Network Architecture Framework Applications with FOCUS-Compliant Ship Designs

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Abstract—Ongoing development of the US Navy's LEAPS data repository, research exploring the use of networks in ship system design by the Naval International Cooperative Opportunities in Science and Technology Program (NICOP), and tool development by the Electric Ship Research and Development Consortium (ESRDC) have provided an excellent opportunity to interface efforts to address preliminary distributed system design and analysis in early-stage ship design. This paper builds on the architecture framework and network-based methods by demonstrating new ways to process FOCUS-compliant data, develop network views, and analyze connectivity and flow of distributed ship systems. This framework decomposes system architecture into three primary views: physical, logical, and operational. Network-based tools targeted on these views and their intersections efficiently explore and analyze broad ranges in the ship system design space. These explorations generate knowledge, encourage innovation, and support the synthesis of affordable, effective ship designs. The authors present the findings of these efforts in consideration for future changes to the FOCUS Product Meta-Model to support integrated advanced network architecture analyses.

Keywords—*Architecture Framework, LEAPS, Network Theory, Ship System Design*

NOMENCLATURE

AFO	Architectural Flow Optimization
C&RE	Concept & Requirements Exploration
FOCUS	Formal Object Classification for Understanding Ships
LEAPS	Leading-Edge Architecture for Prototyping Systems
MEL	Machinery Equipment List
PMM	Product Meta-Model
S3D	Smart Ship Systems Design
SSM	Ship Synthesis Module
SYS	System
VC	Vital Component

I. INTRODUCTION

In the naval ship design community, there exists a critical need to expand the theory and capabilities of early-stage ship distributed system design tools. Addressing this need requires fundamental understanding of foundational systems engineering, an appreciation for the current status of existing tools and ongoing research, and new ideas. The System Architecture Framework described in Section II is a novel system network decomposition approach that offers great promise for understanding and designing ship distributed systems. Section III expands on this framework description and introduces the concept of operational nodes denoting system operations not associated with a single component. Examples of these ideas are provided in later sections using prototyped tools to demonstrate their underlining theory.

Several of these tools create and/or use network descriptions of systems for ship design and analysis. An example of this is the Architecture Flow Optimization (AFO) method described in Section IV. This method accomplishes a linear optimization of energy flows within ship systems in the early stages of ship design to minimize flow cost, ensure operational capabilities are satisfied, and reduce system vulnerability.

The U.S. Navy has developed a standard data repository, the Leading-Edge Architecture for Prototyping Systems (LEAPS) [1], with the goal of providing a single, consistent, reliable framework for storing design data for all Navy design tools. Section V discusses the method of storing system data in the LEAPS repository and describes custom software tools under development supporting the extraction and processing of network architecture from external LEAPS databases in order to develop directed graphs and export data to other tools for further post-processing. Based on experience derived from the development of these tools, the authors also present some of the ways that LEAPS and the Formal Object Classification for Understanding Ships (FOCUS) Product Meta-Model (PMM) may be subsequently modified to further support future network theory analyses.

Section VI describes specific work on a tool developed by Virginia Tech (VT) which transforms the archetypical system data from a singular-flow model into system deactivation diagram(s), providing instantaneous analysis of multiple operational flow patterns in distributed systems. This type of

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system view is commonly used for system availability and vulnerability analysis. An abbreviated theory and design description of the tool accompany the detail of its use with examples developed from the AFO flow model and the VT Concept & Requirements Exploration (C&RE) example ship system model.

In summary, this paper describes and demonstrates methodologies for analyzing naval ship distributed systems, defining required components for operational capabilities, validating early-stage naval ship distributed systems designs, manipulating FOCUS-compliant ship data, creating deactivation diagrams, and proposes additions to the FOCUS PMM and LEAPS tools.

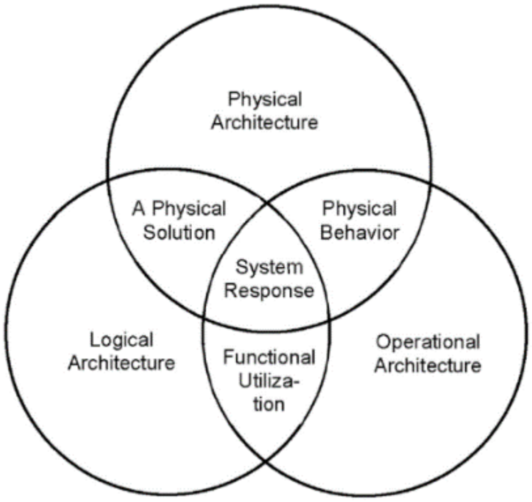


Fig. 1. Representation of an Architectural Framework for Ship Distributed Systems [2]

II. ARCHITECTURAL FRAMEWORK

Brefort et al [2] describes system architecture as decomposable into physical, logical, and operational views by the architecture framework for distributed naval ship systems, as shown in Fig. 1. According to Brefort et al:

> This representation describes the spatial and functional relationships of the system together with their temporal behavior characteristics. […] The physical architecture describes the spatial arrangement, the logical architecture describes information on the functional characteristics of the system, and the operational architecture contains information on the temporal behavioral characteristics of the vessel, in a given mission scenario. [2, pp. 375-377]

This framework enables individual architectures to be implemented separately as illustrated in Fig. 2 and integrated to solve for physical solutions, physical behavior, functional utilization and ultimately the total system response. Being able to access LEAPS component data views applicable to this network framework is a first step to a network theory implementation.

The network logical architecture is the most fundamental aspect of the architecture framework. Fig. 3 shows a simple logical system architecture of a mechanical subsystem or *plex* of a larger integrated power system. This network representation is made up of nodes and the edges that connect them, in which each node is either a vital component ("VC") or system node ("SYS"). System nodes may represent sources, sinks or ports of vital components in other plexes. Each VC in this architecture also has physical attributes and is ultimately located physically in the ship in the "physical solution."

The Propulsion_SYS node shown in Fig. 3 is an operational system node that provides propulsion capability to the operational architecture and pulls energy from the mechanical

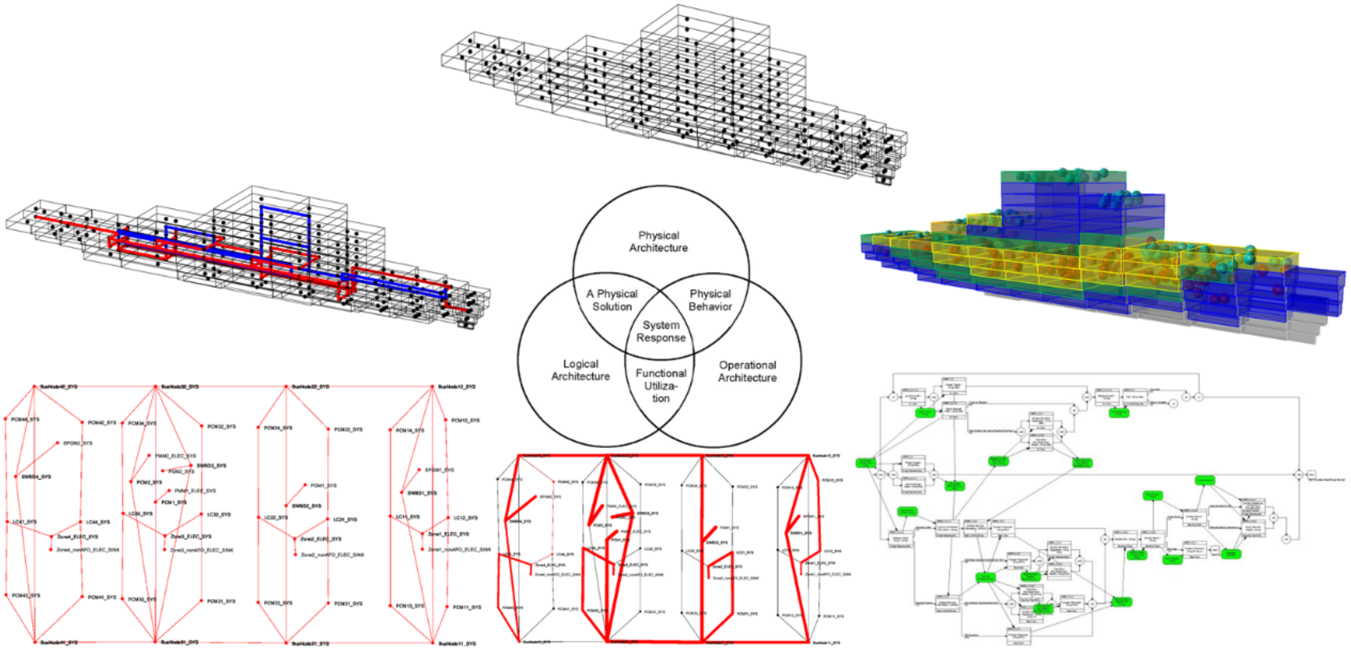


Fig. 2. Notional Architecture Framework Implementation in Ship Concept Exploration [4]

energy plex and ultimately the entire ship system multiplex to support a required level of performance, in this case meeting a designated ship propulsion speed. In order to operate, the mechanical subsystem shown in Fig. 3 requires functional capability of other plexes within the multiplex system, including electric power, machinery control, lube oil, HVAC, seawater, chilled water, and HFC. When viewed in a multiplex deactivation diagram, these systems define the total ship propulsion system as shown in Fig. 10.

Fig. 3. Mechanical (Propulsion) Subsystem or Plex Logical Architecture (PMM in this figure stands for Propulsion Motor Module)

III. OPERATIONAL SYSTEMS

A distribution system is defined as: the group of components and their connections whose purpose is to distribute a commodity (e.g. physical substance, energy, materiel, or information) from sources to sinks [3]. This commodity-based definition of a system is the default definition many marine engineers use. A perfect example of a system following this definition is a traditional chilled water system, which includes any components the chilled water commodity flows through.

An alternate operation-based definition could be: the components and logical connections required to transport energy, carried by other commodities from sources to a single operational sink, including any redundant paths. Operations produce, transform, or consume energy. These operations may interact with the ship's environment or other operational systems within the ship. If an operational sink is also the capability node in a deactivation diagram, this node and the remaining components and their connections in the deactivation diagram form its operational system. This alternate definition was conceived as an important addendum to the operational architecture view established by Brefort et al. [2].

Fig. 3 shows an example of a mechanical propulsion system (mechanical energy distribution system) with an additional operational system node connecting the two shafts. Both propellers connect to this Propulsion_SYS node. This node represents the energy sink of the system, and its demand value is determined by the operational condition of the ship (e.g. sustained speed, endurance speed, battle speed, etc.). Operational conditions may affect which parts of the system are classified as vital or redundant. For example, the sustained speed condition may require both shafts, while the endurance speed condition only requires a single shaft. For this reason, it is important to have a fully defined operational architecture including design reference missions when evaluating marine engineering systems (especially mission systems) [2-4].

Fig. 3 is both an operational system and deactivation diagram when only considering the mechanical components in the propulsion system. The system can be expanded to include all necessary ship system components as shown in Fig. 10. In this view, the propulsion motor modules require electrical power and lube oil cooling. The power generation modules that provide electrical power require fuel oil. The electrical components and lube oil pumps are cooled by chilled water components. Finally, the lube oil and chilled water components are cooled by seawater. All of these components are part of the total propulsion operational system.

IV. ARCHITECTURE FLOW OPTIMIZATION

The network architecture framework facilitates useful applications such as Architecture Flow Optimization (AFO) or linear energy flow optimization. In this approach, complex behaviors like pump curves, engine maps, power conversion, or heat exchange are modeled by simple energy flow coefficients and enforcing conservation of energy at each node. These coefficients are unique to each component type and are stored in a comprehensive Machinery Equipment List (MEL) for the total system. *Through variables* (e.g. current, flow rate, speed) or *cross variables* (e.g. voltage, pressure, torque) are not used.

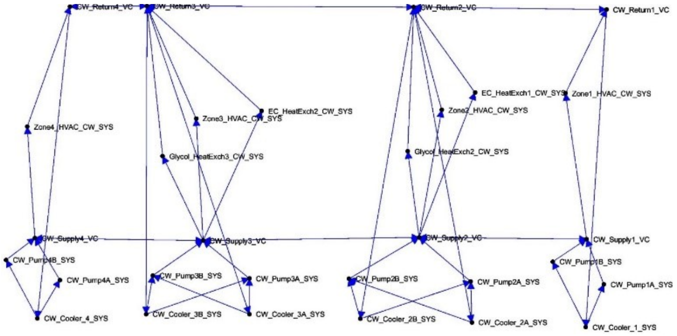


Fig. 4. AFO Chilled Water Plex Logical Architecture

The AFO begins with a system logical architecture (example shown in Fig. 4), applies these energy coefficients in the MEL, and enforces steady-state or quasi-steady-state operational constraints. The objective function in this optimization minimizes the flow cost of the network. This cost has two components: a fixed cost (representing the engineering and instillation costs of connecting components) and a variable cost (which linearly increases with flow). Parsons et al. [5] and Brown [3] provide a complete description of the linear optimization formulation and the operational constraints.

Fig. 5 shows the sustained-speed condition functional utilization of the AFO for the chilled water example provided in Fig. 4. The functional utilization is the intersection of the logical and operational architectures shown in Fig. 1 and represents the time-domain utilization of the system. These energy flows are used to parametrically size the volume, area, and weight of components. Brown [3] states that the application of the network architecture framework in conjunction with this energy flow method has a number of significant advantages:

1. Explicit sizing of major combat, power, and energy components, early in the design process.
2. Consideration of broader ranges of system options and architectures outside of the range of historical data-based parametrics.
3. Enables early preliminary arrangements.
4. Enables early distributed system architecture optimization.
5. Enables a more specific consideration of operational architecture scenarios including warfighting damage.
6. Enables early flow-based maintenance, reliability and availability analyses which,
7. Enables early vulnerability and recoverability analyses.
8. Excellent tool for understanding and communicating energy flow through a complex distributed system of systems.

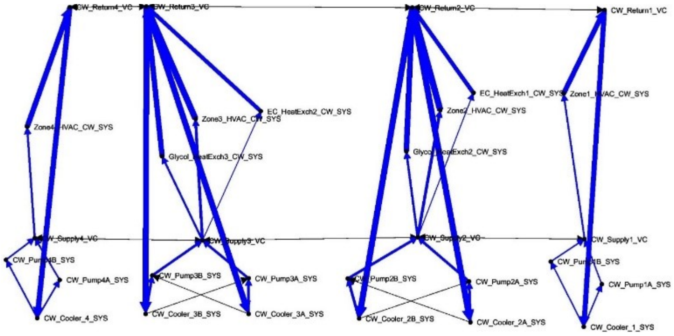


Fig. 5. AFO Chilled Water Plex Sustained Speed Functional Utilization

This energy flow method serves as a potential low fidelity (in terms of both physics and number of components) but sufficient method for concept exploration, initial equipment sizing, and system validation. Tools like S3D have a stronger physics-based commodity flow solver and are better suited to analyzing more detailed/complete system designs with piping, ducting, and other commodity distribution components [4].

V. LEAPS INTEGRATION

The U.S. Navy's LEAPS data repository has been developed to provide a consistent and reliable framework for storing design data. Within a LEAPS database, the data structure of surface ship-related data is strictly controlled by the Formal Object Classification for Understanding Ships (FOCUS) product meta-model (PMM), which maintains the categorization of information according to predefined rules and object types. Additional data may be stored alongside FOCUS data in the database, but is without the organization and quality assurance of the FOCUS PMM. Evolution of the PMM requires procedural updates and a predetermined need, further enforcing consistency rules on the storage and extraction of ship data.

Despite the robustness of the LEAPS database, certain gaps currently exist within the FOCUS framework for seamlessly storing and accessing component data views directly applicable to network theory. Utilizing the extensibility of the LEAPS framework, custom software codes such as those presented in this paper have been independently developed to parse and store additional information within the LEAPS database for network analysis. Ongoing goals of this work include developing the demonstratable benefits of seamless integration of network information into the FOCUS PMM for analytical purposes.

There are several design tools and methodologies which benefit from a robust method of storing system data in LEAPS and extracting system network diagrams from LEAPS. The AFO described in Section IV above is the primary example used in this paper. Some additional tools include the following:

Smart Ship Systems Design (S3D) [6] is a software framework that can be used to define, simulate and analyze shipboard distribution systems in the electrical, thermal and mechanical energy domains. Systems are constructed by selecting components from an equipment library, and arranging and connecting them in discipline-specific views. Power-flow-level simulation can then be conducted on the assembled system designs. The resultant systems are stored in a LEAPS database in a FOCUS-compliant manner.

The *System Builder* [7] software is a body of work with the goal of achieving semi-automated design of ship systems, in which the systems are generated automatically under the guidance of the engineer or designer, using a templating process. Templates in this application are pre-designed sections of systems stored in a LEAPS database; they can be created using the S3D software. The templates are assembled into fully connected, fully functioning ship systems with components placed in three dimensions in a ship hullform. One step of the templating process requires determining maximum power flow through each component making up a system; this enables sizing of the components both in terms of dimensioning and in terms of managing the power. This is achieved by extracting a network representation of the system from the LEAPS database and applying a maximum flow algorithm, described in [7] to that network.

The *LEAPS Network Translator* is the result of an ongoing collaboration between MIT and Virginia Tech (VT) to create merged software that provides straightforward network representations of systems for use in external clients such as the System Builder, AFO, and the VT Ship Synthesis Module (SSM). Utilizing the System Builder framework, additional capability was developed to isolate individual system networks and process source/sink data and graph directionality as required for deactivation diagram analysis. This tool extracts system descriptions from a LEAPS database developed in S3D and applies network theory analysis to the system using a system of recursive algorithms and pre-defined object characteristics to develop a network description exportable to tools currently under development at VT. Output from the tool is formatted to match the Pajek large network analysis software ".net" file format.

Owing to the use of LEAPS as a data repository, all of these tools can be used in conjunction with one another. Systems defined using S3D can be assessed using AFO and the LEAPS Network Translator; templates created in S3D can be assembled, sized and placed using System Builder then analyzed using S3D or AFO.

A. System Diagram Representation in LEAPS

Network theory commonly describes the layout and connections of a system in the form of an adjacency matrix or adjacency list, each uniquely representing a system using nodes (vertices) and edges. Each node is representative of a system component, being a unique vital component or a child sub-system for the parent system. Edges identify the interconnectivity between pairs of vertices and may represent either the direct connections between components or substitute for static distribution system components such as pipes and cables. Additionally, an edge may be identified as an undirected edge for bidirectional flow or a directed edge, also referred to as an arc, for unidirectional flow.

Within the LEAPS database, LEAPS Components take the place of system vertices and the edges are represented by LEAPS Exchange Connections. We note in passing that a LEAPS Node is not the same concept as the graph node discussed herein. Although LEAPS does not specifically store networks either as adjacency matrices or adjacency lists, all the information required to extract such representations is available. See [8] for more information on the specific manner in which a system is stored in LEAPS.

One of the features of LEAPS is that defined system components may be uniquely represented in multiple common views, systems, and diagrams in different manners. As such, a single component such as a water chiller can appear as a thermal source in a chilled water system diagram, a thermal load in a seawater system diagram, and an electrical load in an electrical system diagram.

The mechanical propulsion system shown in Fig. 3 could be represented in LEAPS using FOCUS-compliant components for each VC listed and appropriate connection structure between the applicable nodes of those components. However, in order to represent the operational system functionality shown by the Propulsion_SYS top node and the two PMM_SYS nodes, a new type of LEAPS Component needs to be included in the FOCUS PMM.

At this point, neither LEAPS nor the FOCUS PMM include directionality information for connections. Such information can be parsed from the types of components and types of nodes associated with components, but a more robust method would be to include such information in the FOCUS definition of a LEAPS Terminal, which is a type of LEAPS Node. This is an important addition that is needed for network analysis of systems.

B. Component Analysis Using LEAPS Network Translator

Systems built using S3D are flexible in detail and are typically scoped to the level of detail required by the end user. Fig. 6 shows the chilled water system chosen as a test case for the analysis demonstrated by this paper. Detail design elements, such as pipes and most pipe fittings, are superfluous to this analysis and are omitted from this demonstration model.

Contrasting with the flow analysis model shown in Fig. 4, S3D constrains connections to the number of physical ports on each component. Fig. 6 gives an example of how piping connectivity must be realistically modelled via multi-directional fittings or distribution manifolds.

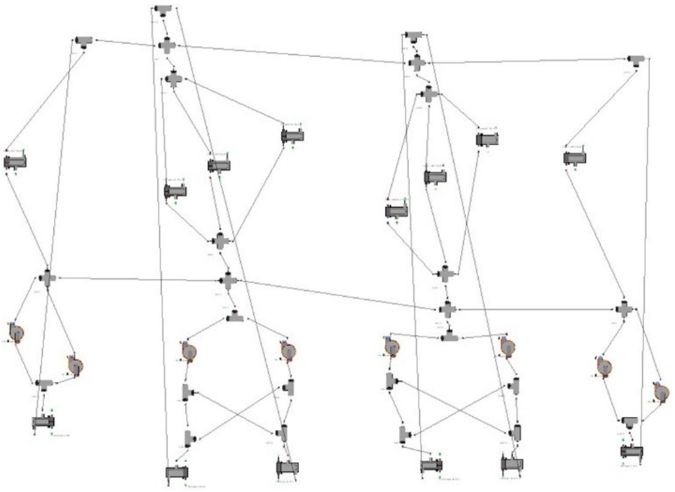


Fig. 6. S3D Chilled Water Piping Schematic

The chilled water system in Fig. 6 demonstrates the physical layout and connections of the system without predefined flow patterns (determined by internal flow analysis). System Builder directionality tools for directed graphs are used to identify and cache fixed input and output nodes by comparing the name and id of each node to a set of carefully-selected criteria. The LEAPS Network Translator provides additional analysis tools and criteria for extracting the necessary connectivity information for building a deactivation diagram. These predetermined criteria include assumptions like uni-directional liquid flow through a typical pump and no power generation by devices not designed to do so.

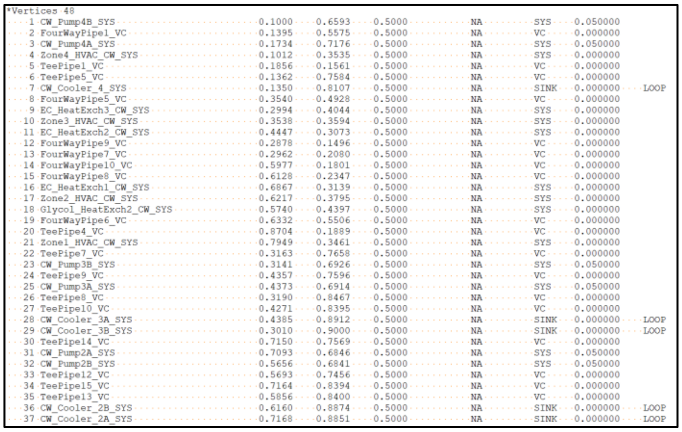
System loads (sinks) are identified by a static list of component types and nodal properties built into the tool. Sinks in the chilled water piping schematic shown in Fig. 6 are located as the hot water inlets in the chilled water heat exchangers. A depth-first search (DFS) algorithm is used to find the system sources as the independent elements farthest from the sinks in the adjacency matrix. Loop systems, where the system sink shows up in its own recursive analysis, are also identified and managed accordingly.

C. Data Export

During the development of the LEAPS Network Translator, the preferred export file format chosen for use by the VT SSM was the space-delimited Pajek ".net" text file format for its ease of maintenance and compatibility with most network graph tools

(Pajek, Gephi, NodeXL, NetworkX, etc). This format allows for additional information to be stored with each vertex definition without affecting the basic operability of the software. This allows for expandability to include data such as S3D properties, network types, and external system connections.

The LEAPS Network Translator export data structure, shown in Fig. 7, contains the vertex definition list and subsequent lists of corresponding arcs and edges. Most vertices are identified as a VC or SYS type in the output text. In each system description, at least one vertex is identified as a system sink ("SINK"), with additional data columns identifying either a system loop pattern or the corresponding network sources for a serial (non-loop) system. Fig. 8 shows the Pajek ".net" format representation of the chilled water system from Fig. 6.



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*Vertices 48
    1 CW_Pump4B_SYS                      0.1000   0.6593   0.5000          NA        SYS    0.050000
    2 FourWayPipe1_VC                    0.1395   0.5575   0.5000          NA        VC     0.000000
    3 CW_Pump4A_SYS                      0.1734   0.7176   0.5000          NA        SYS    0.050000
    4 Zone4_HVAC_CW_SYS                  0.1012   0.3535   0.5000          NA        SYS    0.000000
    5 TeePipe1_VC                        0.1856   0.1561   0.5000          NA        VC     0.000000
    6 TeePipe5_VC                        0.1362   0.7584   0.5000          NA        VC     0.000000
    7 CW_Cooler_4_SYS                    0.1350   0.8107   0.5000          NA        SINK   0.000000    LOOP
    8 FourWayPipe5_VC                    0.3540   0.4928   0.5000          NA        VC     0.000000
    9 EC_HeatExch3_CW_SYS                0.2994   0.4044   0.5000          NA        SYS    0.000000
   10 Zone3_HVAC_CW_SYS                  0.3538   0.3594   0.5000          NA        SYS    0.000000
   11 EC_HeatExch2_CW_SYS                0.4447   0.3073   0.5000          NA        SYS    0.000000
   12 FourWayPipe9_VC                    0.2878   0.1496   0.5000          NA        VC     0.000000
   13 FourWayPipe7_VC                    0.2962   0.2080   0.5000          NA        VC     0.000000
   14 FourWayPipe10_VC                   0.5977   0.1801   0.5000          NA        VC     0.000000
   15 FourWayPipe8_VC                    0.6128   0.2347   0.5000          NA        VC     0.000000
   16 EC_HeatExch1_CW_SYS                0.6867   0.3139   0.5000          NA        SYS    0.000000
   17 Zone2_HVAC_CW_SYS                  0.6217   0.3795   0.5000          NA        SYS    0.000000
   18 Glycol_HeatExch2_CW_SYS            0.5740   0.4397   0.5000          NA        SYS    0.000000
   19 FourWayPipe6_VC                    0.6332   0.5506   0.5000          NA        VC     0.000000
   20 TeePipe4_VC                        0.8704   0.1889   0.5000          NA        VC     0.000000
   21 Zone1_HVAC_CW_SYS                  0.7949   0.3461   0.5000          NA        SYS    0.000000
   22 TeePipe7_VC                        0.3163   0.7658   0.5000          NA        VC     0.000000
   23 CW_Pump3B_SYS                      0.3141   0.6926   0.5000          NA        SYS    0.050000
   24 TeePipe9_VC                        0.4357   0.7596   0.5000          NA        VC     0.000000
   25 CW_Pump3A_SYS                      0.4373   0.6914   0.5000          NA        SYS    0.050000
   26 TeePipe8_VC                        0.3190   0.8467   0.5000          NA        VC     0.000000
   27 TeePipe10_VC                       0.4271   0.8395   0.5000          NA        VC     0.000000
   28 CW_Cooler_3A_SYS                   0.4385   0.8912   0.5000          NA        SINK   0.000000    LOOP
   29 CW_Cooler_3B_SYS                   0.3010   0.9000   0.5000          NA        SINK   0.000000    LOOP
   30 TeePipe14_VC                       0.7150   0.7569   0.5000          NA        VC     0.000000
   31 CW_Pump2A_SYS                      0.7093   0.6846   0.5000          NA        SYS    0.050000
   32 CW_Pump2B_SYS                      0.5656   0.6841   0.5000          NA        SYS    0.050000
   33 TeePipe12_VC                       0.5693   0.7456   0.5000          NA        VC     0.000000
   34 TeePipe15_VC                       0.7164   0.8394   0.5000          NA        VC     0.000000
   35 TeePipe13_VC                       0.5856   0.8400   0.5000          NA        VC     0.000000
   36 CW_Cooler_2B_SYS                   0.6160   0.8874   0.5000          NA        SINK   0.000000    LOOP
   37 CW_Cooler_2A_SYS                   0.7168   0.8851   0.5000          NA        SINK   0.000000    LOOP
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Fig. 7. LEAPS Network Translator Chilled Water Pajek Export Format

VI. DEACTIVATION DIAGRAM TOOL

Adjacency lists or matrices can be developed to represent and analyze most systems; however, they are often insufficient for efficient analysis of multi-directional flow distributed systems. To develop an effective connectivity study of multi-directional ship systems, such as the zonal electric distribution system (ZEDS), it is often helpful or required to treat all system components as unidirectional within the scope of the analysis for much greater throughput. Preprocessing of multi-path system flow by way of a deactivation diagram can offer simultaneous state analysis and significantly improve the performance and capability of other connectivity analyses.

One such example of simultaneous analysis based on deactivation diagram unidirectional connectivity is the rapid ship system vulnerability analysis developed by Goodfriend [9] for incorporation into the VT Concept & Requirements Exploration (C&RE) process. This analysis tool interfaces with the deactivation diagram to apply probable damage to the vessel and calculate survivability metrics for individual ship designs developed as part of the Multi-Objective Genetic Optimization (MOGO) ship design process.

A. *Deactivation Diagrams in Network Theory*

Deactivation diagrams improve upon the structural-representative adjacency list by providing a pre-constructed unidirectional system connection layout to support simultaneous evaluation of all connections in a multi-state system. Deactivation diagrams and adjacency list graphs are considerably similar for ship systems containing no bidirectional connections between components, but in other circumstances the two differ broadly. It is also important to note that the deactivation diagram explicitly identifies and maintains the connections within multi-path systems using logical (AND/OR) gates, whereas an adjacency list does not typically include this additional information.

Building upon system adjacency data, which often only include undirected edges providing no indication of directionality, the development of deactivation diagram requires further analysis to include only directed connections that are utilized during anticipated ship operations. To do so, the Deactivation Diagram Tool pre-processes all data using the Depth-First Search (DFS) recursive algorithm to identify all

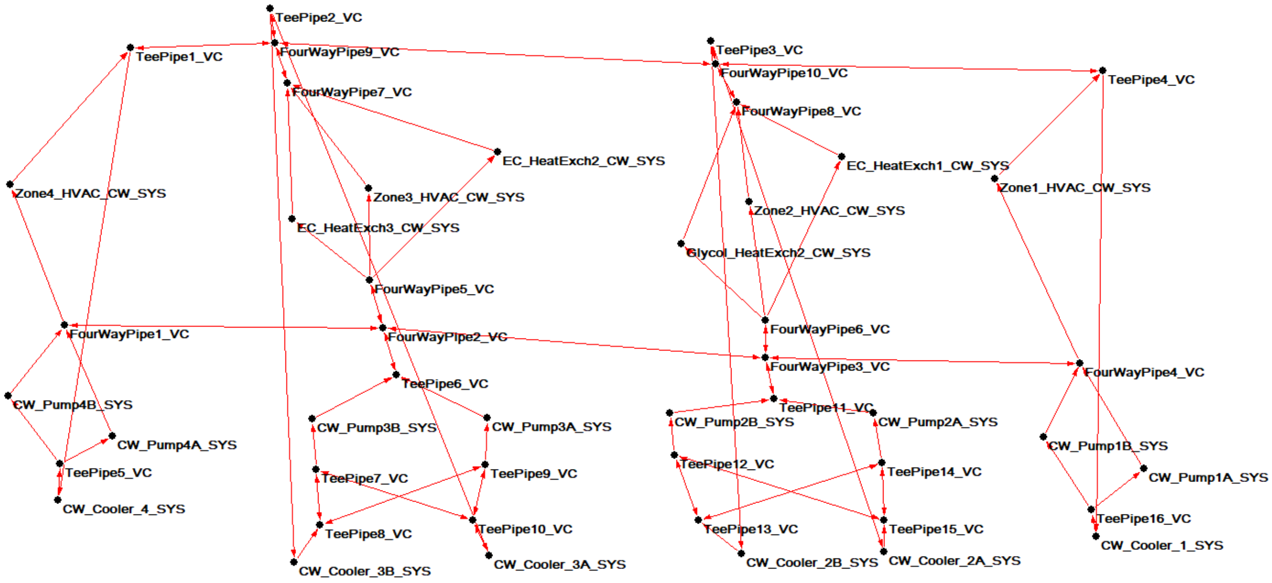

Fig. 8. Visualization of S3D-based Chilled Water Schematic in Pajek

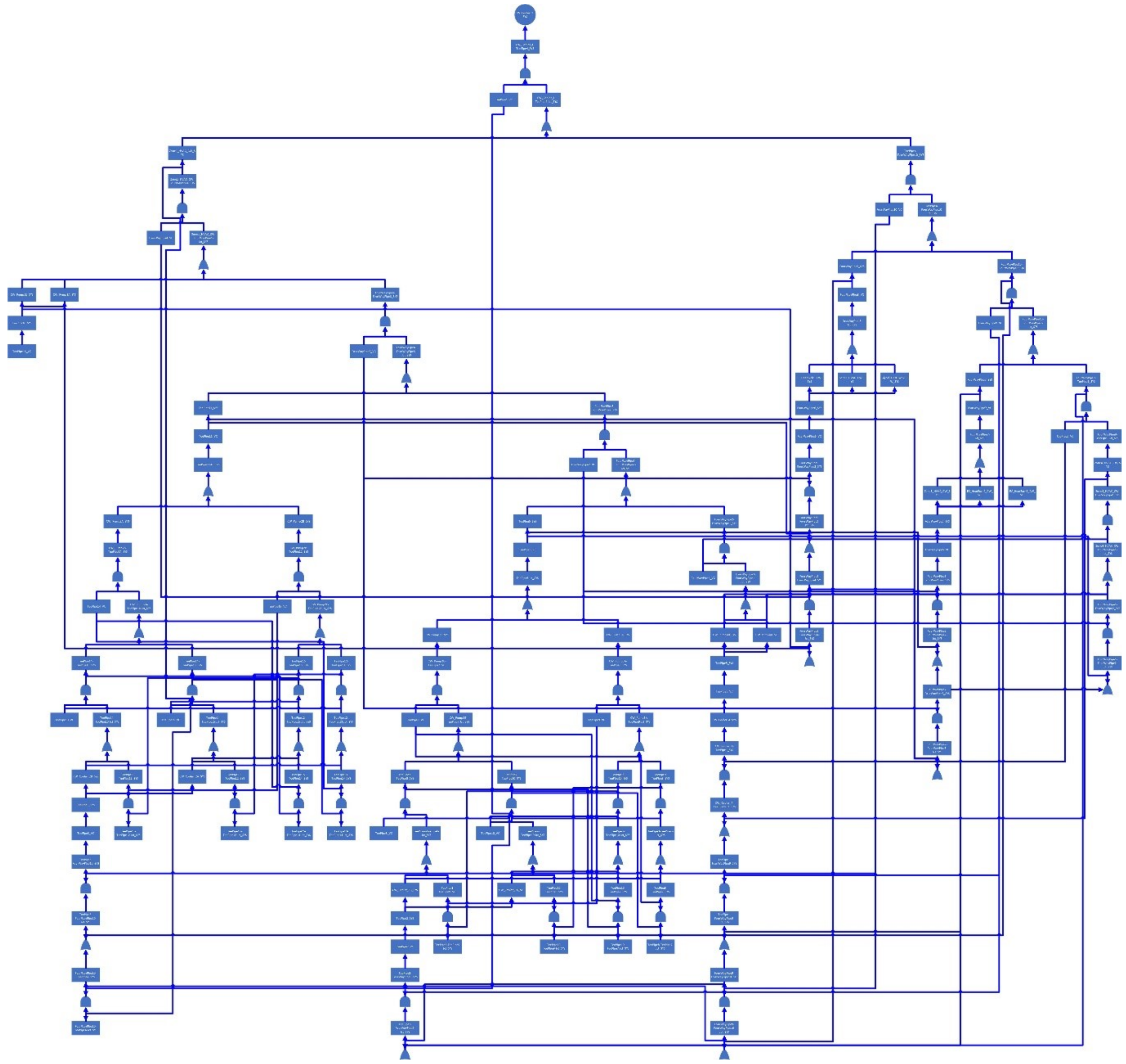

Fig. 9. Visio Single-Sink Chilled Water Deactivation Diagram

valid directed system flow patterns and reduces the adjacency list to represent only valid paths before passing the source data along to the unidirectional representation algorithm.

B. Tool Development

In developing a deactivation diagram layout, existing system components are restructured and the introduction of new components and paths is often required to complete the necessary changes to the system architecture so that all applicable dependencies are retained. To do so, vertices that connect multi-directional paths are abstracted from the system diagram and inserted as VCs for a derived series of substitute unidirectional flow systems. An analysis class in the tool handles looping through each vertex and applies changes to the network structure based on the number of parents, children, flow patterns, and other parameters according a predefined algorithm.

Certain requirements have been set in place for the analysis of systems in the VT C&RE process and are adhered to in the development of deactivation diagrams for the system. The most prevalent of these is the distinction between VCs and SYS's within the layout. Each of these has specific behaviors in the deactivation diagram analysis and must be updated to fit the set of rules governing the analysis. For more information on the distinctions between VCs and SYS's in the VT deactivation diagram, see [9].

Consistent with the current design of VT SSM tools, the Deactivation Diagram Tool was developed using Microsoft Visual Basic for Applications (VBA) embedded in Excel. This tool was developed for incorporation into the VT C&RE process as a supporting tool for preparing ship system data for further analysis. Input data provided to the tool exists in structured worksheet data or the Pajek ".net" network file format. Results of this tool are saved within in the containing workbook and are optionally exported back to a ".net" file and/or to representative diagrams in Microsoft Visio (where supported). Fig. 9 shows an example of the Visio deactivation diagram output for the AFO Chilled Water System.

Fig. 10 presents the results of the complete deactivation diagram analysis of one variant of the mechanical propulsion system developed by VT, previously shown in Fig. 3. The Propulsion_SYS capability node, at the top of the figure, is followed by the totality of the ship system multiplex directly supporting the MECH plex. Large ship systems containing multiple plexes like the one shown present a significant challenge for the validation of the tool operation. Despite manual verification of the Deactivation Diagram Tool utilizing small network diagram samples to ensure expected behavior, validation of large systems is limited by the scope of the analysis. Total system validation of complex systems currently relies heavily on system path checking for consistency and localized verification checks for diagram accuracy. Future efforts may include reverse-engineering analyses of deactivation diagrams into adjacency matrices for improved system comparison and validation.

VII. CONCLUSION

This paper has presented a methodology for extracting network definitions of systems stored in a FOCUS-compliant database and demonstrated how the architecture framework for distributed systems may be implemented in areas of system validation, equipment sizing, vulnerability, reliability, and network design. Figures included in this paper present an example workflow for a system described in LEAPS and utilized by external tools. Developments described in this paper were only possible through the combined efforts of multiple research groups and utilizing the consistent data structure of the LEAPS database.

Software tools presented in this paper have been developed to efficiently access and process the LEAPS database to promote network analysis. Several assumptions were made regarding the purpose of ports/terminals based on observed characteristics, leading to hard-coded object references for system directionality and component roles (sources/sinks). The current FOCUS PMM lacks a standardized methodology for identifying the directionality through ports/terminals; adding standardized port flow direction would greatly increase the flexibility of derived analysis tools to handle unidentified and future components.

Further, the concept of operational system nodes, which capture system operational requirements tied to a logical structure but not necessarily to a physical component or location, is not currently available in LEAPS. The ontology for storage of such a concept in LEAPS needs to be explored and defined.

To date, the development of network analysis tools has remained reliant on predetermined system characteristics and interoperability through external data files. We have shown that most of the source data necessary to run these programs is available in LEAPS and has the potential to be made more available to the end user. With the recommended changes to identify directionality and operational nodes in the FOCUS PMM, the door will be opened to future incorporation of existing network analysis tools into an integrated LEAPS-compatible environment.

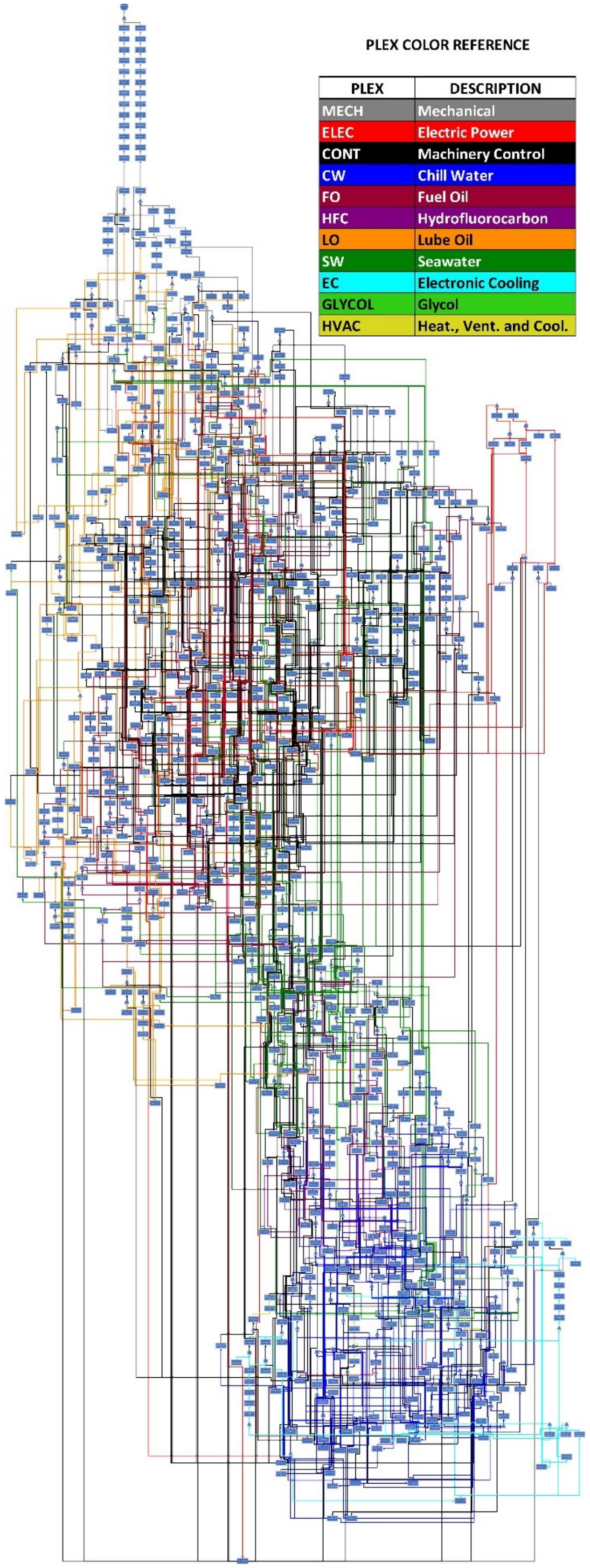

Fig. 10. Mechanical Propulsion Operational System / Deactivation Diagram

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