub-systems. Indeed, what we do in systems analysis starts with the investigation of some phenomenon that could be rooted in many fields including medical, electrical, physical or even a cognitive behavioral, and the purpose is to derive value from this phenomenon. In a large enterprise, we are dealing with multiple people, and multiple sub-systems, and interdisciplinary areas that interface with each other at certain boundaries.

The next question is "Why?". This is an easy question based on our previous definition: to derive value. Indeed, everybody agrees that systems engineering provides many opportunities for the design of large scale systems. Most people ask this question, however, in terms of why do we need to change from the current system? Why is the current approach not adequate? The answer to some of these questions will be discussed in this paper.

The other question is how systems engineering can provide value in a given enterprise? And the answer is: through a set of tools, processes, new theories, and a logic that enables a decision maker to make decisions at the systems level. Throughout this discussion, we shall draw on some parallels in decision analysis [1]. To better understand the components of decision analysis, it is important to recall the six elements of decision quality (for more information about these elements, see [2]; for information on utility theory, see [3] and [4]; for a reference on multiattribute utility theory, see [5]; for applications of decision analysis, see [6] and [7])., and for decision making in large organizations, see [8]-[10].

A. Abstraction and Elaboration

Because we are dealing with a large system, a major part of the workshop considered abstraction and elaboration of various subsystems: what it is why we will be emphasizing and what we will be de-emphasizing in the analysis and considerations. Different people will abstract and elaborate different sub-components based on their training and comfort level.

A main consideration in terms of abstracting and elaboration is that engineers working in one sub-system may have limited knowledge of other subsystems. These other subsystems are then perceived as black boxes with limited knowledge of the interfaces between subsystems. So, one research question is how one conducts abstracting and elaborating initially? How does one conduct abstraction and elaboration at the beginning of a long life-cycle in the design of a large system such as a space shuttle? The current process allocates requirements to the different subsystems, and then negotiates margins above or below the requirements, and iterates. Usually, a "trusted" person with high expertise is involved. Of course, there has been recent literature discussing the loss of value and some ethical implications that might arise by trying to meet arbitrary design requirements [11]-[13].

It is helpful to draw parallels with the idea elaboration and abstraction and the concept of a frame in decision analysis [2]. A frame is a limited description of the world that filters what is relevant. It is helpful because it provides focus on the important issues at hand, but at the same time it omits some detail that might become relevant later. The frame requires the decision maker to think about what is taken as given, what is to be decided now, and what will be decided upon later.

We can think of each decision maker within a sub-system as a person that makes decisions, and in so doing identifying an appropriate frame "what is taken as given, what is to be decided now, and what is to be decided later" as shown in Fig. 1.

The frame happens at the sub-system level. When a systems engineer elaborates and abstracts different sub-components, they are in effect framing the situation from their own

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(organizational) perspective taking into account the different sub-systems. The question under consideration here, is how to combine different frames? This questions has been addressed in a variety of contexts in group decision making [8]-[10], and others treat this situation as thinking of an organization as a single decision maker [2] and using traditional probability and utility encoding techniques [14]-[17]. Another topic of consideration is how different frames exist at different levels of an organization and how to develop a mechanism that enables coherent frames, and one that allows for different levels of the organization to contribute to an overall organizational frame.

A. Interfacing Physical and Social Systems

When viewed as a decision maker who makes decisions at a systems level, the systems engineer will need to interface with various sub-systems and interfaces at the physical and social levels. This observation emanates from the emphasis on domain knowledge without social sciences in some engineering curricula. There have been efforts to bring together individuals with both domain knowledge and the social sciences [18]-[20]. This observation also parallels the identification of both analytical and organizational complexity in decision analysis.

The behavioral aspects include cognitive behaviors including decision traps such as anchoring, representativeness, human-computer interaction, and psychology among others. The multi-person component includes topics like incentive structures, principle-agent formulations, cooperative and competitive game theory, and more. It is known that many incentive structures might result in unintended consequences and loss of value to an organization [2].

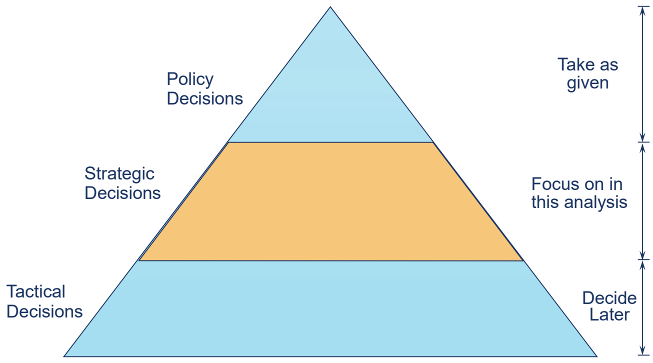

Fig. 1 The frame identifies the boundaries of the decision

Understanding the difference between analytical complexity and organizational and social complexity as depicted by Fig. 2 is an essential component of systems engineering. Additionally, they need to understand behavioral, decision, and organizational theories, as well as principal-agent mechanism designs that address these issues when/if setting objectives.

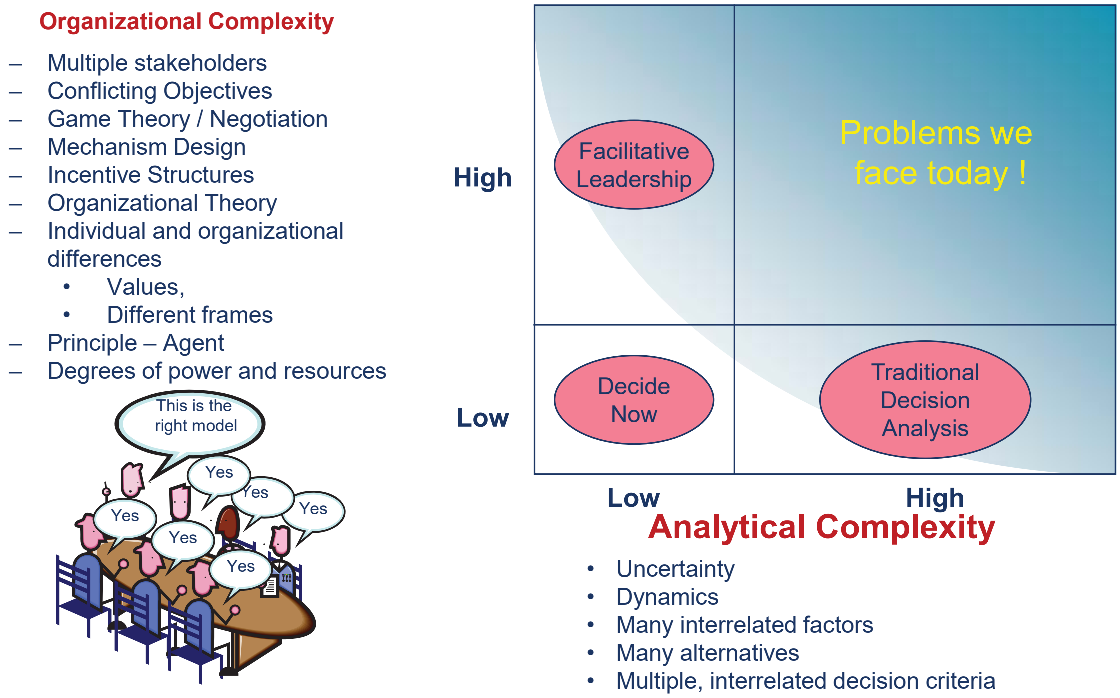

Fig. 2 Analytical complexity vs. organizational complexity (Source Strategic Decisions Group)

II. Axiomatic Frameworks

Much of the research formulations that work at the intersection of group decisions identifies a set of axioms and derives conditions by which the group should operate if it wishes to meet their corresponding conditions.

The flow down of requirements in systems engineering is an example of an axiomatic approach focusing on the interface between physical and social systems. To illustrate, consider two sub-systems working on physical aspects of a design. One group is responsible for attribute, *X*, and the other is responsible for attribute *Y*. The higher the values of *X* and *Y*, the more is the value for the organization. Quite often the physical system that produces a higher value of *X* might result in a lower value of *Y* and vice versa. One possible design could involve levels (x_1, y_2) and another cold involve levels (x_2, y_1), where $x_1 < x_2$, $y_1 < y_2$.

A systems engineer dealing at the interface might be tasked with mediating between the two subcomponents. What currently happens in many organizations is that sub-components are then given requirements. For example, sub-group 1 would be required to exceed a threshold level x_T and sub-group 2 would be required to exceed threshold level y_T. This might lead to the choice of designs that might be less preferred to the organization (Fig. 3).

To illustrate, consider two designs A and B superimposed on contours of constant value in a design space of two attributes *X* and *Y*, where more of each attribute is preferred to less. Design B lies within this region (and therefore meets the target requirements that have been set) but it has a lower value than design A, which is outside this region but lies on a higher value contour. Thus, the design that would be induced by this requirement region is less preferred than one that would be rejected by the requirement. This difference in choice comprises a value gap [x].

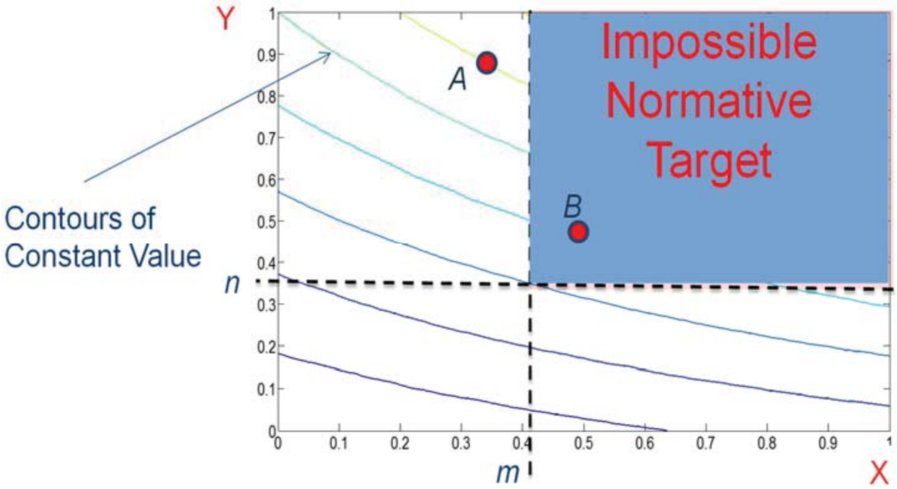

Fig. 3 Requirements must be accompanied by trade-offs

An axiomatic approach could require the following desideratum.

Axiom: *There will be no design that lies within the acceptable target region that is less preferred to one outside the target region.*

If the organization wishes to follow this axiom, then the requirements cannot be set independently for each sub-component; the requirement region must be bounded by a contour of constant preference. This leads to the following Theorem.

Theorem: *If axiom 1 is satisfied, then the requirement region must be defined by a contour of constant preference.*

This implies that an organization must declare trade-offs among requirements instead of setting them independently for each physical sub-component. The systems engineer would communicate the trade-offs and help select the design that would be most preferred to the organization.

III. Additional Points of Discussion

The workshop helped establish research directions for systems engineering, such as the need for a sound terminology by which multidisciplinary teams should operate, the realization of the phenomenon-to-value concept of systems, the quantification of value, aggregating group preferences, sharing rules, negotiations, exchange of payments, incentive structures, and corporate utility functions were all points that were raised. Other topics also included the change of frame as we go down an organization, and how thrust might come from below, and whether the organizational has the capability to allow for frame changes at the different levels? Other topics of discussion also included how to define value measures for trade-offs and indifference curves for an organization, as well as how systems engineers receive/share information from different divisions to make decisions

The workshop also brainstormed numerous other issues including: How do you change a culture or direction? How do you know if systems engineering works? How do we know that this is not only a new approach but a better approach? What can we change if we had the flexibility to start over? What can we change if we cannot start over? What are the cognitive limitations and implications of abstraction and elaboration? How do we identify the common denominator knowledge base for a systems engineer? What is the cost of giving up modularity (treating each sub-component as a black box independently)? How do you make good interfaces? Is the existing structure of modularity locked into the sunk cost principle? How does corporate structure allow for interfacing and change of frame: some companies are rigid, some say wait till next time or next product, others have more flexibility. The role of heuristics and intuition vs theory, anchoring and design fixation, and requirements vs value were other issues that arose in the brainstorming. How do we address the current education gaps? ISE departments teach OR/Optimization because of perceptions and rankings.

IV. Conclusion

Systems engineering provides many opportunities for value creation in large enterprises. It is helpful to think of a systems engineer as one who makes decisions within the context of a system formed of multiple sub-systems. Because of the multidisciplinary nature of this effort, care must be taken when considering the frame that a systems engineer incorporates when dealing with the different sub-components. Considerations for the interfaces at both the physical and social levels should also be considered. Finally, there is room for research on axiomatic derivations that incorporate behavioral aspects and lead to desirable properties in systems engineering.

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