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Acquisition and Development Programs Through the Lens of System Complexity

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Abstract

The approach of the Department of Defense (DoD) to acquisition programs is strongly based on systems engineering. DoD Directive 5000.01 calls for “the application of a systems engineering approach that optimizes total system performance and minimizes total ownership costs” (DoD, 2007). Even when systems engineering best practices are employed, the cost of large systems is always increasing, and a large part of this increase is due to system complexity (Arena et al., 2008).

Part of this system complexity comes from the functionalities of the system, and is thus justified when these functionalities are required. The remaining contribution is due to unnecessary intricacies in the design, to local optimization, and to oversight in the system-level design. This complexity can lead to rising cost and schedule delays, and should be addressed properly. To overcome these issues regarding cost and schedule overruns, researchers have advocated for the adoption of a complexity budget (Sinha, 2014), which can help identify the effects of unintended interfaces between system elements. While most literature seems to agree about the existence of this issue, the solutions to the measurement of complexity are various and based on different approaches.

The purpose of this research is to develop metrics that will allow the DoD to evaluate a complexity budget, particularly in the phases of architecture and design development. The metrics are developed using a set of axioms that can be applied to cyber-physical systems, and they assume that the architecture of the system is known. Knowledge of the system architecture allows for a graph representation of the system and uses graph-theoretic approaches to the evaluation of the topology of the system. Concepts such as graph density and graph energy can be used to build metrics that allow to rank architectures, thus helping identify possible sources of complexity. Additionally, this approach allows engineers to look external to the system to identify the complexity required to interoperate with legacy DoD systems and systems under development. This research effort is limited to a snapshot of the

state of the system, but can be extended to a dynamical approach with a system changing state or changing its structure.

Introduction

Complexity in engineered systems is a double-edged sword. Part of it is due to the functionalities of the system, and part of it to the unnecessary intricacies which deviate the final design from an elegant solution, the optimal one. The excess complexity in engineered systems can potentially contribute to increased partial or systemic risks and increased fragility of the system in face of various shocks and environmental changes.

The first attempts at heavier-than-air flight were carried out by small teams of people that we would today call innovators. The goal of those systems was to achieve leveled flight over a relatively short distance. As time passed, the requirements for airplanes increased in almost all the applications, from military to commercial flight. The need to carry cargo, payloads, or passengers over increasing distances, in shorter time, at a viable cost, safely, and reliably has led to an increase in the complexity of these systems over the last 100 years. As a result, today's airplane manufacturers employ tens of thousands of people, and have a hierarchy of suppliers with an even larger total workforce. In addition, the development time for a new program has also increased due to the overall increase in complexity.

Airplanes are only one of the many examples of engineered systems where an increase in complexity is connected to an increase in cost as well as increased fragility and risks of the system. The costs associated with larger complexity are justified only when they are dictated by system requirements. These design decisions can contribute to the functionality of the system (i.e., functional requirements), or increase system-level characteristics such as resilience, reliability, or safety (i.e., non-functional requirements). According to Carlson and Doyle (2002), robustness is the maintenance of desired characteristics despite the failure or partial performance of some components of the system, and is correlated with complexity. As long as there is a reason for a design decision, and there cannot be a simpler solution obtaining the same effect at the system level, the increase in complexity is justified. When the increase in complexity is unintended and contributes to system fragility, then the design solution is not optimal and should be avoided or modified. Unfortunately, to determine the optimality of a design solution, it is necessary to have a deep knowledge of the specific application field, and to have a large set of possible solutions for comparison.

The Department of Defense (DoD) faces challenges in managing complexity, integration, and management of the complex network of systems that it has developed over the past 30 years. In 1996, the Vice Chairman of the Joint Chiefs of Staff proposed warfighting capability would be more reliant on systems of systems (SoS) and network centric operations (Owens, 1996). As such, DoD systems are becoming more and more complex, interconnected, and reliant on other systems to provide capability to the user. This creates a complex environment in which systems connect to each other through a variety of means that may not be initially evident to systems engineers. When these systems operate on the battlefield, they often cross service boundaries, but their development within the service makes collaboration difficult in traditionally hierarchal military structures (Dahmann & Baldwin, 2008). Additionally, the Government Accountability Office (GAO; 2015) found that the DoD lacked methods and tools for conducting portfolio management at the enterprise level for capabilities, and noted that there were gaps in the DoD’s ability to identify, understand, and assess the capability portfolio.

This paper presents and builds on a complexity theory, network analysis, and systems engineering to propose a method to understand the complexity budget of a network of systems. It examines how the addition of a new system to a network of legacy systems affects the complexity of the network. As an example, the paper examines the addition of the F-35 Joint Strike Fighter (JSF) to the network of DoD systems and its effect on the complexity of the network. It examines the complexity of the network before the DoD fielded F 35A/B/Cs, during the transition to the JSF, and post deployment after the DoD replaced the legacy systems with the F-35 variants.

Literature Review

This section presents a review of the relevant literature to include a discussion on systems engineering, complexity theory, and network analysis. The portion on systems engineering focuses on the foundation of systems engineering and the application of the ilities to help engineers manage complexity and the non-functional attributes of engineered systems. Additionally, the literature review includes a discussion on complexity theory and the impact of increases in technology and reliance on other systems. Finally, the literature provides an overview of network analysis techniques that serve as a basis for the quantification of complexity and analysis of the network of DoD systems.

Systems Engineering

As a discipline, systems engineering faces increased complexity of systems as technology progress and systems are more interconnected. In 2006, a workshop consisting of thought leaders from a variety of disciplines met to discuss the issue of complex systems, and one area that received substantial attention was the modeling of complex systems with an emphasis on the dynamic, networked nature of systems (Rouse, 2007). International Council on Systems Engineering (INCOSE) defines Systems Engineering as “an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem” (INCOSE, 2007).

Systems engineers differ from traditional engineers in that they consider the system in its entirety, lead the conceptual design of systems, and bridge the gaps between traditional engineering (Kossiakoff et al., 2011). As such, systems engineers have developed a variety of means—system architecture, system of systems analysis, and enterprise architecture—to deal with complexity. To manage complexity and the qualitative nature of systems engineering, systems engineers have developed the ilities as a construct for assessing nonfunctional attributes of a system. Systems engineers have begun to recognize the criticality of these non-traditional design criteria and have begun to include them in the design of systems (McManus et al., 2009). However, these properties and attributes of a system often manifest themselves after engineers have designed and put the system into operation (de Weck et al., 2012). Further study of the ilities examines how system-level ilities begin to emerge from the subsystem level, where systems engineers can design in these non-functional attributes (Lee & Collins, 2017).

Complexity Theory

Wade and Heydari (2014) categorized complexity definition into three major groups, according to the point of view of the observer. When the observer is external to the system and can only interact with it as a black box, then the type of complexity that can be measured is called behavioral complexity, since it looks at the overall behavior of the system. When the observer has access to the internal structure of the system, such as blueprints and source code for engineered systems or scientific knowledge for natural systems, then the structural complexity of the system is what is being measured. If the process of constructing the entity is under observation, then it is the constructive complexity being measured, which is the complexity of the building process. This definition relates complexity to the difficulty of determining the output of the system.

Sheard and Mostashari (2011) developed a framework for the categorization of complexity types. Engineered systems have two types of complexity: structural and dynamic. Dynamic complexity can be short term or long term. Short term complexity is related to the operation of the system. System behavior can be unpredictable due to non-linear relationships among the system components. The environment can also play a major role on system behavior. Long-term complexity is related with the evolution of the system, its growth, and its adaptation to its environment which plays an important role in shaping the new generations. Structural complexity is instead interested in a snapshot of the system architecture and can be divided into three components: size, connectivity, and topology.

Metrics of structural complexity have been proposed in literature. The most common type of metrics is based on the concepts of entropy (Akundi, 2016; Gell-Mann & Lloyd,1996), information content, or logical depth (Fischi, Nilchiani, & Wade, 2016). Another common type of structural complexity metrics considers the spectrum (the set of eigenvalues) of the graph representation of the system. These metrics are known as spectral metrics and are the ones adopted in this research. The fist spectral metric, proposed by Gutman in 1978 (Gutman, 2011), is known as Graph Energy and is represented by

$$E_A(G) = \sum_{i=1}^{n} |\lambda_i| \tag{1}$$

where λ_i are the eigenvalues of the adjacency matrix of the graph *G*. A variation of this metric, proposed by Gutman as well (Gutman & Zhou, 2006), is the Laplacian Graph Energy, represented as

$$E_L(G) = \sum_{i=1}^{n} \left|\mu_i - \frac{2m}{n}\right| \tag{2}$$

where μ_i are the eigenvalues of the Laplacian matrix, n the number of nodes and m the number of edges of the graph *G*. Cavers, Fallat, and Kirkland (2010) provided a generalization of these two metrics that can be applied to any matrix representing a graph, which is represented by

$$E_M(G) = \sum_{i=1}^{n} \left|\lambda_i(M) - \frac{tr(M)}{n}\right| \tag{3}$$

where $\lambda_i(M)$ are the eigenvalues of the matrix *M*, and $tr(M)$ its trace.

Graph energy has been embedded in a structural complexity metric provided by Sinha (2014), as a contribution of the topology of the graph. The formula

$$C(n,m,A) = \underbrace{\sum_{i=1}^{n} \alpha_i}_{C_1} + \underbrace{\left(\sum_{i=1}^{n}\sum_{j=1}^{n} \beta_{ij} A_{ij}\right)}_{C_2} \underbrace{\gamma E(A)}_{C_3} \quad (4)$$

where α_i represents the inner complexity of each node, and β_{ij} the complexity of the edges, is based on the idea that structural complexity has three contributions: components, connections, and topology (Sheard & Mostashari, 2011).

Another type of spectral structural metric has been proposed by Wu et al. (2010) considers the eigenvalues of the adjacency matrix as an exponential function, and adjusts the value through a logarithmic scale

$$N_A(G) = \ln\left(\frac{1}{n}\sum_{i=1}^{n} e^{\lambda_i}\right) \quad (5)$$

The coefficient $1/n$ is a way of normalizing the graph according to the number of nodes, which allows one to compare graphs of different sizes. This approach has been used by Sinha as well with the coefficient $\gamma = 1/n$. These metrics have been used as a starting point for the development of 12 metrics that consider the system as a graph and are based on the eigenvalues of a certain matrix representing this graph.

Capability Development in the DoD

The DoD generates requirements through the Joint Capability Integration and Development (JCIDS) process, which they then pass to the acquisitions community to develop and procure warfighting systems. As a part of this process, DoD systems engineers analyze the current state of legacy systems and determine how the new capability will integrate with these systems. The DoD designed the system to ensure validated military capability requirements support resourcing decisions for programs. The 2003 Joint Defense Capability Study first presented the concept of JCIDS and proposed a transition from requirements-based acquisition to a capability-based approach (Joint Chiefs of Staff, 2004). The JCIDS process supports the Chairman's and the Joint Requirements Oversight Committee's (JROC) statutory responsibilities to identify, assess, validate, and prioritize joint military capability requirements (Joint Chiefs of Staff, 2012a). The JCIDS process requires sponsors to generate three main documents—Initial Capability Document (ICD), Capability Development Document (CDD), and the Capability Production Document (CPD)—that support different phases in the development and acquisition process by providing traceability from warfighter capability requirements to fielded systems (Joint Chiefs of Staff, 2012b).

As part of the JCIDS process, the Joint Staff requires several DoD Architecture Framework (DoDAF) viewpoints to support the development of warfighter capabilities. Architecture frameworks assist decision makers by serving as a communication tool by presenting a manageable amount of information from a set of data to assist stakeholders in managing complex systems (Richards et al., 2006). System architects use DoDAF, one of several common frameworks, to capture multiple perspectives of a warfighting capability's system architecture. All architecture frameworks include specific taxonomies, artifacts, and terminologies for describing a system to ensure standardization across multiple individual architectures (Friedenthal, Moore, & Steiner, 2012). DoDAF includes eight different viewpoints that capture data relevant capability requirements, integration, military operations, and program management aspects of a system (DoD Chief Information Officer, 2010). The DoD designed DoDAF to meet the needs of a diverse set of stakeholders and decision makers by abstracting essential pieces of information and presenting them in manageable pieces depending on their perspective (DoD Chief Information Officer, 2010). The required DoDAF products provide valuable data at the individual system level; however, they do not provide much insight into the larger, aggregated network of systems.

One shortfall of the DoDAF architectures used in capability development is that they do not capture a DoD-wide perspective of the interactions between individual systems. Several efforts have attempted to aggregate independent DoDAF products along mission threads; however, they still limit their approach to a subset of the entire DoD capability network of systems. Ring et al. (2009) proposed the Activity-Based Methodology, which aggregates DoDAF architectures into an integrated architecture that captures the organization, system, and role aspects of DoD systems. Another effort proposed aggregating independent architectures through a system, capability, and mission perspective by utilizing independent DoDAF viewpoints (Enos, 2014).

F-35 Joint Strike Fighter

The F-35 JSF is a joint, multi-role fighter and attack aircraft that is entering service with the Air Force, Navy, and Marines to replace a variety of legacy systems. The F-35 is a fifth-generation fighter aircraft that incorporates stealth technology into the design of the aircraft and uses a common airframe across all three versions of the aircraft (Church, 2015). The F-35A is the conventional take-off and landing version of the JSF that incorporates an advanced sensor package and situational awareness capability to drastically improve the effectiveness of the aircraft (U.S. Air Force, 2014). The Air Force plans to replace both the F-16 and A-10 with the F 35A beginning in 2016 as it fields their version of the F-35 in air-superiority, suppression of enemy air defense, and close air support roles (Church, 2015). The Marine Corps began fielding the F-35B short takeoff and vertical landing (STOVL) version of the JSF in that provides the capability to take off and land on extremely short runways. The Marine Corps plans to use the F-35B to replace both the F/A-18 Hornet and the A/V-8B Harrier II with the JSF (JSF Program Office, 2017). The Navy's version of the JSF, the F-35C, includes increased wing area and structural enhancements to support carrier landings and take offs. The Navy plans to replace the F/A-18 with the JSF to serve as its primary air superiority and attack aircraft (JSF Program Office, 2017).

Methodology

This section presents the methodology that the authors adopted in the formulation of new spectral structural complexity metrics, and the data collection strategy for the characterization of the complex tactical aircraft system of systems.

Development of Complexity Metrics

The metrics presented in this paper are all spectral complexity metrics, meaning that they are based on the eigenvalues of a certain graph representation of the system. To represent the graphs, three different matrices are used: the adjacency matrix, the Laplacian matrix, and the normalized Laplacian matrix. The adjacency matrix is the most frequently used representation of an architecture within the systems engineering domain. Also known as Design Structure Matrix (DSM; Yassine & Braha, 2003), or N^2 matrix, it is used to represent the interfaces and their arrangement, and allows one to make considerations on architectural modularity and clustering of components. The Laplacian matrix includes additional information with respect to the adjacency one, specifically regarding the degree of each component. The normalized Laplacian matrix has an interesting spectrum that is related to other graph invariants more than the spectra of the other two matrices (Chung, 1997). These three matrices are considered in their weighted variations, where edges and vertices of the graph carry different weights. The metrics are based on two similar concepts, graph energy and natural connectivity, which as seen in the previous section are both functions of the eigenvalues of the matrix representation of the system. A corrective coefficient $\gamma = 1/n$ to compare graphs with different number of nodes is included in the definition of natural connectivity (Wu et al., 2010) and in Sinha's (2014) structural complexity metric.

The metrics are applied to two sets of random graphs, generated through Erdõs-Rényi (ER) and Barabási Albert (BA) algorithms. The values of each metric are plotted against graph density, which is defined as

$$d = \frac{2m}{n(n-1)} \tag{6}$$

for undirected graphs, and as

$$d = \frac{m}{n(n-1)} \tag{7}$$

for directed graphs, where n is the number of nodes and m is the number of edges in the graph *G*.

Another graph indicator used in this research is graph diameter, defined as the maximum shortest path between all pairs of nodes in the graph. In absence of accurate information regarding the internal structure of nodes, which is usually the case in system of systems applications, where one organization cannot access data belonging to external actors, the complexity of the nodes can be approximated with the degree of the node $\alpha_i = \deg v_i$, and $\beta_{ij} = \sqrt{\alpha_i \alpha_j}$.

Metrics such as graph energy and natural connectivity, which have been introduced in the previous section, can be represented through the following formula

$$C(S) = f\left(\gamma \sum_{i=1}^{n} g\left(\lambda_i(M) - \frac{tr(M)}{n}\right)\right) \tag{8}$$

where $f_1(x) = x,\ g_1(y) = |y|,\ f_2(x) = \ln x\,,\ g_2(y) = e^y$ are the possible values for the functions f and g, the coefficient γ can be $\gamma_1 = 1, \gamma_2 = n^{-1}$, and the matrix representation of the graph can be either $M_1 = A, M_2 = L, M_3 = \mathcal{L}$, which have been defined in our previous publication (Nilchiani & Pugliese, 2016).

Table 1 shows the metrics that can be derived from this formula through combinations of these parameters. Two sets of functions, two values for the coefficient γ, and three matrices, give 12 possible metrics. Throughout this paper, the metrics are referred to using acronyms: graph energy (GE), Laplacian graph energy (LGE), normalized Laplacian graph energy (NLGE), natural connectivity (NC), Laplacian natural connectivity (LNC), normalized Laplacian natural connectivity (NLNC), and where $\gamma = 1/n$, the acronym has a trailing n, such as in (GEn). These metrics will be applied in the next section to sets of random graphs, and to the TACAIR system of systems.

Table 1. Twelve Examples of Spectral Structural Complexity Metrics

	Adjacency Matrix	Laplacian Matrix	Normalized Laplacian Matrix
$\gamma = 1$	$E_A(G) = \sum_{i=1}^{n} \lvert\lambda_i\rvert$	$E_L(G) = \sum_{i=1}^{n} \left\lvert\mu_i - \frac{2m}{n}\right\rvert$	$E_{\mathcal{L}}(G) = \sum_{i=1}^{n} \lvert\nu_i - 1\rvert$
	$N_A(G) = \ln\left(\sum_{i=1}^{n} e^{\lambda_i}\right)$	$N_L(G) = \ln\left(\sum_{i=1}^{n} e^{\mu_i - \frac{2m}{n}}\right)$	$N_{\mathcal{L}}(G) = \ln\left(\sum_{i=1}^{n} e^{\nu_i - 1}\right)$
$\gamma = \frac{1}{n}$	$E_{An}(G) = \frac{1}{n}\sum_{i=1}^{n} \lvert\lambda_i\rvert$	$E_{Ln}(G) = \frac{1}{n}\sum_{i=1}^{n} \left\lvert\mu_i - \frac{2m}{n}\right\rvert$	$E_{\mathcal{L}n}(G) = \frac{1}{n}\sum_{i=1}^{n} \lvert\nu_i - 1\rvert$
	$N_{An}(G) = \ln\left(\frac{1}{n}\sum_{i=1}^{n} e^{\lambda_i}\right)$	$N_{Ln}(G) = \ln\left(\frac{1}{n}\sum_{i=1}^{n} e^{\mu_i - \frac{2m}{n}}\right)$	$N_{\mathcal{L}n}(G) = \ln\left(\frac{1}{n}\sum_{i=1}^{n} e^{\nu_i - 1}\right)$

TACAIR System of Systems

This section presents an overview of the methodology to develop three individual networks of systems that capture the "as-is," "transitional," and "to-be" networks. A variety of publicly available sources provide the necessary data to develop the network of systems and identify connections between the systems (Church, 2015; JSF Program Office, 2017). The network captures interoperability connections between the systems that include information flows, shared resources, and physical connections (Enos & Nilchiani, 2017). Table 2 presents an excerpt from the entire adjacency matrix for the tactical aircraft network of systems. A complete matrix for each of the networks captures the data required to analyze the complexity of the network.

Table 2. Excerpt From Adjacency Matrix

	A-10C	AIM-120	AIM-9X	F-16C	F-22	F-35A	GPS III	Link-16	JDAM	KC-46
A-10C			X				X	X	X	X
AIM-120				X	X	X				
AIM-9X	X			X	X	X				
F-16C		X	X				X	X	X	X
F-22		X	X			X	X	X	X	X
F-35A		X	X		X		X	X	X	X
GPS III	X			X	X	X				
Link-16	X			X	X	X				
JDAM	X			X	X	X				
KC-46	X			X	X	X				

The "as-is" network captures the systems that comprise the DoD's tactical aircraft system and consists of aircraft, munitions, sensors, and communication systems prior to the fielding of the F-35. The "transitional" includes all the legacy aircraft as well as the JSF and its connections that represents the DoD network as the Air Force, Navy, and Marine Corps transition to the F-35 from their legacy aircraft. Finally, the "to-be" network depicts the DoD's network of tactical aircraft and systems after the three services retire the systems the F-35 is scheduled to replace.

Figure 1 presents the graphical depiction of the “as-is” network of DoD tactical aircraft systems and represents the past version of the network prior to the deployment of the F-35 JSF variants. This network captures various types of systems that operate together to provide the DoD with tactical aircraft capability to include the aircraft, munitions, sensors, satellites, weapons, and command, control, communications, computer, and intelligence (C4I) systems. In the graph, the colors represent the various services, the shapes of the nodes represent the type of system, and the size of the node represents its degree. This network represents the DoD’s tactical aircraft systems prior to the development of the JSF and provides the baseline for analyzing the complexity of the network.

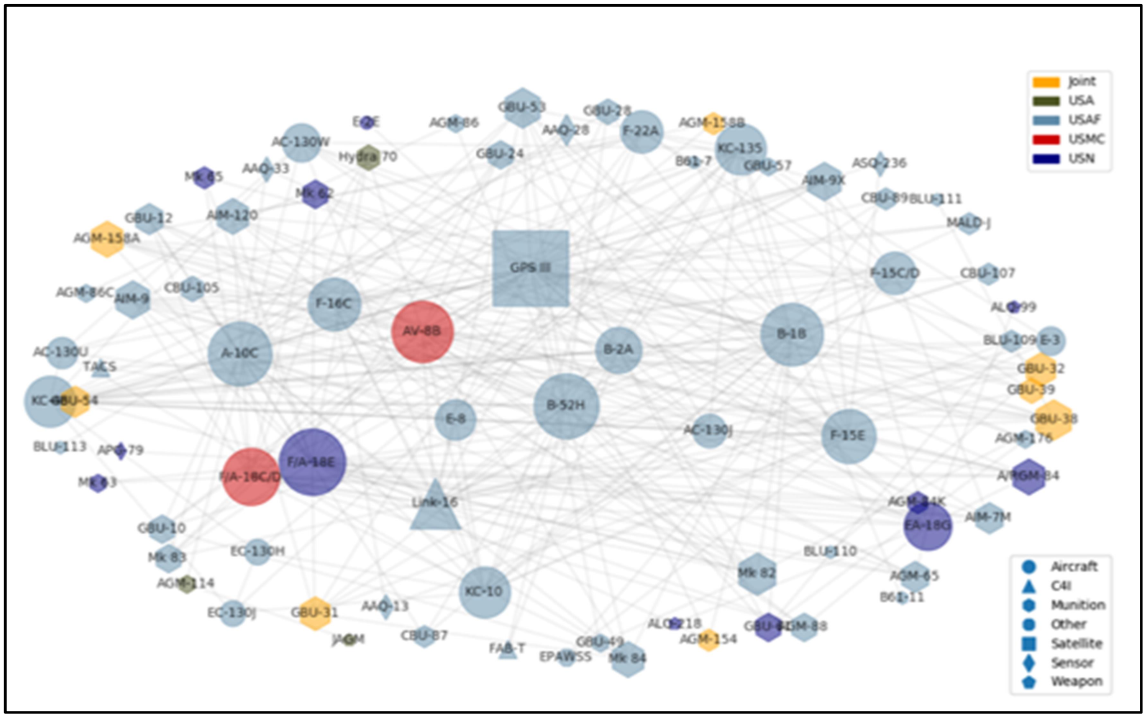

Figure 1. As-Is Network of DoD Tactical Aircraft Systems

Figure 2 presents the graphical depiction of the network and the connections that will be present during the transition from the legacy aircraft to the JSF variants. In this case, both the JSF and the aircraft the services plan to replace with the F-35 variants are included in the network along with any of their connections to other systems in the network. This version of the network provides a means to evaluate the complexity of the network during the transition period to the JSF which could impact resource expenditures, maintenance, supply operations, and tactical operations of the DoD.

Figure 3 presents the final version of the network and represents the “to-be” tactical aircraft network after the services retire the legacy systems that they are replacing with the F-35. In this case, the network does not include the retired A-10, F-16, F/A-18, and AV-8B systems from the Air Force, Navy, and Marine Corps. In addition to the four retired systems, the network removes systems that may not be retired but no longer connect to the network to include the Hydra Rockets, AN/APG-79 AESA Radar, and Mk 63 Sea Mine. This does not indicate that these systems could also be retired as they may be used by other systems; however, it does affect the complexity of the tactical aircraft network. This version of the network provides the means to calculate the complexity of the network after a complete transition to the JSF and can determine if the DoD increased or decreased the complexity of its tactical aircraft network.

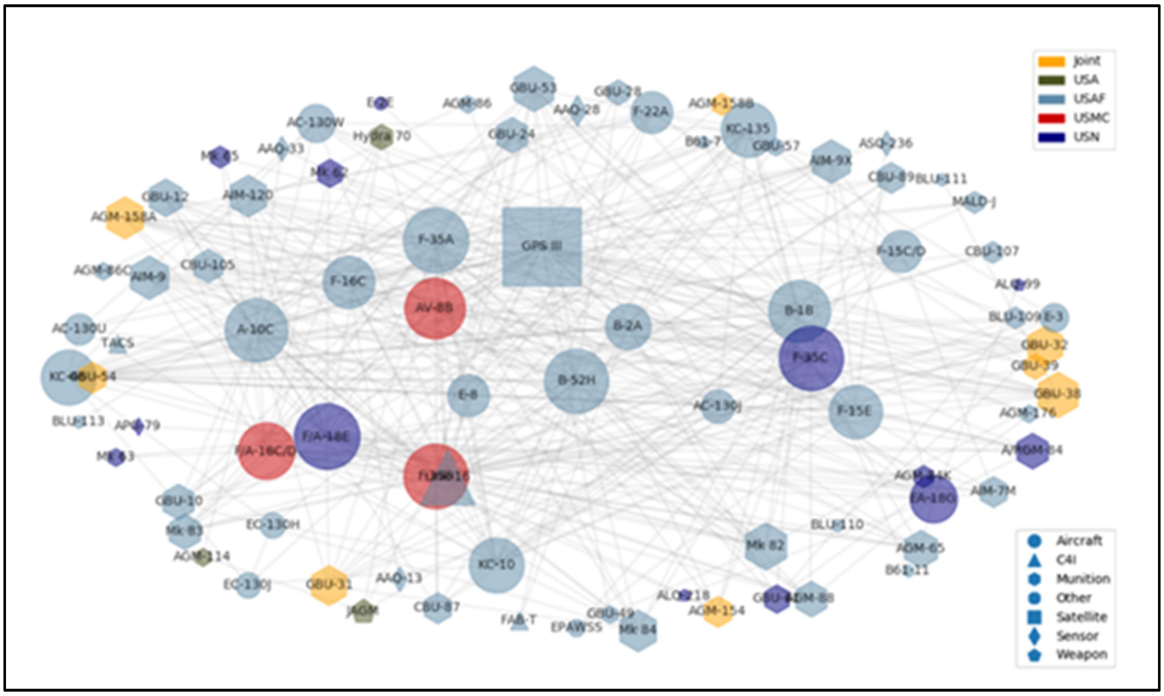

Figure 2. "Transitional" Network of DoD Tactical Aircraft Systems

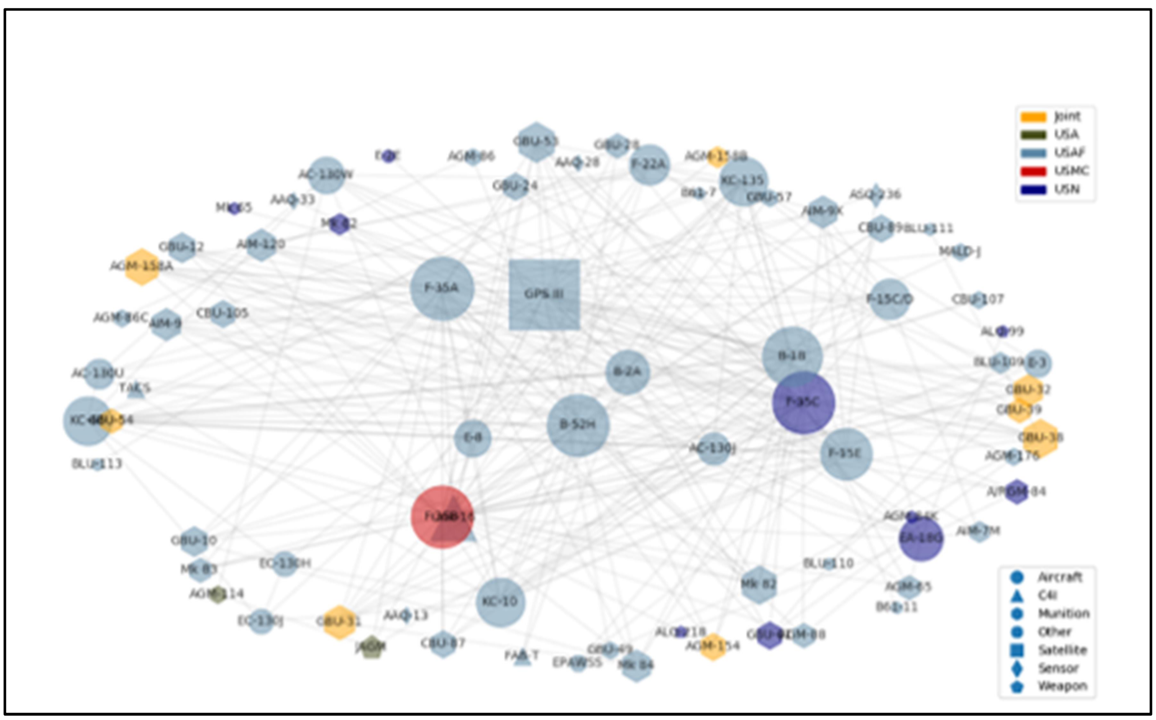

Figure 3. "To-Be" Network of Tactical Aircraft Systems

Analysis and Results

The metrics have been applied to two sets of random graphs, generated with ER and BA models respectively. The sets of graphs contain approximately 23,000 and 38,000 unique labeled graphs.

Figure 4 represents the values that the 12 spectral structural metrics assume when applied to the ER set of random graphs. Most of the metrics have a positive correlation with the number of nodes in the graph, meaning that the metric value is higher when the number of nodes is higher. This is the expected behavior for a complexity metric, and the two metrics that do not follow it, NLGEn and NLNCn, are not suitable as complexity metrics.

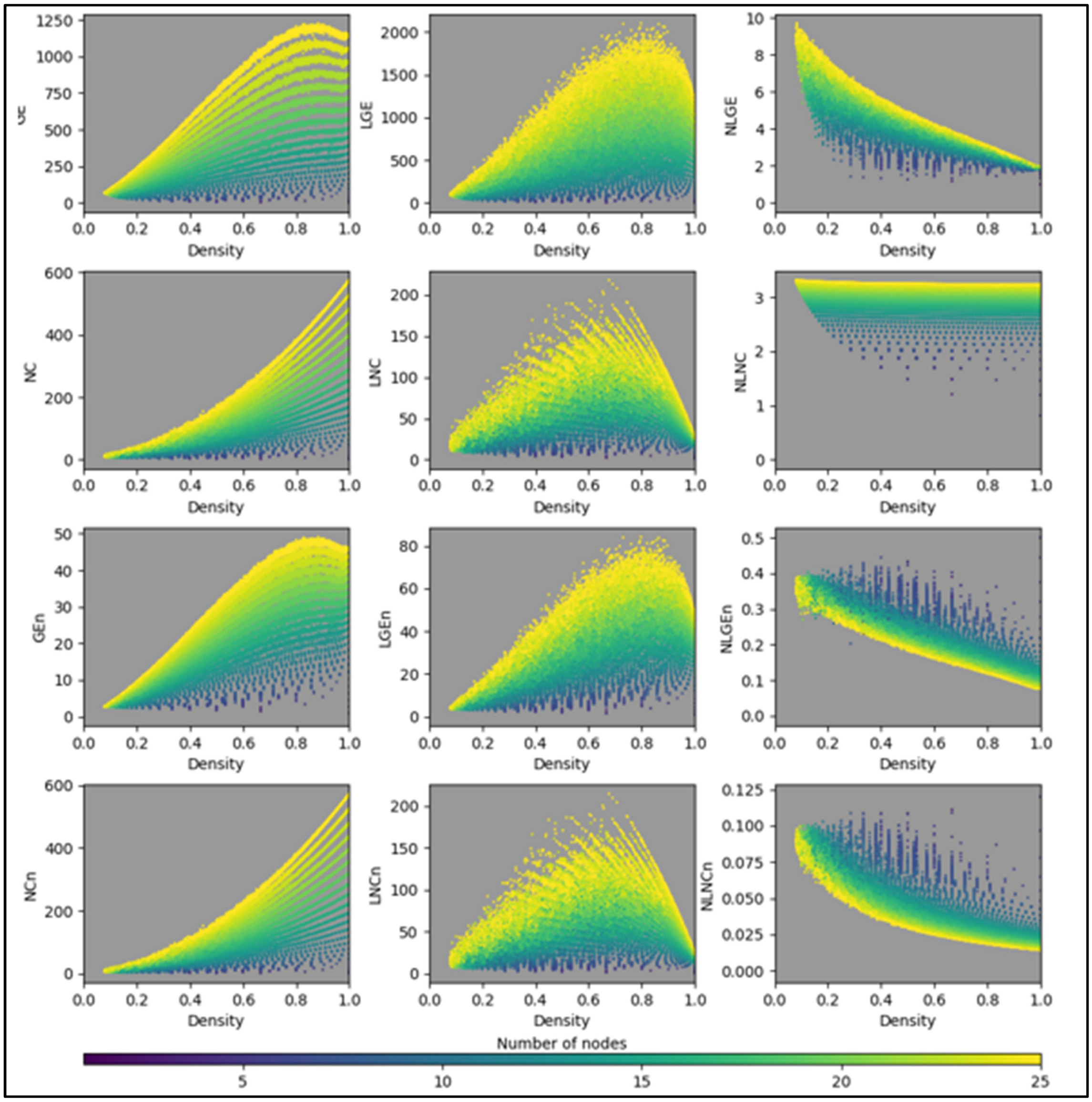

Figure 4. Metric vs. Density Plots With Color Scale According to Number of Nodes, for Each Metric, for Graphs Generated Using the Erdõs-Rényi Algorithm

From Figure 5 it is possible to see that for ER random graphs the diameter is high with low density graphs, and low when the density is high. This relationship is expected since the complete graph has diameter one and removing edges creates an increase of the shortest path between pairs of nodes. Although valid for ER graphs, the relationship between density and diameter is not general, since star graphs and path graphs with the same number of nodes have the same density, but the former have diameter 2 while the latter have diameter $n-1$. This means that for high n, the diameter of these two types of graphs is very different. This is one limitation of the ER algorithm, which will not generate star graphs, or graphs with highly skewed degree distributions, given its uniform probability of edge creation.

To overcome the limitations of the ER model, and to better mimic the topology of engineered systems with heterogeneous components, a set of graphs has been generated using the BA model. These graphs have a more skewed degree distribution, given by the preferential attachment strategy.

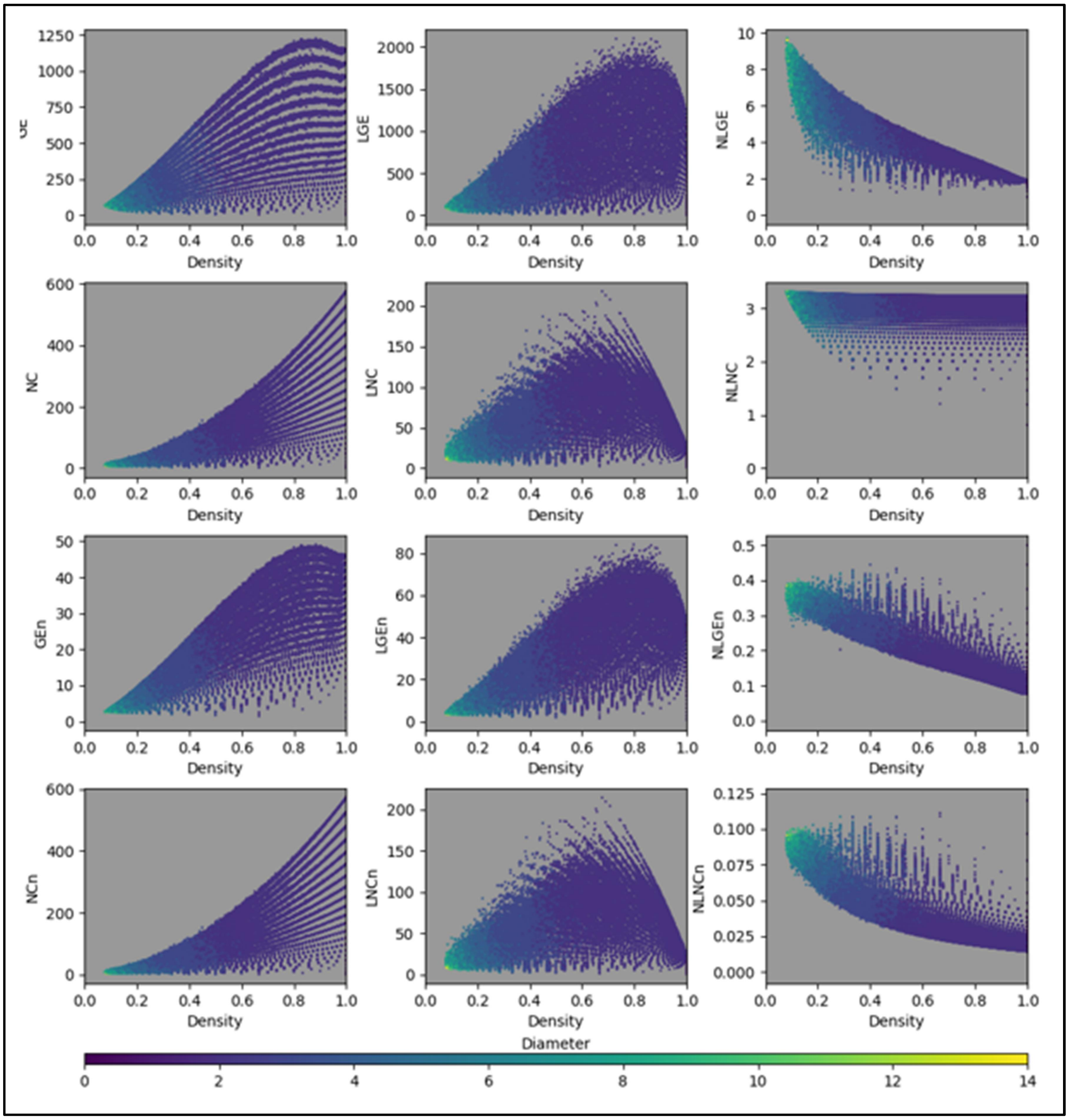

Figure 5. Metric vs. Density Plots With Color Scale According to Diameter, for Each Metric, for Graphs Generated Using the Erdõs-Rényi Algorithm

Figure 6 shows the metrics evaluated for the set of BA random graphs. Given the way the algorithm works, these graphs do not span the whole density range, but stop at $d = 0.57$. The main feature of these point clouds is a folding, a bifurcation, so that graphs with the same density will belong to two distinct sets with a high and low value of each metric respectively. This bifurcation gives meaning to the metrics, highlighting the fact that they are responsive to topological changes.

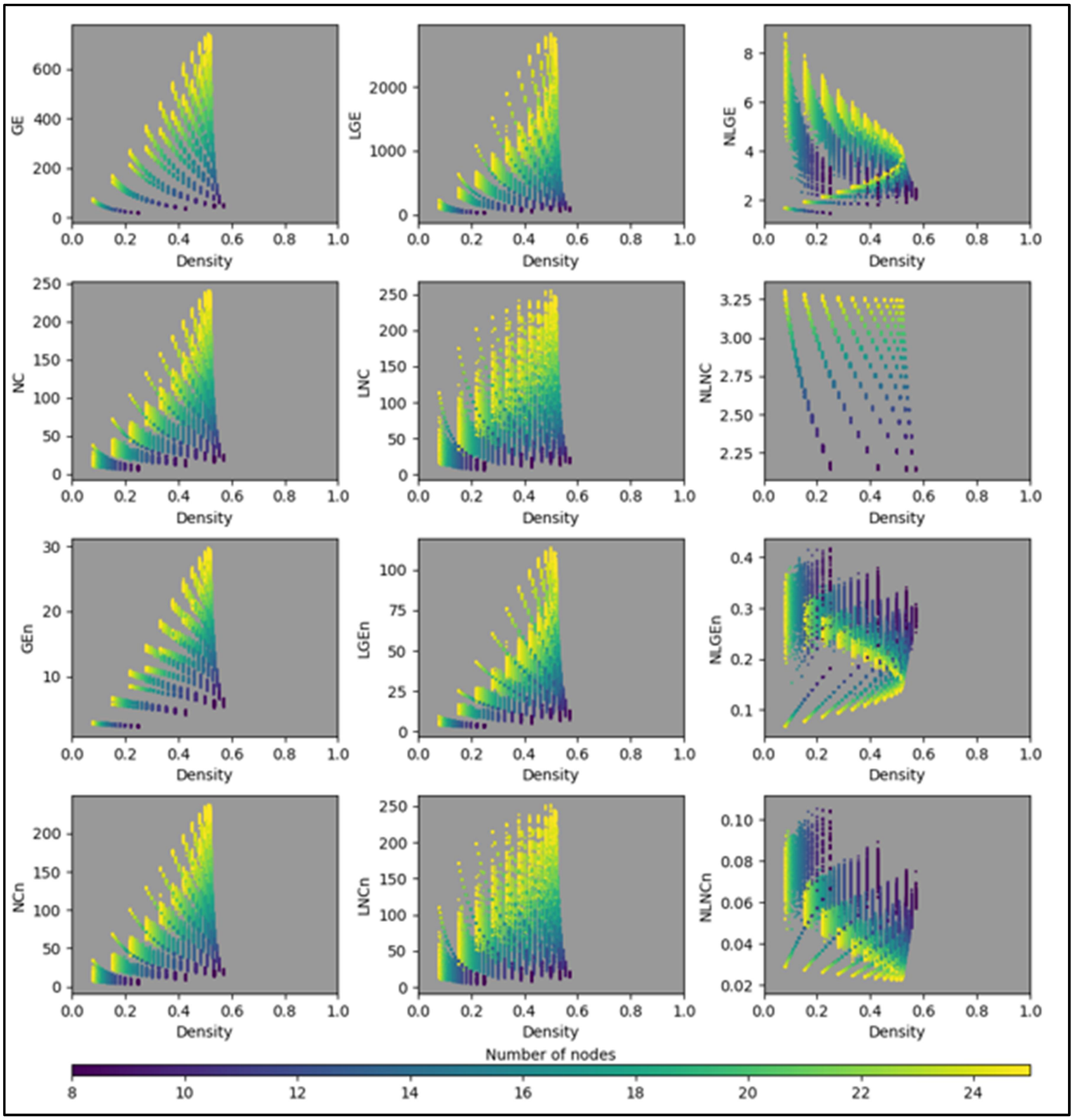

Figure 6. Metric vs. Density Plots With Color Scale According to Number of Nodes, for Each Metric, for Graphs Generated Using the Barabási-Albert Algorithm

Figure 7 shows that this bifurcation in BA random graphs is related to the diameter of the graphs. The diameter does not have the same trend as in ER graphs. Graphs with low density which have high diameter and low diameter exist. These two sets are represented by trees with high depth and stars, respectively. While a star topology is not common in engineered systems, since it is subject to bottlenecks and the complexity of the central node would tend to be too high, trees are common structures for engineered systems, where a certain level of decentralization is in order. Even in the presence of cycles, when the graph is not a tree anymore, a diameter value of 10 in a graph of 25 nodes is representative of engineered systems.

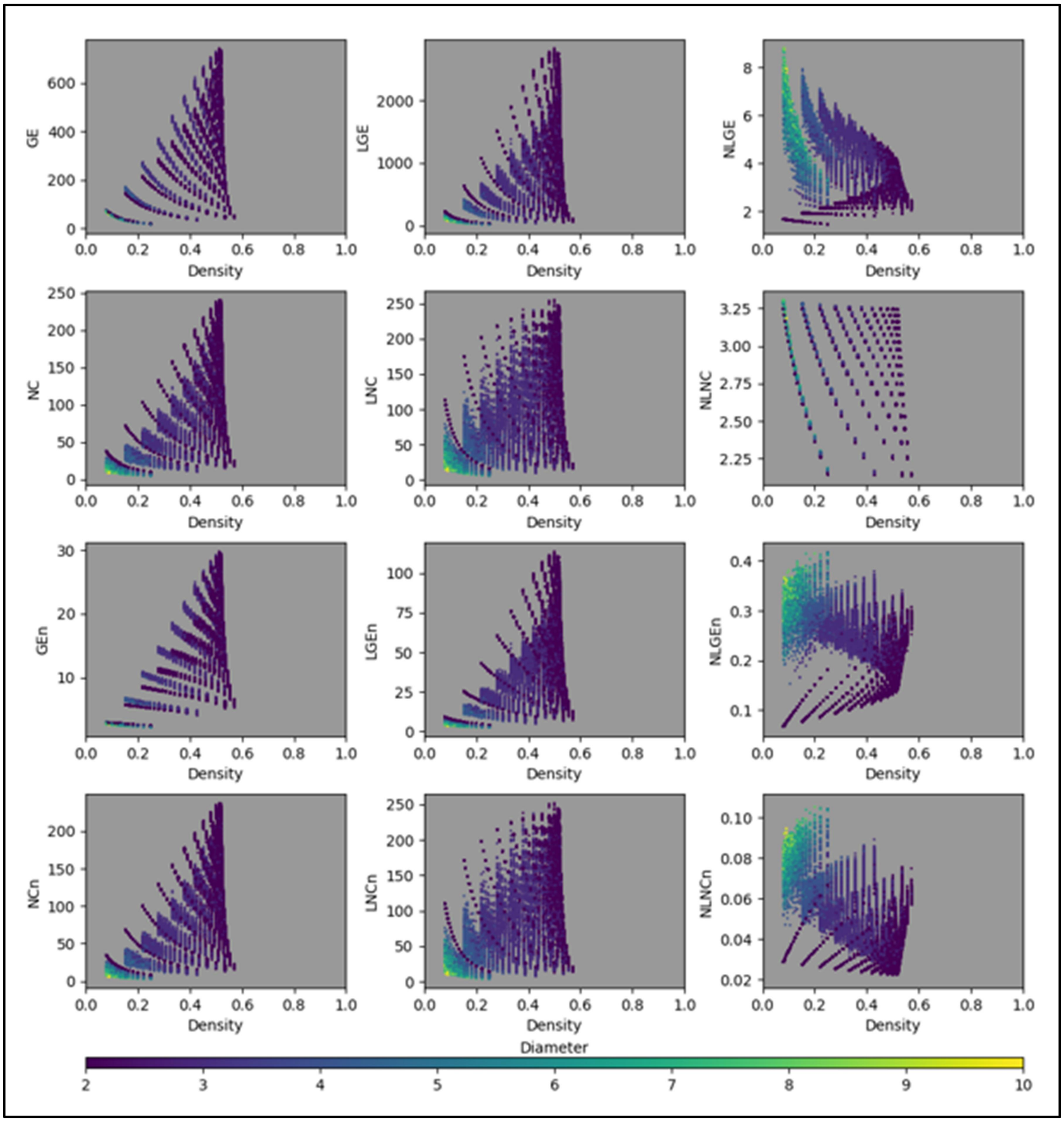

Figure 7. Metric vs. Density Plots With Color Scale According to Diameter, for Each Metric, for Graphs Generated Using the Barabási-Albert Algorithm

Analysis of the TACAIR System of Systems

The TACAIR system of system, in its three versions presented earlier, is undergoing radical changes. The introduction of the F-35 in the operational scenario and the subsequent retirement of legacy systems is causing modifications to the network topology. The number of nodes went from 82 to 85 and will go down to 77, and the number of interfaces went from 384 to 466 and will be 347 once the transition is complete. This leads to a density value going from 0.115 to 0.130, and to 0.118 in future. This density variation is not accompanied by a change in diameter which remains constant to 5, due to the centrality of the nodes that are being added and removed from the network. In this case, the metrics are beneficial to the network analysis, since they can tell more than the diameter about the topology of the network.

Figure 8 shows the metrics applied to the TACAIR system of systems. Other than NLGEn and NLNCn, which we have already ruled out as reliable complexity metrics, and NLGE, the other metrics agree that the introduction of the F-35 represents an increase in the complexity of the network. Most of the metrics, other than NC and NCn, also agree that the retirement of the legacy systems is beneficial for the network and will lead to a simplification of the overall network.

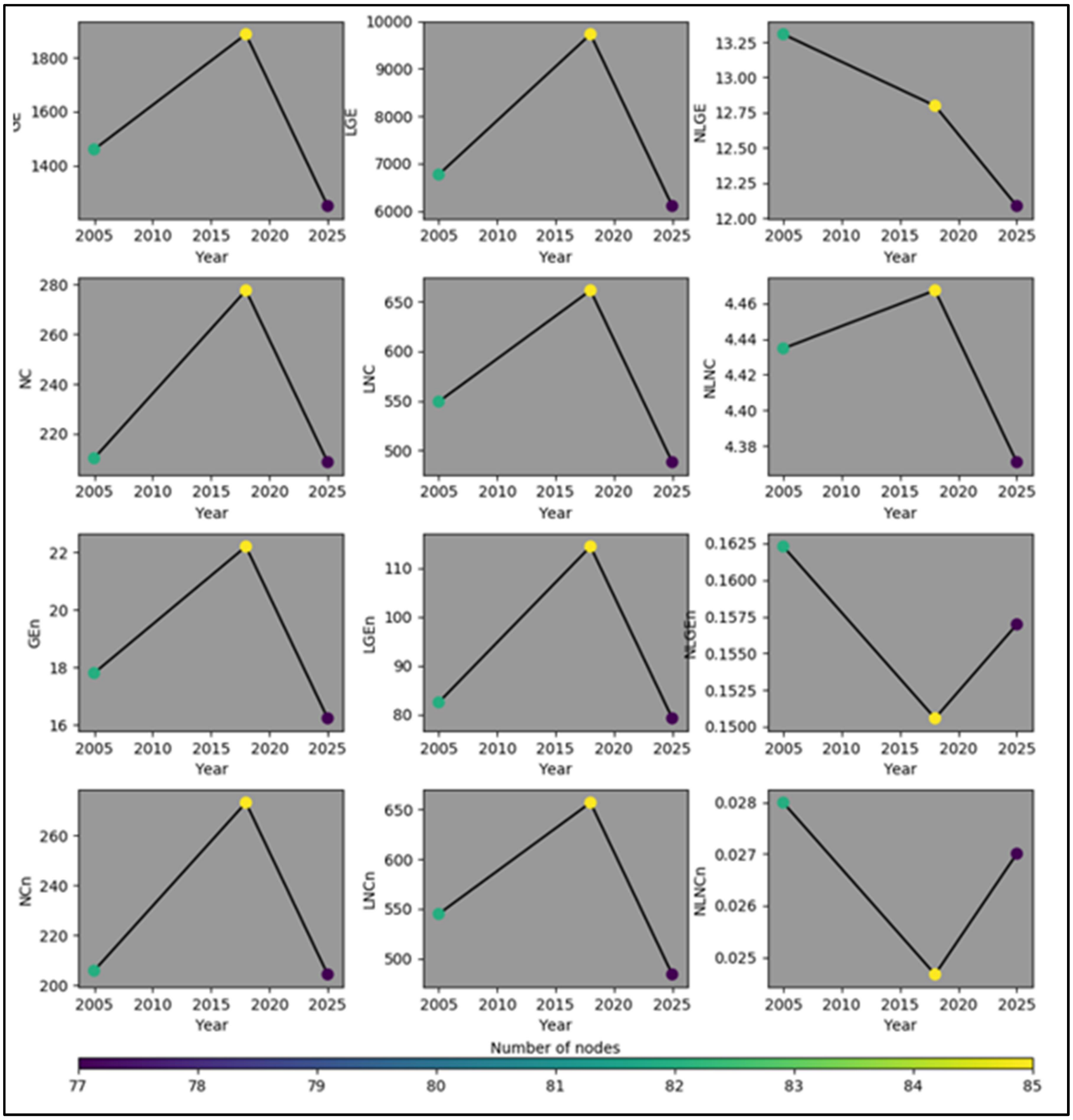

Figure 8. Evaluation of Spectral Structural Complexity Metrics With the Evolving Versions of the TACAIR System of Systems

Conclusion and Future Work

This paper presented an approach to the measurement of structural complexity that involves the measurement of the eigenvalues of a matrix representation of the system. Twelve spectral metrics have been created, based on features of existing metrics. The metrics have been applied to two sets of graphs, generated using the Erdõs-Rényi (ER) and Barabási Albert (BA) algorithms respectively. It is argued how the application of these algorithms to the generation of graphs representing engineered systems should be carried out together with considerations about the heterogeneity of the components of the system and the expected distribution of node degree. ER models having a close to uniform distribution of node degree are applicable to the representation of homogeneous graphs, such as networks of routers, in which all the components have the same tasks and functionalities. When specialization arises, and the components of a system are wildly heterogeneous, the degree distribution is highly skewed, and BA models are more appropriate.

The application to the TACAIR system of systems is an example of how the operational scenario can become complex thanks to the relationships between different types of systems, and how the introduction of new systems and the retirement of legacy ones can be beneficial to the management of the network, by streamlining the supplying of common resources and reducing the diversity of systems that achieve the same functionalities. Of course, this type of analysis can be improved when details about the architecture of each system are available, and the interfaces can be modeled with high fidelity regarding the timing and range of connections.

Limiting the approach to publicly available data allowed us to assume the point of view of an external actor who is interested in introducing a new system in an already existing environment. Examples of such systems can be the introduction of a new type of transportation system, such as the hyperloop concept, within the already existing network of air, sea, and land transportation systems, or the introduction of a new surgical tool to be used in conjunction with the existing set of operation room equipment.

In the future, if detailed data is available regarding one of the existing systems in the network, it would be possible to analyze the network and yield more insightful considerations about the retirement of such systems and the effect on the overall network.

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