2021 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm)

2021 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm) | 978-1-6654-1502-6/21/$31.00 ©2021 IEEE | DOI: 10.1109/SMARTGRIDCOMM51999.2021.963

A Multigraph Modeling Approach to Enable Ecological Network Analysis of Cyber Physical Power Networks

Abheek Chatterjee,* Hao Huang, *Student Member, IEEE*†,
Katherine R. Davis, *Senior Member, IEEE*†, Astrid Layton*
*Department of Mechanical Engineering Texas A&M University, College Station, TX, USA
†Department of Electrical and Computer Engineering Texas A&M University, College Station, TX, USA
Email: achatt31@tamu.edu, hao_huang@tamu.edu, katedavis@tamu.edu, alayton@tamu.edu

***Abstract*—The design of resilient power grids is a critical engineering challenge for the smooth functioning of society. Bio-inspired design, using a framework called the Ecological Network Analysis (ENA), is a promising solution for improving the resilience of power grids. However, the existing ENA framework can only account or for one type of flow in a network. Thus, the previous applications of ENA in power grid design were limited to the design and evaluation of the power flows only and could not account for the monitoring and control systems and their interactions that are critical to the operation of energy infrastructure. The present work addresses this limitation by proposing a multigraph modeling approach and modified ENA metrics that enable evaluation of the network organization and comparison to biological ecosystems for design inspiration. This work also compares the modeling features of the proposed model and the conventional graphical model of Cyber Physical Power Networks found in the literature to understand the implications of the different modeling approaches.**

***Index Terms*—Cyber-Physical Power Networks, Ecological Network Analysis, Bio-Inspired Design, Network Modeling**

I. Introduction

Modern power grids consist of distinct but interdependent cyber and physical interactions between its constituent systems, to ensure its reliability and economics. The cyber and physical interactions are highly overlapping to support each other's operation [1]. However, due to this interdependence, a disruption in one domain can propagate to the other domain, causing cascading failures. Recent incidents of cyber and physical attacks on energy infrastructure highlight the importance of evaluating power grids' structural and functional characteristics from the *overall* cyber-physical perspective [2], [3]. An overall evaluation of Cyber-Physical Power Networks (CPPN) can provide more situational awareness for operators to better understand the current state and prepare against contingencies.

Different situational awareness methods have been proposed in the literature. Work from refs. [4], [5] ranks the importance of power system components based on the cyber attack paths in cyber network and the impact on physical network. Umunnakwe et al. used the cyber network topology and component vulnerabilities to represent a weighted graph and ranked the device's risk using the betweenness centrality metric [6]. Such analyses can provide an understanding of how important a device is, but it does not capture the overall

978-0-7381-3184-9/21/33.00/$31.00 ©2021 IEEE

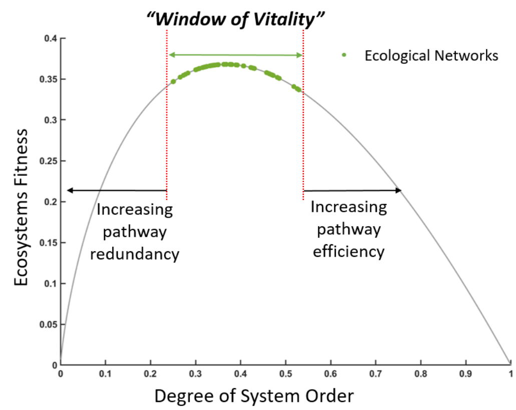

Fig. 1: The window of vitality observed for ecological networks (data from [7]), showing a unique balance of pathway efficiency and redundancy. Figure based on ref. [8].

structural and functional characteristics of the CPPN. A framework that can account for the multiple types of interactions in the CPPN, and evaluate the architectural organization of the network would provide greater insights for the design of reliable and resilient CPPN.

Previous work by this research team proposed Ecological Network Analysis (ENA) as a framework for the design and evaluation of power grids [9], [10]. ENA is a tool used by ecologists to study the complex interactions among species in ecosystems by modeling them as flow networks. ENA provides a set of metrics to study the structural and functional characteristics of ecological networks [11]. Degree of System Order (*DoSO*) is an ENA metric (ranging between zero and one) that indicates the trade-off between *pathway efficiency* (*DoSO* = *1*) and *pathway redundancy* (*DoSO* = *0*) in a flow network [12]. Ecologists have found that long-surviving ecosystems have evolved to avoid both these extremes, maintaining a unique range of *DoSO* (centered around ≈ 0.4) called the 'Window of Vitality' (WoV) that favors pathway redundancy slightly more than efficiency (see Fig. 1) [8], [13], [14]. The fact that ecosystems avoid extreme *DoSO* values suggests that those may be *unfit* for survival and evolution. Networks with values of *DoSO* close to zero are hypothesized to utilize resources ineffectively for survival, while networks with *DoSO* values close to one are vulnerable to perturbations.

A unique balance between efficient and redundant pathways allows ecosystems to be flexible enough to survive and recover from perturbations, while still effectively utilizing resources for survival under normal conditions [8], [14].

The analogy between caloric transfers (predator-prey relationships) in biological food webs and power flows in a power grid was used to model electric power grids in the ENA framework and design power grid architectures that have DoSO within (or close to) the ecological WoV [9], [10]. That work showed that bio-inspired grid designs experienced significantly fewer violations in various disruption scenarios compared to traditional configurations. While the results were promising, the study could not account for the monitoring and control systems and their interactions that are critical to the operation of the power grid. This was because the existing ENA framework is set up to only consider one type of flow between actors in a network. The present work addresses this limitation by proposing a novel *multigraph model* of CPPN that enables evaluation of the network organization and comparison to biological ecosystems for design inspiration. The modeling decisions for the proposed multi-graph model are discussed in detail and compared to previously studied ENA models [9], [10] of power grids and the conventional graphical model of CPPN found in the literature [15]. Finally, The proposed framework is used to analyze the organizational differences between two possible architectures of a hypothetical 3-substation CPPN.

II. Ecological Network Analysis

Before discussing the proposed ENA model for networks with multiple flow types, a brief discussion of the existing ENA framework is warranted. The first step in ENA is modeling the network (ecosystem) as a flow digraph (or directional graph). The nodes in the digraph represent the species and the directed arcs represent the transfer of energy or nutrients between them and their immediate environment. The flows between the actors (or nodes) within the system boundaries as well as the system inputs, outputs and dissipation exchanged with the environment are all stored in the flow matrix **T** (see Fig. 2). The elements T_{ij} of the matrix represent the flows from node i to node j.

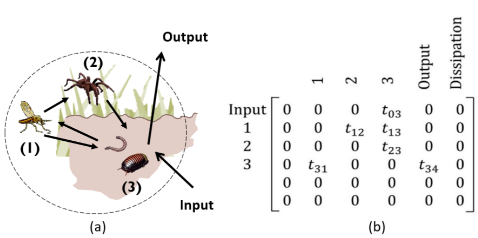

Fig. 2: A schematic of the modeling procedure used in ENA, describing the (a) hypothetical food web as a (b) flow matrix. Figure based on ref. [16]

The $DoSO$ and R_{eco} metrics are calculated from the flow matrix described above. A more pathway constrained/organized network is more efficient at transferring flows between two points in the network. The level of network pathway organization or constraints is measured using the metric Average Mutual Information (*AMI*, Eq. 1). The upper limit upper limit on the organizational development of a flow network is indicated by the Shannon Index (H, Eq. 2). The ratio of *AMI* to *H* quantifies the relative pathway efficiency of a flow network that is the *DoSO* metric (Eq. 3). Finally, Ecosystems fitness (R_{eco}, Eq. 4) was formulated as a function of *DoSO* to mathematically describe this ecological principle: minimal fitness at the extremes of *DoSO*, and peak fitness inside the WoV. Evaluation of *AMI* and *H*, first requires supporting calculations given by Eq. 5. The total magnitude of flow through the network is quantified by the metric Total System Throughput (TST_p), and the magnitudes of flow in and out of each node are given by the node throughputs ($T_{i.}$, and $T_{.j}$). Additionally, while using Eqs. 1- 2, the terms with $T_{ij} = 0$ (no flow) should be treated as zero. This follows from the fact that $\lim_{x\to 0^+} x log_b(x) = 0$, where x is an infinitely small positive real number and b is the base of the logarithm ($b \in R^+$ & $b \neq 1$).

$$AMI = \sum_{i=0}^{N+2}\sum_{j=0}^{N+2} \frac{T_{ij}}{TST_p} log_2[\frac{T_{ij}\cdot TST_p}{T_{i.}\cdot T_{.j}}] \quad (1)$$

$$H = -\sum_{i=0}^{N+2}\sum_{j=0}^{N+2} \frac{T_{ij}}{TST_p} log_2[\frac{T_{ij}}{TST_p}] \quad (2)$$

$$DoSO = \frac{AMI}{H} \quad (3)$$

$$R_{eco} = -DoSO\ ln(DoSO) \quad (4)$$

Where,

$$TST_p = \sum_{i=0}^{N+2}\sum_{j=0}^{N+2} T_{ij};\quad T_{i.} = \sum_{j=0}^{N+2} T_{ij};\quad T_{.j} = \sum_{i=0}^{N+2} T_{ij} \quad (5)$$

This existing ENA framework has proven to be a promising design tool for various engineering applications in addition to its previous power grid applications. The *DoSO* and R_{eco} metrics have been used to analyze industrial networks [17], improve the robustness of water distribution networks [18], and shown to be able to guide System of Systems design towards desirable resilience and affordability trade-offs [19], [20]. However, it is currently limited to analyzing networks with only one type of flow. The next section details the proposed framework for *DoSO* and R_{eco} evaluation in networks with multiple types of flows.

III. Proposed Multigraph Model

Figure 3 shows the typical systems and interactions in a CPPN using a hypothetical 3-substation case study. The CPPN consists of the physical systems, cyber systems, and cyber physical connections between them. The physical systems include buses, generators, loads, branches, etc. to generate and distribute energy to the end users. The cyber systems include communication devices, such as routers, firewalls, etc., that

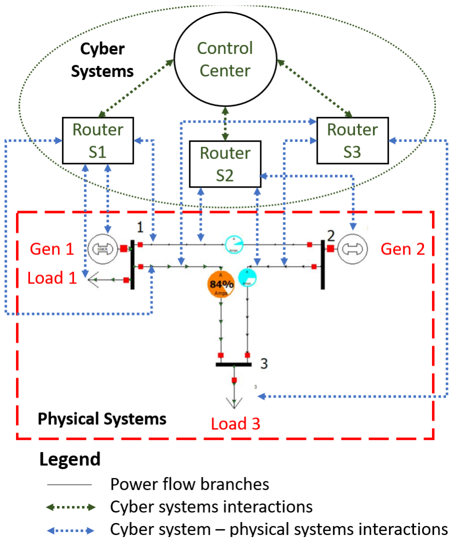

Fig. 3: The general features of a Cyber Physical Power Network shown using a hypothetical 3-substation case study.

will concentrate data from the physical network to the operators for processing and operating the system securely, reliably, and economically. For simplification, a router node is used to represent all communication devices. The connection between the routers and the physical systems form the cyber physical connection. This connection is achieved using programmable logic controllers (PLCs) built in to the physical systems. PLCs can act as smart meters, and protective relays that have the capability to communicate with other communication devices. All data is sent to the control center (through the routers) for processing and deciding regulatory actions.

CPPNs, like the example described above, can be understood as System of Systems: networked integration of *heterogeneous* and *independent* constituent systems that together produce capabilities that cannot be obtained by using any of the constituent systems alone [21], [22]. The constituent systems such as the generators, transmission systems (branches), and the control center serve useful purposes on their own and are integrated to fulfill the goal of reliable power supply to the end-users. The overall behavior of the power grid *emerges* from the interactions between the constituent systems. The constituent systems interact using *multiple distinct but interdependent flows*: power flows, state information flows, and control information flows. Power flows are self-explanatory: they are the flows of electrical power between the physical systems. The state information flows contain information regarding the operation of the physical systems (such as power generated) collected by the metering devices. The control center processes the state information received to decide control actions for the physical systems. The dissemination of these control decisions to the physical systems is represented using the control information flows. A multigraph is a suitable tool for describing and modeling such interactions. The following general procedure can be used to develop the multigraph model of the CPPN:

1) Identify constituent systems (nodes).
2) Add directed links between the physical systems representing the real power flows between them under normal operation. The magnitude and direction of these flows can be can be simulated using the PowerWorld Simulator [23] (discussed in detail in the authors' prior work [9], [10]).
3) Assign a value to a quantum of complete state information flows (say 5 units) for each physical system. Add flows links of the same magnitude from each physical system to their routers. It will be discussed later that this assumption does not affect the evaluation of network organization.
4) Check if routers are designed to communicate with each other. If yes, add links between routers with flow values equal to the amount of state information originally received from physical systems.
5) Model redundant state information streams at the router as dissipation and add one link modeling the transfer of one stream of total information collected at each router to the control center.
6) At the control center, model redundant streams of state information as dissipation. Model one stream of state information that will be productively used as export flow.
7) Import an equivalent amount of control information to the control center (this models the *transformation* of flow).
8) Add control information flow links from control center to routers. Assign the magnitude of each flow link to be equal to the number of physical systems connected to that router and any routers communicating with it.
9) If routers communicate with each other - add links to model the redundant sharing of control information. Set magnitude of these flows equal to the amount of control information received by the source router from the control center and useful to the sink router.
10) Model redundant control information streams at the routers as dissipation. Add links between each router and their connected physical systems and assign values equal to one quantum of control information.
11) Model an export of control information at the physical systems indicating productive use of control information for regulation. Model any redundant control information streams as dissipation out of the physical systems.

The multigraph model for the hypothetical 3-substation CPPN presented in Fig. 3 is developed using the steps described above and presented in Fig. 4. The multigraph model can be described using a 3 dimensional flow matrix where any element T_{ijl} represents the flow of type l from node i to node j. To facilitate the *DoSO* (and R_{eco}) evaluation of the overall network, the modified *AMI* and *H* metrics, shown in Eqs. 6 and 7, are proposed. The symbols in the metrics have the same meanings as described in section II and the new subscript l is used as an index for the different flows between from node i to node j. Once AMI and H are calculated using the modified metrics, DoSO and R_{eco} can be calculated using Eq. 3 and 4. The formulation of these modified metrics is described in detail in [24]. The modified metrics have previously been used to analyze supply chains with multiple physical flows [25] and surveillance networks with multiple information flows [26].

$$AMI = \sum_{i=0}^{N+2} \sum_{j=0}^{N+2} [\prod_{l} (\frac{T_{ijl}}{TST_{pl}})] \cdot log_2 [\prod_{l} (\frac{T_{ijl} \cdot TST_{pl}}{T_{i.l} \cdot T_{.jl}})] \tag{6}$$

$$H = - \sum_{i=0}^{N+2} \sum_{j=0}^{N+2} [\prod_{l} (\frac{T_{ijl}}{TST_{pl}})] \cdot log_2 [\prod_{l} (\frac{T_{ijl}}{TST_{pl}})] \tag{7}$$

IV. Discussion

Three unique features of the proposed model warrant further discussion: (a) *Unbalanced* information flows, (b) *transformation* of flows, and (c) *scale invariance*.

ENA typically requires flow balance of physical flows at all nodes (other than import, export, and dissipation) based on the laws of conservation of mass and energy. However, information flows are not bound by the same conservation laws as physical flows: New information can be generated and existing information can be copied (redundant communication pathways). For instance, the metering devices output information about the operation of the physical systems they are built-in to. Adding an import to balance these flows is not meaningful because this information is not received from the external environment, rather it is generated at the node. In addition, the calculation of the AMI and H metrics (that are used for $DoSO$ and R_{eco} evaluations) do not require flow balance at all nodes. Therefore, unbalanced flows are theoretically acceptable in the model as long as they do not violate physical laws of the network under consideration. The power flows are always balanced at each constituent system (node) but information flows are not necessarily balanced.

Another distinguishing feature of the proposed model is the modeling of the *transformation* of flows from one type to another using export and import flows. This feature can be observed at the control center. The control center receives state information regarding the physical systems (including redundant information streams). Part of the information received is *productively processed* by the control center and this is modeled using an export flow of state information at the control center (straight arrow leaving the system boundary in Fig. 4). The redundant information input is not utilized under normal operation and that is modeled as dissipation flow of state information at the control center (curly arrow leaving the system boundary in Fig. 4). The processing of state information results in the *transformed* control information. This is modeled as an import flow of control information at the control center (straight arrow entering the system boundary in Fig. 4).

Finally, modelers may use different units/scales for different flows. However, such a modeling decision should not affect the architecture evaluation. The proposed model has been tested to not be affected by the unit/scale selection of one (or more) type(s) of flow. For instance, a quantum of state/control information for one physical system was set as 5 units in section III. However, a modeler could set each of them as 10 units or 1 units without affecting the results. Given that for each type of flow, the flow magnitudes are modeled logically (do not violate network/flow rules) the proposed model will return the same *DoSO* (and R_{eco}) values for a network regardless of the unit/scale chosen for a type of flow.

The proposed multi-graph model was used to evaluate the ENA metrics of interest for two possible architectures of the 3-substation CPPN case-study:

1) The control center and routers are connected in a *star* topology: Each router is connected only to the control center. This is the architecture shown in Figs. 3 and 4.
2) The control center and routers are connected in a *mesh* topology: The routers are connected to each other as well as the control center.

TABLE I: 3-Substation Cyber-Physical Network Architecture Evaluation Using Ecological Metrics

Network	AMI	H	DoSO	Reco
Power Flows Network (proposed model)	2.858	3.488	0.819	0.164
Previously studied Power Flows Network ENA Model [9], [10]	1.962	2.869	0.684	0.26
State Information Flows Network (Star topology)	2.009	3.316	0.606	0.304
Control Information Flows Network (Star topology)	2.372	4.373	0.542	0.332
Overall Cyber-Physical Power Network (Star topology)	6.704	10.332	0.649	0.281
State Information Flows Network (Mesh topology)	1.320	3.699	0.357	0.368
Control Information Flows Network (Mesh topology)	1.337	4.616	0.290	0.359
Overall Cyber-Physical Power Network (Mesh topology)	4.744	9.014	0.526	0.338

The biological ecosystems studied using ENA were found within the DoSO range of $\approx$ 0.25 to 0.53 and R_{eco} values between $\approx$ 0.34 to 0.367 [7]. A network with DoSO within this range would be considered to have an ecologically-similar organization. Networks with $DoSO \gtrapprox 0.53$ would be classified as more pathway efficient than biological ecosystems, and networks with $DoSO \lessapprox 0.25$ would be considered more pathway redundant than biological ecosystems.

The single flow layer level analyses showed that the two *star* topology based information flow networks had slightly more pathway efficiency (see Table I) compared to the biological ecosystems. The *mesh* topology based state information flow network and control information flow layers were found to have ecologically similar network organization. Finally, the power flow network (same in both architectures) was observed to be the most pathway efficient network layer. This analysis indicates that the power flow network was most vulnerable to disruptions amongst the three flow layers in the CPPN. Analysis of the overall CPPN showed that the *star* topology

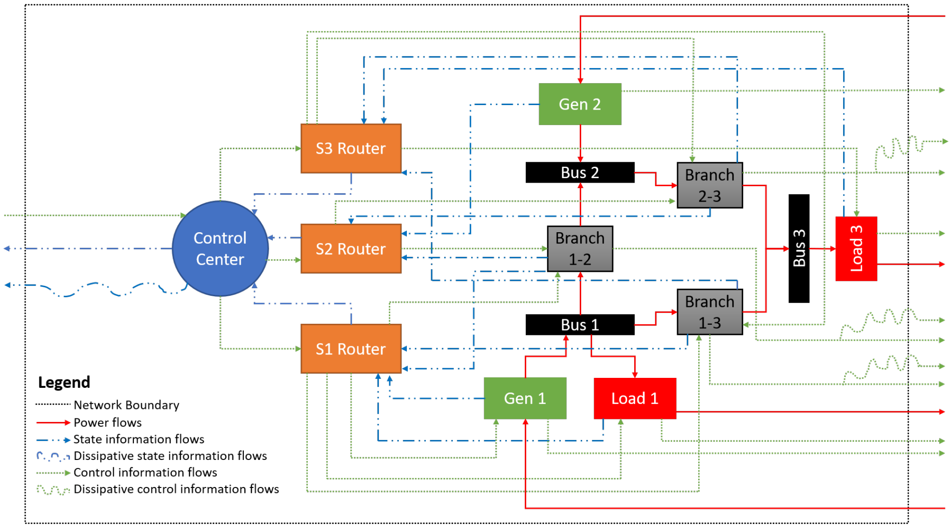

Fig. 4: The proposed multi-graph model of the 3-substation Cyber Physical Power Network case-study. Flows entering the system boundary are imports and flows leaving the system boundary are export (straight arrows) or dissipation (curly arrows).

based architecture was more pathway efficient than biological ecosystems. The added pathway redundancy of the information flow layers in the *mesh* topology-based architecture shifts the overall DoSO to just within the ecological window of vitality range, making it significantly more ecologically-similar than its *star* topology-based counterpart. This indicates that it is more suited to survive and adapt to perturbations. However, even with the added pathway redundancy of the information flow layers, the high level of constraints in the power flow layer leads to the overall CPPN being borderline pathway efficient with respect to the window of vitality.

The loads and the branches (transmission systems) play essential roles in the CPPN and they possess a certain level of operational independence: For instance, a branch or a load can be disconnected from the network in the case of a power surge. As such they should be treated as constituent systems in the overall System of Systems and modeled as nodes in the network. In addition, there are information flows to and from these physical systems to the routers. In any network model, links should exist between two nodes and not between a node and another link. Because of these reasons the branches and loads are described as nodes in the proposed multigraph model. This is a point of difference between the proposed model and previous ENA models of the power grid [9], [10] that modeled branches as links and loads as export flows. This approach neglected to consider the constraint that the power flow must go through these systems for successful operation that adds points of failure in the network. The ENA model of the CPPN proposed in this work was compared to the previously studied power flow network ENA models and it was seen that accounting for branches and loads as nodes in the networks makes the power flows more pathway efficient (see Table I) indicating they may be more vulnerable to disruptions than previously realized.

The proposed multi-graph model of the CPPN is also compared to the conventional graphical model of CPPN in the literature [15], where the nodes are classified into two categories: cyber and physical (see Fig. 3). The interaction between the cyber nodes results in the cyber network layer and the interactions between the physical nodes results in the physical network layer. There are also inter-layer interactions between nodes in these two layers that represents the inter-dependency between the two layers. The primary distinction between the conventional approach and the proposed approach is that the proposed model classifies flow types instead of node types. This distinction leads to two different models of the same CPPN.

TABLE II: 3-Substation Cyber-Physical Power Network Analysis Using Topological Metrics.

Network	$\bar{d}$	$\bar{c}$	$\bar{l}$	$\bar{b}$
Cyber Network	3	0	1.5	0.25
State Information Flows Network	2.364	0	0.245	0.007
Control Information Flows Network	2.364	0	0.245	0.007

To understand the implications of two different modeling approaches for CPPN design evaluation, the cyber network in the conventional model of the 3-substation CPPN was compared to the state information flow network layer and the control information flow network layer from the proposed multi-graph model of the 3-substation CPPN. Only the star topology based architecture was used in this analysis. The networks were compared using four metrics commonly used in the literature for topological analysis of cyber networks: average node degree ($\bar{d}$), clustering coefficient ($\bar{c}$), average shortest path ($\bar{l}$), and average betweenness centrality measures ($\bar{b}$) [27]. The results of this analysis are presented in Table II.

A significant difference was observed between the topological metrics calculated for the cyber network from the conventional model and the the two information flow networks from the proposed model (except for the clustering coefficient). This difference was attributed to the fact there are more nodes in the later networks and a lower density of connections. Thus, different modeling choices will provide different evaluation perspectives for CPPNs. In addition, the two flow network layers from the proposed model had identical values of these topological metrics. While the topological metrics are useful, they can only assess the structure of the network, whereas the ENA metrics (like $DoSO$ and R_{eco}) can also capture the subtle functional differences amongst networks with the same topology (to an extent) - as can be seen from the different values of the ENA metrics for the two information flow network layers in Table I

V. Concluding remarks

The article proposed a multigraph-based modeling approach and modified ENA metrics that enable the evaluation of CPPN's architectural organization and comparison to biological ecosystems for design inspiration. Unlike refs. [9], [10], [28], that only modeled one *homogenous* flow in either the cyber or physical network, the proposed model includes the *heterogeneous* flows between cyber and physical systems. The proposed modeling approach was shown to be able to distinguish between different CPPN architectures using a hypothetical 3-substation CPPN case study. Further work is needed to validate the value of the proposed framework by testing different architectures using contingency analyses as presented in [29]. Finally, while the multi-graph model was proposed here for CPPNs, it has the potential to be a valuable tool for the architectural design and evaluation of a variety of System of Systems including pipeline distribution infrastructure and aerospace operation networks

Acknowledgment

This work received financial support from the Systems Engineering Research Center under contract WRT-1027.

References

[1] M. Korkali, J. G. Veneman, B. F. Tivnan, J. P. Bagrow, and P. D. Hines, "Reducing cascading failure risk by increasing infrastructure network interdependence," *Scientific reports*, vol. 7, no. 1, pp. 1–13, 2017.

[2] D. U. Case, "Analysis of the cyber attack on the ukrainian power grid," *Electricity Information Sharing and Analysis Center (E-ISAC)*, 2016.

[3] I. Ivanova, "Texas winter storm costs could top $200 billion - more than hurricanes harvey and ike," Feb 2021. [Online]. Available: https://www.cbsnews.com/news/texas-winter-storm-uri-costs

[4] K. R. Davis, C. M. Davis, S. A. Zonouz, R. B. Bobba, R. Berthier, L. Garcia, and P. W. Sauer, "A cyber-physical modeling and assessment framework for power grid infrastructures," *IEEE Transactions on smart grid*, vol. 6, no. 5, pp. 2464–2475, 2015.

[5] H. Huang and K. Davis, "Power system equipment cyber-physical risk assessment based on architecture and critical clearing time," in *2018 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm)*. IEEE, 2018, pp. 1–6.

[6] A. Umunnakwe, A. Sahu, M. R. Narimani, K. Davis, and S. Zonouz, "Cyber-physical component ranking for risk sensitivity analysis using betweenness centrality," *IET Cyber-Physical Systems: Theory & Applications*, 2021.

[7] S. R. Borrett and M. K. Lau, "enar: An r package for ecosystem network analysis," *Methods in Ecology and Evolution*, vol. 5, no. 11, pp. 1206–1213, 2014.

[8] B. D. Fath, "Quantifying economic and ecological sustainability," *Ocean Coastal Management*, vol. 108, pp. 13–19, 2015.

[9] V. Panyam, H. Huang, K. Davis, and A. Layton, "Bio-inspired design for robust power grid networks," *Applied Energy*, vol. 251, p. 113349, 2019.

[10] H. Huang, V. Panyam, M. R. Narimani, A. Layton, and K. R. Davis, "Mixed-integer optimization for bio-inspired robust power network design," in *2020 52nd North American Power Symposium (NAPS)*. IEEE, 2021, pp. 1–6.

[11] R. E. Ulanowicz, "Quantitative methods for ecological network analysis," *Computational Biology and Chemistry*, vol. 28, no. 5, pp. 321–339, 2004.

[12] R. E. Ulanowicz, S. J. Goerner, B. Lietaer, and R. Gomez, "Quantifying sustainability: Resilience, efficiency and the return of information theory," *Ecological Complexity*, vol. 6, no. 1, pp. 27–36, 2009.

[13] A. C. Zorach and R. E. Ulanowicz, "Quantifying the complexity of flow networks: How many roles are there?" *Complexity*, vol. 8, no. 3, pp. 68–76, 2003.

[14] R. E. , "The dual nature of ecosystem dynamics," *Ecological Modelling*, vol. 220, no. 16, pp. 1886–1892, 2009.

[15] R. V. Yohanandhan, R. M. Elavarasan, P. Manoharan, and L. Mihet-Popa, "Cyber-physical power system (cpps): A review on modeling, simulation, and analysis with cyber security applications," *IEEE Access*, vol. 8, pp. 151 019–151 064, 2020.

[16] A. Layton, B. Bras, and M. Weissburg, "Ecological principles and metrics for improving material cycling structures in manufacturing networks," *Journal of Manufacturing Science and Engineering*, vol. 138, no. 10, pp. 101 002–101 002–12, 2016.

[17] ——, "Ecological robustness as a design principle for sustainable industrial systems," in *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, vol. Volume 4: 20th Design for Manufacturing and the Life Cycle Conference; 9th International Conference on Micro- and Nanosystems, Volume 4: 20th Design for Manufacturing and the Life Cycle Conference; 9th International, 2015, p. V004T05A047.

[18] T. Dave and A. Layton, "Designing ecologically-inspired robustness into a water distribution network," *Journal of Cleaner Production*, vol. 254, p. 120057, 2020.

[19] A. Chatterjee, R. Malak, and A. Layton, "Exploring system of systems resilience versus affordability trade-space using a bio-inspired metric," *Journal of Computing and Information Science in Engineering*, vol. 21, no. 5, 2021.

[20] ——, "Ecology-inspired resilient and affordable system of systems using degree of system order," *Systems Engineering*, 2021.

[21] M. W. Maier, "Architecting principles for systems-of-systems," *Systems Engineering*, vol. 1, no. 4, pp. 267–284, 1998.

[22] M. Jamshidi and A. P. Sage, *System of systems engineering: innovations for the 21st century*. John Wiley Sons Incorporated, 2009, vol. 58.

[23] J. Duncan Glover, M. Sarma, and T. Overbye, *Power System Analysis and Design*, 5th ed. Cengage Learning.

[24] A. Chatterjee and A. Layton, "Bio-inspired human network design: A multi-currency robustness metric inspired by ecological network analysis," in *ASME 2019 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, vol. Volume 7: 31st International Conference on Design Theory and Methodology, Conference Proceedings.

[25] ——, "Mimicking nature for resilient resource and infrastructure network design," *Reliability Engineering System Safety*, vol. 204, p. 107142, 2020.

[26] A. Chatterjee, R. Malak, and A. Layton, "A bio-inspired framework for analyzing and predicting the trade-off between system of systems attributes," in *Conference on Systems Engineering Research*. Virtual, Online, October 8-10, 2020, 2020, Conference Proceedings.

[27] B. Bollobás, *Modern graph theory*. Springer Science & Business Media, 2013, vol. 184.

[28] H. Huang, A. Chatterjee, A. Layton, and K. Davis, "An investigation into ecological network analysis for cyber-physical power systems," in *Submitted to 2021 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm)*. IEEE, 2021, pp. 1–6.

[29] S. Zonouz, C. M. Davis, K. R. Davis, R. Berthier, R. B. Bobba, and W. H. Sanders, "Socca: A security-oriented cyber-physical contingency analysis in power infrastructures," *IEEE Transactions on Smart Grid*, vol. 5, no. 1, pp. 3–13, 2014.