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Convergent Anthropocene Systems: Towards an Agile, System-of-Systems Engineering Approach

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Abstract—**The greatest societal challenges are numerous, daunting, and seemingly unrelated, collectively spanning almost every discipline of science and engineering. Societies confronted with these complex challenges need to manage synergies and trade-offs across multiple systems, scales and levels of analysis. Unfortunately, if the goal is to overcome each of these challenges separately, we must embrace convergence as a means to merge disciplines, methodologies, and technologies, and we must do this for every one of the challenges, which is a truly daunting, and perhaps even impossible, task. Fortunately, however, societal challenges of the Anthropocene share the abstract common characteristics of broad scope, complex interdependencies, and multi-faceted causality, and also share several common systems. Seizing on this conceptual opportunity, we evaluate the "convergence potential" for systems-of-systems engineering methods. We then present a way forward that addresses the unique characteristics of Anthropocene systems by developing an agile systems-of-systems engineering framework and associated decision-support system to integrate fragmented data and disciplinary knowledge into a new systemic understanding. The proposed framework provides a fresh perspective on an entire family of societal challenges of the Anthropocene.**

Keywords—Anthropocene systems, decision support systems, Earth systems, engineering systems, system of systems

I. Introduction: The Rise of Anthropocene Systems

Humans have made significant and irreversible changes to the Earth. Although biological evolution gave rise to ecosystems and early humans, cultural evolution gave modern humans the ability to transform the planet. Human culture is a sophisticated, knowledge-sharing system, which enables groups of people to resolve complex problems that are far beyond the ability of individuals [1]. It was this human cooperation in groups, combined with competition and conflict among groups, that led to the unprecedented Anthropocene [2], with early biophysical systems becoming connected to the more recent sociocultural and sociotechnical systems (collectively, we refer to these systems as Anthropocene systems). The ensuing societal challenges of the Anthropocene are numerous, daunting, and seemingly unrelated, with examples in Table 1 (modified from [3]) that collectively span almost every discipline of science and engineering. The challenges are often framed in terms of resilience or sustainability, are complex and systemic, and have causes, interactions and consequences that cascade across the globally-connected Anthropocene systems [4, 5].

TABLE I. SOCIETAL CHALLENGES OF THE ANTHROPOCENE.

Stabilize carbon emissions
Manage the nitrogen and phosphorus cycles
Provide access to clean water
Adapt to climate change
Improve infrastructure for an urbanized population
Feed a growing global population sustainably
Clean the world's oceans of solid waste
Restore and improve global biodiversity
Supply human needs for energy sustainably

Unfortunately, when attempting to address any of these challenges, managers, stakeholders, and policy makers cannot evaluate trade-offs across multiple complex systems, nor can they advantageously align goals in specific systems with those in others. Furthermore, these complex challenges emerge from multiple systems of varying scales that ultimately requires multiple levels of analysis with deep integration across disciplines. To make matters worse, many of the societal challenges are interdependent, meaning that separate initiatives to address them will likely result in conflicting policies because so many of the relevant systems (e.g., in a specific region, the land use, watershed, energy, transportation, air, climate, economic, and social systems) are either similar or the same. Furthermore, while cultural evolution enabled the scientific and industrial revolutions with many associated technological benefits, it also resulted in the fragmentation of knowledge with sharply-focused specialization. This division of knowledge into many disciplines, subdisciplines, and disparate knowledge domains, while bringing great benefits in terms of focused research and development, is simultaneously one of the greatest scientific and societal challenges, severely impeding progress because we cannot "see the forest instead of the trees."

For example, the Chesapeake Bay Watershed (CBW) has a population of 17 million and several stressed systems. In the CBW, management of flood risk, crop loss, and water quality are interrelated through land use, watershed, estuary, airshed, economic, and other infrastructure systems. Unfortunately, they are currently siloed in different management structures. Regulations and policies are not adopted quickly or comprehensively enough to decrease risks. The Chesapeake Bay Program (CBP) is a consortium of governmental and non-governmental entities that manage various components of the CBW and through their committee structure and outreach provide an avenue for effective stakeholder engagement. The CBP management and research teams include representatives from six states (DE, MD, NY, PA, VA, WV) and Washington DC, ten federal agencies led by the EPA, and other stakeholders and advisors. They are seeking integrative tools because they have realized the limits of a reductive modeling approach for engaging stakeholders as problem-solvers [6]. A significant effort has been expended to model sources and effects of nutrients and sediment influxes from agricultural practices and urban development. However, the management system is now challenged by the need to engage partners in nutrient reductions who have additional, higher priority, goals that are not captured by models or directly addressed in management processes. The lack of integrated modeling prevents stakeholders from examining synergies (e.g., nutrient reduction and flood risk mitigation) or tradeoffs (e.g., nutrient reduction and fish productivity). Together, the CBW and the CBP provide a compelling example of the societal challenges of the Anthropocene.

The need for coordination across multiple systems to address the multiple societal challenges of the Anthropocene is consistent and pervasive. Just one of the societal challenges (e.g. feed a growing global population sustainably) could potentially include interactions among at least 10 systems (e.g., land-use, agriculture, watershed, climate, energy, transportation, communication, economic, governance and other social systems). Furthermore, each of the 10 individual systems has many subsystems that not only create the internal dynamics specific to that system, but also interact with subsystems in the other systems. When addressing societal challenges such as those listed in Table 1, researchers in most disciplines (e.g., hydrology, energy, transportation, ecosystems, agriculture) tend to begin with their own subsystem and incrementally add a few interactions to a few other subsystems across a wide range of often arbitrary scales. For example, a systematic review of 245 publications on the food-energy-water nexus [7] revealed that most do not even capture interactions among water, energy and food – the very linkages they conceptually purport to address – let alone the complex dynamics among the larger systems. If these interactions among the subsystems are studied two or three at a time, which is usually the case, we will need many thousands of research projects (likely taking decades) to characterize the interactions among the subsystems, and in the end, we will still not understand how the individual systems interact. To make matters even worse, such an incremental approach entirely overlooks the fact that the societal challenges are interdependent [8] because several of the relevant systems within a region or urban area are the same across many of the challenges. This fragmented approach to science is paralleled in policy circles, where government agencies invest in modeling for their primary mandate (e.g., USDA for agriculture and EPA for pollution) at scales determined by regulations that were not designed to tackle societal challenges across issues and scales [9, 10].

Given these societal challenges of the Anthropocene, this paper seeks to evaluate the "convergence potential" for systems-of-systems engineering methods in Section II. It then presents a way forward that addresses their inherent characteristics in Section III. Section IV brings the paper to a conclusion.

II. The Potential for Systems-of-Systems engineering

While the need for coordination across multiple systems to address the multiple societal challenges of the Anthropocene is daunting, these challenges ultimately share the abstract but common characteristics of broad scope, complex interdependencies, and multi-faceted causality [11, 12]. In many cases, the challenges also share several common systems. Seizing on this conceptual opportunity suggests the existence of a convergence paradigm rooted in systems engineering that serves as a meta-problem-solving skill set [13]. It has the potential to address many societal challenges simultaneously, including new challenges that will occur in the future. Such a convergence paradigm can be inspired by system-of-systems (SoS) approaches [4, 5] where scientists and engineers work across disciplines to combine the structural, behavioral, and technological approaches needed to address large-scale societal challenges [14].

Substantial progress is being made in modeling coupled systems in several closely-related fields that use integrative approaches (e.g., system-of-systems engineering [15], integrated assessment and modeling [16], social-ecological systems research [17], land systems science [18], socio-environmental systems modeling [19], multi-scale modeling [20], and multi-fidelity modeling [21]). Many of these approaches include more than a single discipline and integrate multiple subsystems. Many also employ participatory processes that support social learning and decision-making for improved outcomes [19]. Despite their advancements, these approaches often inherit the peculiarities of their disciplinary origins. Consequently, their methods and problem domains have yet to converge; leaving a collection of disparate and potentially confusing approaches. At present, there is no unified system-of-systems approach and major obstacles to an actionable convergence paradigm remain [4, 19].

These limitations are particularly evident in Anthropocene systems that are dynamic, heterogeneous, multi-level, biophysical, sociocultural, and sociotechnical in nature [22]. Indeed, several major challenges associated with developing integrated Anthropocene system models have recently been identified [19], including bridging epistemologies across disciplines, multi-dimensional uncertainty assessment and management, scales and scaling issues, combining qualitative and quantitative methods and data, furthering the adoption and impacts of Anthropocene systems modeling on policy, capturing structural changes, representing human dimensions, and leveraging new data types and sources [19]. Similar challenges, no doubt, apply to the other integrative approaches, but these are not being addressed in a systematic fashion that converges across these rapidly emerging fields.

Perhaps one reason that these integrative approaches have yet to converge sufficiently to address Anthropocene systems is that they exhibit inherent characteristics that are insufficiently considered in these approaches. For example, many systems engineering [23] and SoS engineering [24-26] approaches rightfully presuppose an engineered system that is *synthesized* from concept to real-life deployment. This forward-engineering paradigm means that the associated methods have limited applicability for Anthropocene systems that have long existed [27] Instead, the societal challenges of the Anthropocene demand *analytical* methods that seek to first reverse-engineer these systems from their current state prior to synthesizing meaningful and well-considered human interventions [28]. Next, unlike purely technical systems, the societal challenges of the Anthropocene have biophysical, sociocultural, and sociotechnical systems with structural interactions and dynamic behaviors that are not yet well-understood. In such a case, the analytical approaches must not only rely on a data-driven understanding of these systems, but also integrate with our existing theory-informed knowledge of these systems. Such a task is complicated by a lack of consensus on the underlying ontologies, meta-data, and mental models. This means that the inherent characteristics of Anthropocene systems require a convergence of data-driven machine learning with theory-guided model-based systems engineering. As these methods converge, SoS engineering models are more likely to support interventions with fewer unintended consequences and greater synergies between systems.

The societal challenges of the Anthropocene are also impeded by the nature of their decision-making. Unfortunately, the present-day SoS engineering literature offers only limited insight because it originates from aerospace and military applications where the systems-of-systems are often "directed" in that they are centrally managed to achieve a high-level purpose [24-26] (e.g. coordinated navy, air force, marine operations). In contrast, Anthropocene systems are either "collaborative" or "virtual" [24-26], where multiple decision-making entities sometimes act together towards a high-level purpose, but more often act independently or even at odds and high-level behavior emerges. In comparison to their directed counterparts, collaborative and virtual systems-of-systems have received far less attention in the literature and cannot be applied directly to the societal challenges of the Anthropocene.

III. An Agile Systems of Systems Engineering Aproach

To address the unique SoS characteristics of Anthropocene systems, we are developing an agile systems-of-systems engineering framework and associated decision-support system [4, 5] to integrate fragmented data and disciplinary knowledge into a new systemic understanding (see Figure 1). We choose an agile, system-of-systems engineering approach because: systems are about interconnected elements that together serve a higher function; a system of systems recognizes that there are multiple different systems; engineering is a scientific field devoted to improving such systems in service of humanity, so we are referring to engineering in the broadest sense; and agile represents an iterative approach to engineering systems that can manage their inherent complexity.

Transforming an abstract convergence paradigm into an actionable one requires a computational framework that integrates disparate forms of qualitative knowledge, quantitative data, and system models [4, 5, 19]. In addition, it must recognize the central role of human behavior in coupled Anthropocene systems. This includes dynamic behavior endogenous to the computational framework, but also includes a comprehensive decision-support system [29] that facilitates participatory modeling processes involving experts, managers, stakeholders and policy-makers. Such participatory processes are, by definition, convergent as they are employed to co-produce knowledge [30], analyze multiple scenarios, and adaptively manage future pathways [5]. Finally, given the vast scope of this family of societal challenges, there is an equally urgent need for a convergence-centric pedagogical approach to educate and train students, academics, and professionals to think holistically and abstractly, conceptualize societal problems more coherently, and identify methods to effectively organize, influence and leverage research that spans multiple disciplines, knowledge domains, and societal challenges [5].

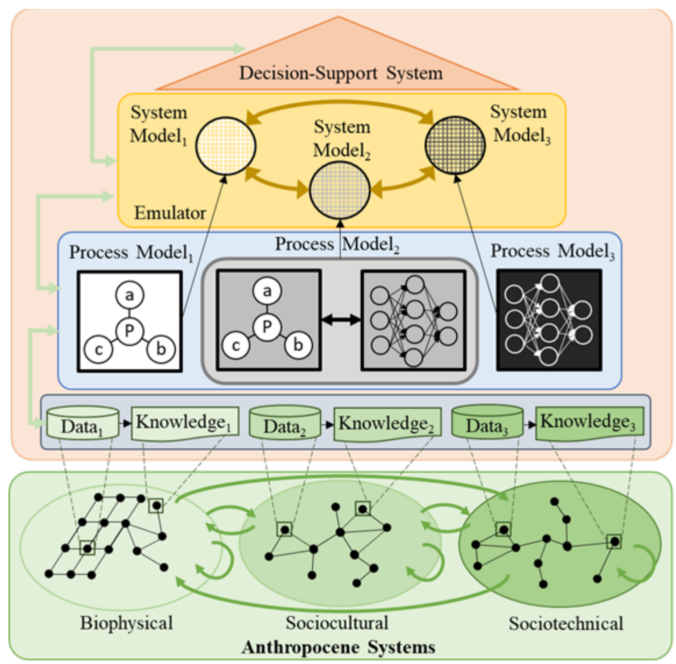


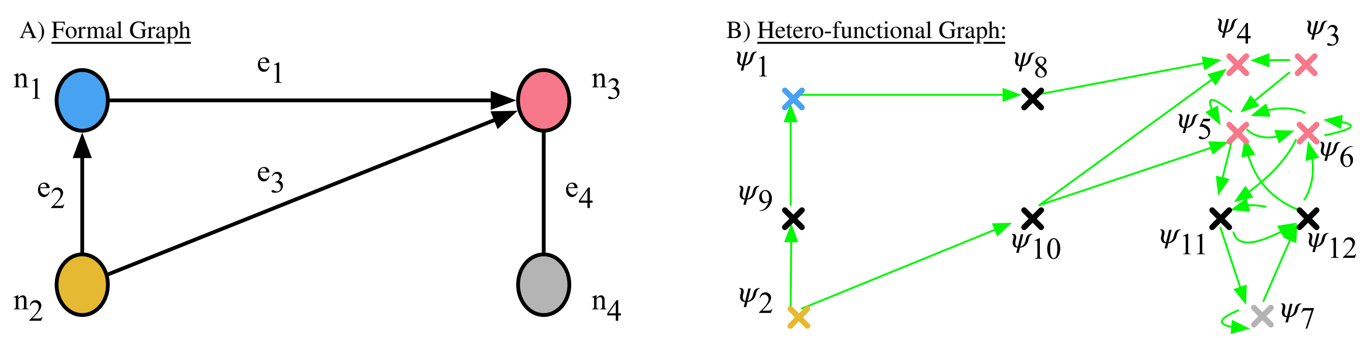
Figure 1. The agile systems-of-systems engineering computational framework and associated decision-support system.

Figure 1 illustrates our agile systems-of-systems engineering framework. The green box includes many interacting real-life systems including (1) biophysical systems such as ecosystems or hydrology; (2) sociocultural systems dominated by human behavior, decision-making and collective social dynamics such as political institutions and social networks; and (3) sociotechnical systems dealing with material interactions of social and biophysical systems such as infrastructure and agriculture [31]. Together, these interacting real-life systems constitute a *de-facto* SoS that requires concerted effort to understand and ultimately manage. To understand these systems and derive knowledge about them, domain experts and practitioners must apply their often-disparate perspectives, and represent these systems with their own ontologies, meta-data and mental models (purple box) [32]. From this multi-knowledge reality, practitioners use system-specific theoretical knowledge and data to develop process models (cyan box) as simulations of the underlying complex systems. Each process-level model P_i is a complex system built using system-specific theoretical knowledge and data. First-principles or mechanistic models are preferred (white box). In cases where the theoretical knowledge is insufficient, we can use theory-guided data science algorithms (grey box) to automatically extract patterns from data while incorporating the knowledge accumulated in scientific theories [33]. For systems where a comprehensive theoretical foundation is unavailable we can use data-based models (black box) until theoretical knowledge improves. In the context of the CBP discussed in Section I, these process models include land use, watershed, estuary, governance and economic models of the CBW. Unfortunately, the complex dynamics, feedback loops, and cascading effects of this *de-facto* SoS cannot be understood from simulating the uncoupled individual systems. Instead, we must converge their process models into an SoS convergence paradigm (yellow box) that reconciles the ontologies, meta-data and mental models inherent to their system-specific process-models [11, 28, 34]. This reconciliation must also make the models coherent across nested scales (e.g., local, urban, regional, global) and more reusable across the family of societal challenges [5]. Furthermore, to make this convergence paradigm actionable, it requires a computational framework that simulates the coupled SoS dynamics (yellow box) and a coupled decision-support system (orange box). Finally, this SoS computational framework is agile because it will need to be continually refined as new data and theory are introduced.

The complexity and computational cost of integrating many process-level models directly can be prohibitive, especially at the urban and regional scale, and when there is a need to run thousands of simulations to evaluate sensitivity and uncertainty and explore future scenarios. By creating simpler emulation models and coupling these at the system level (Figure 1), the interdependent dynamics of many individual systems can be captured [4, 5], providing vital information about system-level drivers that is almost never included in Anthropocene system models. Although the systems will be coupled at the system level, the knowledge in the process-level models will remain accessible (Figure 1, green arrows), allowing us to "drill down" to the process level and associated data and theoretical knowledge where the problem in the individual systems is characterized in greater detail, enabling iterative improvement in both process and system-level models.

Perhaps the greatest challenge in the development of this agile systems-of-systems engineering computational framework is the knowledge integration required when passing from the process models (in the cyan box) to the SoS models (in the yellow-box). Here, we propose to use SysML [35] as a meta-data management tool that ultimately specifies the reference architecture [36] of the system-of-systems as a whole. This includes: 1.) a description of system form with its associated classes, attributes, and interfaces, 2.) a description of system function with its associated actions and interactions, and 3.) their allocation of one to the other. Interestingly, the reference architecture can equally accommodate system functions based upon first-principle theoretical models as well as data-driven machine learning models. The process of developing such a reference architecture ultimately creates a coherent framework for managing meta-data throughout the entire system-of-systems model.

The translation from a SysML meta-data reference architecture to a SoS computational model is greatly facilitated by Hetero-functional Graph Theory (HFGT) [11, 34, 37, 38]. HFGT has been applied to numerous sociotechnical systems including electric power, water distribution, natural gas, oil, coal, hydrogen, transportation, manufacturing, and healthcare systems [34, 37, 39-45]. The recent HFGT text shows its ability to model an arbitrary number of systems of arbitrary size and topology connected to each other in an arbitrary manner [11, 34]. In contrast, the (formal) graphs and multi-layer networks in the network science literature have found numerous limitations [34, 46]. HFGT has been used to conduct analyses of system structure as well as simulations of system behavior [11, 34, 37-



Legend: **Nodes**: {$\mathbf{n_1}$-Water Treatment Facility, $\mathbf{n_2}$-Solar PV, $\mathbf{n_3}$-House with Rooftop Solar, $\mathbf{n_4}$-Work Location} **Edges**: {$\mathbf{e_1}$-Water Pipeline, $\mathbf{e_2}$-Power Line 1, $\mathbf{e_3}$-Power Line 2, $\mathbf{e_4}$-Road} **System Capabilities**: {ψ_1-water treatment facility treats water, ψ_2-solar PV generates electricity, ψ_3-house generates electricity, ψ_4-house consumes water, ψ_5-house charges EV, ψ_6-house parks EV, ψ_7-work location parks EV, ψ_8-water pipeline transports water from water treatment facility to house, ψ_9-power line 1 transports electricity from solar PV to water treatment facility, ψ_{10}-power line 2 transports electricity from solar PV to house, ψ_{11}-road discharges EV from house to work location, ψ_{12}-road discharges EV from work location to house}

Figure 2. Comparison of Formal Graphs and Hetero-Functional Graphs

46]. HFGT also distinguishes between physical and decision-making entities and explicitly admits centralized, hierarchical, decentralized, and collaborative decision-making structures conducive to the agent-based, sociocultural and sociotechnical phenomena that we find in Anthropocene systems. In addition to these many convergence-friendly benefits, HFGT relies on a simple but highly expressive ontology based on subject+verb+object sentences called “capabilities” that serve as nodes in hetero-functional graphs (HFGs). To a natural or engineering scientist, HFGs are able to reconstitute the conservation laws of matter and energy for systems with explicitly heterogeneous resource-subjects, process-verbs, and operands. To social scientists, the linguistic roots of HFGs provide a straightforward means of traversing the often-formidable gap between qualitative knowledge and quantitative models. To a systems engineering, HFGs are a quantitative representation of (an important subset of) SysML. Finally, to applied mathematicians HFGT builds upon extensive foundations in graph theory and tensor analysis. In short, HFGT has the potential to serve as an actionable convergence paradigm that not only brings together many disparate disciplines but also does so within a single computational framework.

We envision that this agile system-of-systems modeling framework will be used together with decision-support methods [29] to engage with communities through mutual social learning [30] and the co-production of knowledge. It could also be combined with integrated assessment [16], which is an established methodology to improve decision-making for complex societal problems. Integrated assessment synthesizes diverse knowledge, data, methods and perspectives, including approaches such as participatory modeling, stakeholder engagement, adaptive management, and scenario analysis to characterize hypothetical future pathways. In addition, problems involving Anthropocene systems are characterized by deep uncertainty and many approaches to decision-making under deep uncertainty have been developed to enable quantitative analyses that support deliberation among multiple parties [47]. These methods generally identify robust or low regret management strategies that perform well across a wide range of uncertain conditions.

Thus, our computational framework and associated decision-support system could be used in Anthropocene systems. For example, in the CBW it can be used to help maintain an economically viable food production system while also managing pollution and climate impacts in the face of high costs and limited space for urban flood management technologies. In this way, it could help CBW stakeholders identify more sustainable approaches to these multidimensional problems with alternatives like “sponge” cities that increase water storage throughout the watershed, and with combined social and economic incentives to re-build away from flood-prone areas.

IV. Conclusion

As discussed in Section I, researchers addressing societal challenges tend to begin with their own subsystem and incrementally add a few interactions to a few other subsystems. Such incremental approaches ignore the dynamics of the larger systems and entirely overlook the fact that the societal challenges are interdependent. This fragmented approach to science is paralleled in policy circles, where government agencies invest in modeling at scales that are incompatible with the approaches needed to tackle the societal challenges. In addition, while it is increasingly recognized that the integration of multiple systems is necessary, current integrative approaches have yet to converge, and are potentially confusing.

The proposed agile system-of-systems engineering framework provides a fresh perspective on an entire family of societal challenges of the Anthropocene. In addition, we focus on the evolution of actual systems that are the traditional focus of many engineers (examples include land use, watersheds, transportation, agriculture, forestry, mining, infrastructure, energy, climate, and ecosystems). We then show how these traditional systems of interest can be connected to a wide range of other important sociocultural (e.g., communication, economic, legal, political and other social systems) and sociotechnical systems in a coherent and systematic way.

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