System Definition, System Worldviews, and Systemness Characteristics

Article in IEEE Systems Journal - April 2019
DOI: 10.1109/JSYST.2019.2904116

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System Definition, System Worldviews, and Systemness Characteristics

Dov Dori, Fellow, IEEE, Hillary Sillitto, Regina M. Griego, Dorothy McKinney, Eileen P. Arnold, Patrick Godfrey, James Martin, Scott Jackson, and Daniel Krob

Abstract—The definition and characteristics of system have eluded humans for a very long time, as different people refer to the concept of system in various ways. A set of surveys conducted by us revealed seven distinct worldviews on system. We describe the surveys, analyze their results, and comment on differences between the responses. Based on the outcomes, we offer a comprehensive definition of system that can be accepted by the various worldview holders as an arrangement of parts or elements that together exhibit behavior or meaning that the individual constituents do not. Further, we present a compiled list of systemness characteristics—features that different worldview holders expect any system to exhibit. Then we present and describe the different worldviews on system, compare them with previous system definitions, and map them to five system domains. We conclude that the various system worldviews offer useful perspectives for systems engineers, who should have the flexibility to accept the fact that different worldviews may be appropriate for different situations and be ready to adopt them as necessary.

Index Terms—Object-Process Methodology, system definition, systemness, systemology, worldviews.

I. INTRODUCTION

An accepted current definition of system [1] is couched in terms of real (i.e., non-conceptual) systems, and further restricts its scope to artificial technology-based systems:

... an integrated set of elements, subsystems and assemblies that accomplish a defined objective. These ... include products (hardware, software, firmware), processes, people, information, techniques, facilities, services, and other support elements.

Expressing his frustration at the current state of affairs with respect to the definition of system, Ruhm [2] wrote:

Is every configuration of items a system? Searching definitions of the term system is really amazing. ... we could claim that they differ altogether and in many respects. This fills whole books and leaves us disoriented and inclined to abandon the topic.

A decade later, not much progress has been made. In summer 2016, at the request of the INCOSE president and president elect, an INCOSE Fellows initiative started to review and possibly improve INCOSE's definitions of “system” and “systems engineering.” The current INCOSE definition needs to enable transdisciplinary integration across the different schools of thought for INCOSE’s 2025 Vision [7] to be realized. In support of this aspiration, Dori and Sillitto [8] and Sillitto et al. [9] have set out a family of systems definitions that provide an encompassing framework for the full range of worldviews discussed in this paper and leads to the system definition we present below.

In this paper, we refer to worldview as a cognitive orientation of an individual toward a concept or set of concepts—in our case, the concept of system. A worldview might involve a particular philosophy and a set of themes, values, assumptions, and emotions. The German word Weltanschauung (world view or world outlook), from which worldview originated, is a fundamental concept that refers to a wide world perception, a framework of ideas and beliefs that together form a global description for interpreting and interacting with the world.

Rousseau [10] employed a general structure of worldview he had developed to view any problem as a special case of the general problem, considering the following six components:

1) Ontology—What exists?
2) Metaphysics—What is the nature of what exists; what does it do?
3) Epistemology—What can we know about what exists and how?
4) Cosmology—What is its origin and destiny?
5) Axiology—What is important and why?
6) Praxeology—How should we live and why?

Sillitto et al. [9] have described how the team elicited inputs from the INCOSE Fellows—a population of about 60 senior SE practitioners and researchers recognized by the International Council on Systems Engineering—via extensive email correspondence, reviewed over 100 definitions of system and formed assumptions and hypotheses about the different worldviews represented by different groups of definitions. The team then...
conducted online surveys to gather data from different subsets of the systems community, both within and outside INCOSE. The surveys’ aim was to understand the range of worldviews about system and assess the extent to which different groups in the community hold the various worldviews.

In December 2016, we issued a survey to INCOSE Fellows, and in January 2017, a slightly modified version was administered to INCOSE Systems Science Working Group (SSWG). Five distinct worldviews were identified from the survey responses, and two more were revealed in subsequent correspondence. Along this journey, we also collected, defined, and classified a set of systemness characteristics: attributes or features that a system-in-question is expected to exhibit to be considered a system. In this paper, we propose a definition of system, summarize the worldviews and systemness characteristics, providing a unified ontological framework that accommodates them. The worldviews and systemness characteristics are important building blocks in the effort to advance Systemology [10].

We had long discussions and deliberations in mostly virtual bi-weekly meeting that lasted two years, in which we made all effort to account for the different worldviews and attempted to accommodate them all. As a conclusion of this effort, we came up with the following definition of system, which is being proposed for adoption by INCOSE:

A system is an arrangement of parts or elements that together exhibit behavior or meaning that the individual constituents do not.

In what follows, we lay out the background and describe the different system worldviews and systemness characteristics as they emerged from our research. We argue for why the above system definition caters to the needs and wants of the various worldview holders to the extent that it can serve as a common unifying definition of system by a vast majority of the people who use the concept of system, if not all of them.

II. BACKGROUND: SYSTEM WORLDVIEWS IN PHILOSOPHY AND PRACTICE

In the Fourth Century BCE, Aristotle made the famous proposition that the whole is something over and above its parts and not just the sum of them all. Two thousand years later, Descartes’s reductionism—the practice of analyzing and describing a complex phenomenon in terms of its simple or fundamental components—led to rapid progress in Europe in experimental physics, biology, and medicine from the 17th Century.

Fig. 1 is an Object-Process Diagram, OPD [3], [4] that summarizes key influences in the evolution of the system concept, as applied to science and engineering. This concept is prominent in Adam Smith’s philosophical treatises, authored around 1750, and is also evident in Carnot’s work on thermodynamics, published in 1824. In 1850, Clausius extended Carnot’s work, adding the notion of environment. In the 1930’s, Gödel launched what was to become theoretical computer science, leading to Turing’s foundational work in the 1940s, and Shannon’s seminal work on information theory published in 1948. Bertalanffy’s work on General Systems Theory was also first published in 1948, as was Wiener’s work on Cybernetics, on which Ashby built his work in the 1950’s.

Systems Engineering (SE) became recognized in the 1950’s and 1960’s, initially in the context of applying cybernetics principles to the design of complex engineered technological systems. With the benefit of hindsight, SE was recognized much earlier in history [11], and notably during WW2. Miller[12] built on the biological aspects of Bertalanffy’s work to develop his Living Systems Theory. Systems thinking was applied to management from the 1970’s [5], and Complex Adaptive Systems emerged and developed in the same era.

In his 1750 Essay on Astronomy, Adam Smith clearly viewed system as a mode of description, writing: a system is an imaginary machine invented to connect together in the fancy those different movements and effects which are already in reality performed. However, this is not his only system worldview; in the same paragraph he appears also to adopt a realist system worldview: a machine is a little system, created to perform, as well as to connect together, in reality, those different movements and effects which the artist has occasion for. In his collected works published posthumously [6], the word “system” appears 327 times, emphasizing the centrality of this term in his thinking.

In the early 20th Century, we find definitions of a system as both a thing that exists in the real world and a mental construct in one’s mind. For example, Müller–Freienfels [13] described a system as the following two complementary concepts:

1) an objective concept: a coherent whole of things and their relations, of processes (e.g., of the world system or the “closed system” of mechanics);
2) a logical, ideal concept: a unified [whole], in accordance with principles arranged, internally connected, and an articulated whole of insights.

By the 1950’s, more definitions adopted an explicitly realist worldview, signifying that systems were considered to exist in the real world. Following are a few examples:
1) a set of objects together with relationships between the objects and between their attributes [16];
2) a set of interacting units with relationships among them [17];
3) any entity, conceptual or physical, which consists of interdependent parts [19]. Here we see that Ackoff explicitly embraced the notion that systems can be both physical and conceptual.

From 1968 onward, many sources are explicit about the duality between real or physical, and abstract or conceptual, systems. For example, Davis [20] made the following assertions.

Systems can be abstract or physical. An abstract system is an orderly arrangement of interdependent ideas or constructs. … A physical system is a set of elements that operate together to accomplish an objective. Examples of physical systems are the circulatory system of a body, a school, … and a computer …a system … consists of elements that can be identified as belonging together because of a common purpose, goal, or objective. Physical systems are more than conceptual constructs; they display activity or behavior. The parts interact to achieve an objective.

A major problem with the above distinction of Davis [20] between abstract and physical system is that the criterion distinguishing between the two types is, as expressed in the last sentence of this quote is that the parts interact to achieve an objective. This is true only for human-made systems, not for any natural system or subsystem, such as the circulatory blood system of a body, where we, humans, ascribe to it a purpose such as “supplying oxygen to the cells.” While this is true, it is a result of natural evolution, not a premeditated intent. According to ISO/IEC 15288:2008, 4.3.1, a system is a combination of interacting elements organized to achieve one or more stated purposes. Obviously, this definition is also limited to human-made systems even though this is not explicitly stated. One of the main categorization criteria for systems we elaborate on in the sequel, aimed at solving this confusion, is the system’s origin [3, p.72]: whether the system’s source is natural or human-made.

Systems thinking is a human qualification whose importance is increasingly recognized [21]. Citing Ossimitz/Tzafestas [22] wrote: Systems thinking requires the consciousness of the fact that we deal with models of our reality and not with the reality itself. Most schools of systems thinking adopt this position, maintaining that system models are mental constructs used to abstract and reason about the world, rather than accurate representations. For example, in Soft Systems Methodology [24], A human activity system is a notional system which expresses some [purpose…] The systems are notional in the sense that they are intellectual constructs and not descriptions of actual real-world activity. This is one manifestation of the “system as a mode of description” worldview. This view is embraced by Aslaksen [27] and by Blockley and Godfrey [28], who apply systems engineering to their domain of civil engineering.

Many systems engineers adopt the moderate realist worldview, recognizing that systems can be abstract/conceptual, or physical/real, or both. Increasingly, systems engineering, or what has become to be known as model-based systems engineering (MBSE), depends on use of models that correspond to, and allow us to make predictions about, real systems, be they actual (“as-is” systems) or intended (“to-be” systems) or both. MBSE puts models as the primary SE artifacts and the authoritative source of truth. Rosen [25] is explicit about the modeling relationship between real (natural) and conceptual (formal) systems. Emergence is the ability of a system to do something its separate parts cannot. Emergence is an elaboration of Aristotle’s observation that the whole is more than the sum of its parts in that it focuses on what the system as a whole can do—its behavior, which is more than what each part can do in isolation. The shift here is from structure to behavior. Structure and behavior are indeed the two major aspects of any system, but at least for human-made systems, behavior is of greater interest, because it enables the system’s function, which, in turn, provides the expected value to the system’s beneficiaries. This is a plausible explanation for the reason that many systems engineers and systems scientists regard emergence as a defining property of system.

Hitchins [11] has defined a system as an open set of complementary interacting parts, with properties, capabilities and behaviors emerging, both from the parts and their interactions, to synthesize a unified whole. Rechtin [29], Dickerson [30], and Sillitto [31] proposed similar definitions along the lines of: [a system comprises] parts interacting to create properties of the whole not possessed or exhibited by any of the parts on its own.

The emphasis on the system’s parts as interacting with each other, exhibiting a specific set of behaviors, has led many researchers to defining a system in terms of its behavior – the process(es) it performs, rather than its structure and static relations among them. For example, the notions of system-process duality and even processes’ superiority over objects are evident in the discussion of Blockley [14] about “the importance of being process,” and the discussion of Ruhm [2] on system-process duality. Object Process Methodology, OPM ISO 19450:2015 [3], [4], is founded on the dual representation of things: objects as things that exist and processes as things that transform objects by creating or consuming them, or by changing their states. According to Dori [3, p. 256], a system is a function-carrying object. Both natural and human-made systems are characterized by something central they do—their function. The difference between these two kinds of systems is that only the function of a human-made system is expected to provide value to some beneficiary.

Sillitto [18] has discussed how an observable process provides evidence for the existence of a real system and emphasized the process perspective in the logical architecture view of many model-based systems engineering methods, as described for example by Voirin [32]. The recognition of emergence as a key system property is the basis for the following definition of system we propose for adoption by INCOSE and repeat here: A system is an arrangement of parts or elements that together exhibit behavior or meaning that the individual constituents do not. We used the surveys data, elaborated and analyzed next, to ensure that our proposed system definition covers the full range of discovered worldviews.

III. System Definition Survey Questions

Although INCOSE has a single definition of system, individual Fellows use a wide range of different, and apparently...
mutually incompatible definitions. The survey questions were designed to quantify the range and relative frequency of the different worldviews, and to better understand the specific assumptions behind each. The questions in the questionnaire we administered to the Fellows appear in Table I, along with the results. Below, we highlight the intent of each question with a short explanation, complementing the question itself.

1) **Realist or constructivist?** The first question was intended to elicit the respondents’ position on the basic realist/constructivist spectrum.

2) **Human-made or naturally occurring?** This question probed beliefs about whether systems are human-made, occur in nature, or both. To avoid excluding constructivists, the question was couched in terms of systems, or entities designated as systems.

3) **Do systems only exist if an observer designates them as such?** This question inquired about respondents’ beliefs on a major source of debate regarding the independence of the concept of system: Do systems only exist because someone calls them that, or do they have objective properties that warrant their existence regardless of whether someone observed them.

4) **System boundaries: Observer-designated or intrinsic?** This question elicited respondents’ views on whether a system’s boundaries are designated by its observer or can be located based on objective criteria.

5) **Exploring systemness:** Here we sought essential or defining system characteristics. Respondents could choose as few or as many as they liked, and this question turned out to be a discriminator between different respondent groups. Answers provided additional, unexpected information about the range of worldviews that respondents hold, enabling us to refine the set of systemness characteristics, which we present and discuss next. The last five items in this list were offered as “other” responses in the survey issued to the Fellows and included as options in the modified survey issued to SSWG members. The other questions in the survey collected demographic information, including age band, institution membership, native language, and geographical area.

IV. ANALYSIS OF FELLOWS SURVEY RESPONSES

The main points that emerged from the Fellows’ survey responses (N = 26) are the following.

1) Nearly 90% considered that emergent properties were an essential characteristic of a system, justifying our definition.

2) About 80% are moderate realists, holding that systems can be both mental constructs or entities in the real world.

3) All except two respondents considered that “more than one part” was an essential characteristic.

4) About 20% are constructivists, who consider that systems are only human mental constructs.

5) All except one respondent hold that systems can be both human-made and naturally occurring.

6) About 75% consider systems to exist in the real world independently of human observation or thought. A similar percentage think that objective criteria can be used to define the system boundary.

7) About 65% considered a boundary to be an essential characteristic of system. The rest, mostly realists, did not.

8) The majority considered interactions between parts to be an essential system characteristic. Others noted that certain kinds of conceptual systems are composed purely of abstract information elements, which cannot interact unless placed in a real host system, such as a computer for computer code, a human brain for thoughts and ideas, a biological system for DNA-stored information, or a social system for laws, policies, and religious or political belief systems.

9) About 25% considered a defined purpose or goal to be an essential system characteristic. This implies their possibly unconscious reference to human-made systems only.

10) Most respondents took a modest or even a minimalist approach to the essential attributes defining a system. About 12% listed all the characteristics as essential.

A couple of weeks after the INCOSE Fellows survey, the same survey, with minor changes, was administered also to the INCOSE Systems Science Working Group (SSWG) members (N = 33), many of whom were also members of the International Society for the Systems Sciences (ISSS). Some of the “other” system characteristics suggested in the Fellows survey were added as options here. In Table I, we present the surveys’ results, a summary, and a comparison between the two groups.

Few SSWG respondents, who took a formal approach to defining a system, suggested a set of systemness criteria that was different than that of the majority. Salient differences between SSWG and Fellows’ responses are listed below.

1) A much higher percentage of SSWG respondents (15% versus 4%) believe that systems only exist in the real world.

2) Similarly, more SSWG respondents (15% versus 4%) believe that objective criteria can define the system boundary.

3) Some characteristics, proposed by Fellows and added to the SSWG survey, attracted many positive responses, including dynamic and integrity limits, input/output behavior, and the characteristics of being whole or complete. SSWG survey respondents checked more characteristics as “essential” than respondents in the Fellows survey.

1) Write-in responses to the systemness question included the following:

a) Many of the above are the same and so [are] redundant.

b) If the phrase had been “a defined ‘function’ instead of purpose/goal, I would have checked it.

c) [Systems] exhibit recursive patterns.

d) Distinction should be made between simple and complex (adaptive) systems.

e) Some other attributes are associated with some kinds of systems but not all.

f) Behavior of each interacting system component depends on its state; states in turn depend on past
<table>
<thead>
<tr>
<th>Fellows</th>
<th># of respondents = 26</th>
<th>SSWG</th>
<th># of respondents = 33</th>
<th>Total</th>
<th>Difference: SSWG – Fellows</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Question</strong></td>
<td><strong>respondents</strong></td>
<td><strong>#</strong></td>
<td><strong>%</strong></td>
<td><strong>respondents</strong></td>
<td><strong>#</strong></td>
</tr>
<tr>
<td>1) [Intent: Realist or constructivist?]</td>
<td>Do you think that systems...</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>...exist in the real world</td>
<td>1</td>
<td>4%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>...are a mental construct</td>
<td>4</td>
<td>15%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>...can be both of the above</td>
<td>21</td>
<td>81%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2) [Intent: Human-made or naturally occurring?]</td>
<td>Do you think that systems, or entities designated as systems, in the real world, can be...</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>...human made</td>
<td>1</td>
<td>4%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>...naturally occurring</td>
<td>0</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>...either or both of the above</td>
<td>25</td>
<td>96%</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>3) [Intent: Do systems only exist if an observer designates them as such?]</td>
<td>Considering entities in the real world designated as systems, do you think</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>systems only exist if they are designated by a human?</td>
<td>6</td>
<td>23%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>systems can exist in the physical universe independent of human observation and thought?</td>
<td>19</td>
<td>73%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4) [Intent: System Boundaries – observer designated or intrinsic?]</td>
<td>Considering again entities in the real world described as systems, do you think</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>system boundaries are always a free choice of the observer</td>
<td>19%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>while an observer is always free to designate the boundary for a particular analysis, 'system' boundaries can at least in some cases be discovered and refined</td>
<td>20</td>
<td>77%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>the 'correct' system boundary can always be discovered and refined based on objective criteria</td>
<td>1</td>
<td>4%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>other</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5) [Intent: Exploring systemicity]</td>
<td>Do you think that the following are essential characteristics of &quot;systems&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>more than one part or element</td>
<td>24</td>
<td>92%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>relationships between the parts</td>
<td>24</td>
<td>92%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>interactions between the parts</td>
<td>22</td>
<td>85%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a boundary (physical or logical) separating the system from its environment</td>
<td>18</td>
<td>69%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;emergent properties&quot;, properties of the whole system not possessed by the individual parts acting separately</td>
<td>22</td>
<td>85%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;homeostasis&quot;, the ability to maintain a condition of equilibrium within its internal environment, even when faced with external changes</td>
<td>6</td>
<td>23%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a defined &quot;purpose&quot; or &quot;goal&quot;</td>
<td>7</td>
<td>27%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>viability, the ability to survive in a non-benign environment</td>
<td>6</td>
<td>23%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>internal communication between parts</td>
<td>11</td>
<td>42%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>internal decision making processes</td>
<td>3</td>
<td>12%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>adaptive control using internal feedback</td>
<td>5</td>
<td>19%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>resilience, the ability to absorb and recover from major disruption when deployed into their operational environment, systems both change and adapt to their environment</td>
<td>4</td>
<td>15%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>when deployed into their operational environment, systems both change and adapt to their environment</td>
<td>10</td>
<td>38%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Interactions; overall system combinatorial state depends on Hamilton’s Principle (see [33]).

Interaction and internal communication are the same, but with two different perspectives; adaptive control and resilience are one and the same, they both mean the system is striving for its existence; systems changing in an environment is only for natural systems not for manmade systems, unless we build a mind into it.

There are no “essential” characteristics. Almost anything can be a system.

In summary, the SSWG respondents presented a higher diversity of views, ranging from a formal, possibly mathematical perspective, to a practical, realist view of systems as a mode of organization of nature, with complex properties associated with viability and persistence. The SSWG survey outcomes validated the full range and scope of the various belief systems were properly considered, and we did not have to change our system definition because of this extra input.

V. Systemness Criteria

We define systemness as the extent to which a thing, entity, or concept—the system-in-question—can be called a system. Based on our initial list of systemness criteria in the closed questions, the responses to the open questions we gathered from participants, our own understandings and interpretations, and additional criteria of our own, below, we have compiled a list of systemness criteria names and definitions.

1) Holism: Being whole or complete.
2) Functionality: Ability to perform a function—a process that affects at least one object (the operand) within or outside the system-to-be.
3) Modularity: Ability to cluster cohesively as a module, component, or subsystem, with many internal connections within each module and few with others.
4) Environmental context: Immersion of the system-in-question in its environment and the exchange of matter, energy, and information between the two.
5) Hierarchical emergence: Organization of the system-in-question in a hierarchy of integration levels, each giving rise to new emerging properties.
6) Integrity limits: The dynamic envelope of conditions within which the system-in-question can function before disintegrating.
7) Homeostasis: Ability to maintain equilibrium while facing changes in the environment.
8) Resilience: Ability to absorb and recover from a major disruption or survive in a nonbenign environment.
9) Sensing: Ability to monitor the environment by receiving and processing external signals.
10) Feedback: Ability to apply adaptive control in response to internal and external stimuli or signals.
11) Environmental mutuality: Adaptation of the system-in-question to its environment and the effect it has on the environment.
12) Communication: Ability to receive and send signals both internally, between the system-in-question’s parts, and externally, between it and its environment.
13) Self-healing: Ability to repair damaged parts of the system-in-question by itself.
14) Reproducibility: Ability of the system-in-question to create copies of itself.
15) Intelligence: Ability to acquire, develop, and process knowledge logically and make judicious decisions.
16) Goal orientation: Being driven by an objective that must be achieved.
17) Personality: Ability to have feelings, emotions, and aspirations.

Obviously, as we go down the criteria list, the complexity level of the system-in-question that meets the criterion increases and the criterion is more difficult to fulfill, making it increasingly characteristic of a living organism, ultimately a human. Thus, criteria 1–5 are agreed by all or most of our respondents. As we move down the list, consensus on whether the system-in-question must possess or exhibit that criterion decreases.

VI. Revealed System Worldviews

The surveys and related discussions revealed a rich and diverse spectrum of system worldviews. Rather than being separate distinct islands of belief, the worldviews that emerged are stable points on a continuous belief spectrum. Indeed, most respondents would likely not identify themselves as holding exactly one of the worldviews defined below.

A. System Worldview 1: Formal Minimalist

Rooted in logic and theoretical computer science, the Formal Minimalist worldview holds that a rigorous scientific basis entails defining a system conceptually and abstractly, and that real systems can be modeled by conceptual ones. In this worldview, system is a term reserved for the conceptual world. Complex properties can be developed from a minimalist definition, such as the description of Bertalanffy [17] of a system as an entity that can be mathematically modeled as a dynamical system built up from basic elements. The small number of respondents who hold this worldview seek to improve mathematical and scientific tools for systems practice for generating real systems from mathematically or ontologically grounded models: model-based generation of both artificial and natural systems.

A seeming implication of this worldview is that what cannot be modeled is not a system. While some SE practitioners would find this claim problematic, it sits well with OPM [3], [4]. OPM is founded on a minimal universal ontology of things and relations among them, where things are objects—things that exist or might exist physically or informally, and processes—things that happen to and transform (create, consume, or change the state of) objects. This ontology is universal in the sense that it can represent the four-dimensional universe we live in—the three spatial dimensions and the fourth, temporal one. It therefore lends itself to modeling any system in any domain. Moreover, equipped with in-zooming–out-zooming and unfolding–folding as refinement-abstraction mechanisms, the level of complexity
of the system it can model is unlimited. Thus, the assertion that a real system is a thing that must be amenable to being modeled should not deter practitioners.

B. System Worldview 2: Constructivist

The constructivist worldview is held by a substantial minority (about 20%) from the two surveys, who espouse a more conventional approach than the formal minimalist. Most constructivist respondents agree that a system comprises two or more related and interacting parts, and that it has emergent properties, which none of its parts alone possesses. The majority also consider a system to have a boundary, which an observer can freely choose. Constructivist worldview holders are divided on whether a system must have a purpose or a goal. This division is almost equivalent to the disparity between those who view systems only as human-made artifacts, which are built with a purpose, aim, and value proposition in mind, versus those who see an abundance of systems also in nature.

We refer to an abstracted system as a system that represents parts of the real world [9], following [17]. When a conceptual system is an abstracted one, it is in fact a model—there is a mapping from the abstracted system to parts of the real world that the abstracted system represents.

Constructivist worldview holders do not consider the real-world configuration represented by an abstracted system to be itself a system. Checkland [24] has clearly articulated this distinction, describing the ensemble of relevant parts of the real world as “the mosaic” and defining a system in terms of a model of parts of the mosaic considered relevant to the purpose or interest of the observer. This idea is consistent with the view of Checkland [24] on a Human Activity System—a notional system which expresses purposeful human activities as intellectual constructs, or models humans have in their minds about how personal and organizational processes operate.

C. System Worldview 3: Moderate Realist

The Moderate Realist worldview, which most respondents hold, maintains that systems can exist as purely mental constructs, or in the real world, or both, and they exist in nature or as human-made artifacts [8]. This worldview seems to be the most appropriate one for practicing systems engineering [10]. The majority of the respondents champion some variant of this worldview, but they differ on systems’ essential characteristics, or systemness criteria. The Moderate Realist worldview is consistent with the modeling relation between models and real-world systems [24] and the identification of an abstracted system, recognizing pure informational systems that do not directly correspond to real-world systems.

Equally importantly, this worldview is in line with the tenets of model-based systems engineering (MBSE) of first producing conceptual models of both the problem to be solved and the intervention system, and use them to generate the actual intervention system. Both the model and its realization are systems, with a modeling or representation relation from the former to the latter. Many of the Moderate Realist worldview holders consider emergence, or emergent properties, to be a defining characteristic of systems. However, they do not consider boundary as an essential part of a system, as it can be discovered, changed, or refined during the investigation of the system.

D. System Worldview 4: Extreme Realist

The few (7%) holders of the Extreme Realist worldview maintain that systems only exist in the real world. With respect to the system’s boundary, some Extreme Realists, as well as some Moderate Realists, maintain that the system boundary can always be discovered and refined based on objective criteria.

E. System Worldview 5: Complexity- and Life-Focused

The Complexity- and Life-Focused systems worldview holders maintain that for a thing to be a system, it must be sufficiently complex, rendering it capable of sustaining life processes. This worldview correlates best with the Extreme Realist worldview, and to a lesser extent, with the Constructivist and Moderate Realist worldviews. In terms of systemness criteria, the Complexity- and Life-Focused worldview is the strictest, and it is diametrically opposed to the Formal Minimalist worldview. These worldview holders are maximalists, deeming almost all the systemness criteria to be essential for a system-in-question to be defined as a bona fide system. While recognizing many of the systemness criteria as common, holders of other worldviews do not view them as essential characteristics of systems.

The Complexity- and Life-Focused worldview holders group includes those who are mainly interested in viable autonomous systems, capable of reproducing themselves, such as biological systems, as described by Miller [12], and viable organizational systems, like those described by Beer [5]. Many of these attributes (except, for now, the ability to reproduce themselves) are increasingly being expected of engineered systems.

F. System Worldview 6: System as a Mode of Description

The System as a Mode of Description worldview was not identified from the survey data; it emerged from prior and subsequent discussions. This worldview has long historical precedents, first described by Adam Smith as early as 1750. In email correspondence quoted with permission, Aslaksen explained that system is a mode of description as follows: any aspect of an entity can be described in terms of three sets: a set of elements, a set of interactions between these elements, and a set of interactions with the outside world (possibly an observer). [In this worldview] nothing is a system, and everything can be described as a system. Ontologically, a system is not a thing, descriptions are a separate ontological class. The purpose of describing something as a system is to handle its complexity … an entity can correspond to a number of systems (i.e., descriptions), depending on what aspect of the entity we are interested in, such as cost, reliability, performance, etc.”

Indeed, OPM [3], [4] takes a top-down complexity management approach in modeling a system: at the top level is the system diagram (SD)—the zeroth level, presenting an Object-Process Diagram (OPD) with the system’s function—the main process and its operand(s), i.e., the objects that this process transforms. For human-made systems, SD also contains the beneficiary group, and the value that the system delivers to the beneficiary is explainable by the operand transformation.
This bird’s eye view of the system is gradually refined in subsequent, more detailed levels by applying one of two refinement mechanisms: in-zooming, in which a process is blown up to expose its subprocesses with their top-to-bottom execution order, and unfolding, in which an object exposes its part features, or specializations. The result is a tree of OPDs that together specify the system to any desired level of detail, using only stateful objects and processes—the minimal set of universal ontological building blocks.

G. System Worldview 7: System as a Process

This worldview was not identified either from the survey data, but rather through correspondence. As we noted previously, there is a substantial body of literature related to the concept of object/process or system/process duality or correspondence, and several of our sources argue that a system is primarily defined not by its structure but by its ability as a whole to do things or perform process(es) that cannot be performed by its parts acting independently. According to Blockley [14], a system is a process. He argues that the function of a system—what it does or can do—is its persistent characteristic. Indeed, normally we think of structure as persistent and behavior as transient, but the structure goes through a lifecycle, so if we consider a sufficiently long timescale, it too is transient. For example, to perform the function of transportation, people used horses. Now they use cars, and in the not so distant future—flying taxis.

Following this mindset of process first, OPM [3], [4], advocates starting the construction of any human-made system model by defining the function of the system as a major process and its operands—the object which the process transforms, then adding the stakeholders and expressing the value they extract from the transformation.

VII. CONSEQUENCES FOR SYSTEMS ENGINEERING

The results and analysis of our surveys indicate that there is divergence in worldviews within the SE and Systems Sciences community, and an even wider divergence between the way the concept of system is used and viewed by systems-oriented theoretical computer scientists and all other systems theorists and practitioners. To explore the implications of these observations, we consider five domains of application of the systems sciences and systems engineering, to illustrate how the worldviews we have identified may influence both current practice and the prospects for improvement.

Domain 1—Software systems and formal models of engineered technological systems. At the risk of oversimplification, we suggest that practice in this domain is divided between empiricists, who focus on producing working code at the one extreme, and theory-based practitioners who draw on theoretical computer science and work at the model level at the other extreme. The goals of the latter group are to:

1) develop and operationalize theory-based approaches to improve the determinism and efficiency of those engineered systems that can be deterministic and efficient;
2) extend the dynamic and integrity envelopes of systems to reduce the incidence of behavior becoming nondeterministic and counterintuitive as integrity limits are breached;
3) develop theory to underpin and apply deep learning to allow automated and autonomous systems to respond to nondeterministic situations in ways that are nonetheless appropriate to the situation and acceptable to humans.

This domain, which we associate with System Worldviews 1 and 2, can potentially make an important contribution to systems engineering practice and to the development of autonomous systems by providing solid theoretical underpinnings to current modeling languages. The challenge [15] is that there is a radical difference between holders of System Worldview 1, who develop tools for software and model-based engineering, and holders of System Worldview 3, the moderate realists, creating a barrier to effective take-up of MBSE. This difference is reflected in the views of systems engineers and computer-science-oriented software engineers on how systems should be developed. Efforts are now underway, e.g., by the INCOSE Joint Software Interface WG (SaSIWG), to reconcile the systems and software engineering approaches, which, after all, are reflections of the same end product or system.

Domain 2—Traditional deterministic technological engineered systems. In this domain, which Hybertson [23] refers to as traditional systems engineering, and we associate with System Worldviews 3 and 4, the focus is on technology-based product systems, which use components that are essentially deterministic, and seek to achieve deterministic behavior also at the system level. These systems typically involve diverse disciplines and technologies, whose individual engineering practices are often model-based, but their system-level integration is still done in a traditional document-centric and 3-D CAD methods, focusing on the physical architecture. The dynamic aspect of such systems is largely empirical, based on currently perceived best practices, or on “what worked last time.” Systems in this domain are expected to be deterministic within defined environment and scenarios. Their performance and behavior are typically undefined outside the specified envelope. Such systems may fail unexpectedly or behave unpredictably and counterintuitively if dynamic integrity limits are exceeded.

Domain 3—Enterprise and organizational systems. We associate this domain with System Worldviews 3 and 5, because systems of this nature involve elements from all parts of our system definition framework, but are fundamentally complex. These are nondeterministic systems at the micro and macro scales. At the macro, individual scale, this is due to human agents, who make independent and often irrational decisions. At the macro, enterprise scale, these systems are also subject to nondeterminism, because humans are still the ones making the decisions. Such systems typically evolve and adapt to deal with progressive change, but disruptive changes can harm their viability; they can collapse unexpectedly if dynamic and integrity limits are exceeded, saturating their adaptive capacity. This happens to organizations with no clear mission statement as they fail to realize that technological advances make their flagship product obsolete (e.g., Polaroid).
Pragmatic practice for project organizations is set out in the Bodies of Knowledge of the various project management associations, but like traditional systems engineering, their ability to deal with unknown or unknowable complex or chaotic situations is limited [15, 16]. Current “good practice” methods for complex situations and larger, more diffuse and decentralized enterprises draw on “learning organization” and “social network” theories, leveraged by economics, management theory, systems thinking, behavioral psychology, the Viable Systems Model [5], and Enterprise Systems Engineering [26].

Domain 4—Naturally occurring systems. These systems are complex, adaptive, and resilient at the subatomic, molecular, biological, and cosmological scales. They can evolve and adapt to deal with progressive change, and may go through drastic changes if affected by disruptive change, possibly at the expense of system participants’ viability. Naturally occurring systems can collapse unexpectedly and catastrophically (e.g., dinosaurs) because of cascading failure modes, if dynamic and integrity limits are grossly exceeded to the extent that their adaptive capacity is saturated.

Current practice concerning naturally occurring systems draws on Living Systems theory, leaning heavily on such concepts as homeostasis—the ability to maintain internal equilibrium in a changing environment. The focus in this field is scientific understanding and guardianship, considering biological and ecological systems at all scales from sub-molecular to cosmic. We associate this domain with System Worldviews 4 and 5, but increasingly we need to consider, integrate and manage such systems in conjunction with engineered socio-technological systems, which involve the more inclusive perspective of System Worldview 3.

Domain 5—Autonomous adaptive technological systems. These pose new challenges to systems engineering and related disciplines, as the goal is to design systems that will be able to adapt to unforeseen and even unforeseeable situations, while behaving in ways that are compatible with human value systems, even when dynamic and integrity limits are violated. Since these systems are required to deal with nondeterministic scenarios, their decision processes are inevitably nondeterministic. A “linear” or incremental response to developing such systems, based on deterministic engineering paradigms, would be a brute force attack: to define more and more scenarios, and more and more rules for recognizing and dealing with different scenarios.

An alternative, or perhaps complementary, approach is offered by Artificial Intelligence (AI), including the disruptive concept of deep learning, a modern implementation of neural nets. Benefiting from current and future computer processing power, AI aims to allow autonomous systems to learn on their own for themselves and to share their learning with other systems of similar types. In this domain, at system level, practice is ahead of the theory. While the approach shows promise, it is expected to cause fundamental problems of validation and integration with existing, deterministically-designed systems. The core technology for autonomous systems is being successfully developed using System Worldview 1, but the development of successful and trusted autonomous systems is not merely a technical challenge. Complex technical systems exist within a wider socio-technical context. Considering the scale of legal, ethical, regulatory and environmental challenges and issues of societal perception, success will depend on improved collaboration across a wide range of activities and disciplines, spanning the full spectrum of engineering activities and extending to social sciences, ethics, and liberal arts. To achieve this span, System Worldviews 1 and 3 will need to integrate with concepts from System Worldview 5, and with new or emerging worldviews on systems engineering. Currently this is not happening, except perhaps in some organizations in private, and in some small fora in professional societies, such as the current research.

VIII. Summary and Conclusion

This paper has three main theoretical contributions to the body of knowledge on the study of systems and on systems science and engineering: system definition, system worldviews, and systemness characteristics. They emerged primarily from surveys we administered to senior, experienced members of the systems community, which triggered our systems thinking to gain new insights. Our driving underlying assumption has been that a narrow view of systems from a systems engineer’s perspective in particular, and from any human’s perspective in general, is problematic, because if two communicating parties have different interpretations of such a fundamental concept, miscommunication, which is often detrimental, is inevitable.

We found seven system worldviews along a spectrum stretching from extreme realist to strictly constructivist. Extreme realist worldview holders maintain that systems exist only in the real world. On the other side of the spectrum, those who hold a strictly constructivist worldview maintain that systems are mental constructs that humans create in their minds to explain aspects of how the world works. Within these two extremes, there are many nuances: systems exist purely in the mind, or purely in reality, or both; systems are human-made, or naturally occurring, or both; systems are a mode of description of any aspect of reality, or a formal model of certain types of current or intended reality.

Our second contribution is the identification and definition of 17 systemness criteria, including holism, cohesiveness and modularity, environmental context, hierarchical emergence, integrity limits, resilience, sensing, homeostasis, feedback, environmental mutuality, communication, self-healing, reproducibility, intelligence, and personality. While this list is most likely not complete, it is a solid foundation for advancing systemicity. Table II summarizes the mappings between the different system worldviews and the SE domains we discussed. More work is needed to associate with and map each criterion to the appropriate worldview and system domain.

A major contribution of this paper would be materialized if successful practitioners become more aware of the possibility that peers or counterparts often hold worldviews that are different than their own, accept this fact, and operate while considering this reality, even if their core system worldview is different. We are optimistic that this can be accomplished based on the observation that people who hold quite different worldviews are able to collaborate successfully on real-world problems [18].

Widening systems scientists’ and engineers’ view of systems to explicitly accommodate the range of worldviews we have
identified and characterized is part of the transdisciplinary integration challenge faced by IEEE, INCOSE and other groups [15]. We believe our prior work on system definition [8], [9] recognizes the worldviews found in the systems engineering community and allows them to be understood, providing an effective basis for their integration or mutual recognition and consideration. Perhaps most significantly, based on the system worldviews and systemness characteristics we identified as a result of the surveys’ analysis, we offer the following encompassing definition of system: an arrangement of parts or elements that together exhibit behavior or meaning that the individual constituents do not.

This definition caters to the various system worldviews, offering useful perspectives for systems engineering as an emerging discipline. Indeed, systems engineers should have the flexibility to accept the fact that different worldviews may be appropriate for different situations, and they should be ready to adopt them as necessary.

As a future work, a more exhaustive sampling from researchers, engineers, and engineering students at different career stages would help to confirm and refine the findings, possibly pointing to differences among these various population groups.

REFERENCES


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