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Hidden Structures: Using Graph Theory to Explore Complex System of Systems Architectures

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Abstract

- Increasing interconnectivity in complex engineered systems of systems (SoS) leads to difficulties ensuring/understanding quality, flexibility, reliability, etc.
  - Reductionist approaches may fail to provide insight into key properties.
- Here, a NATO Architecture Framework for a Search and Rescue use case, is analysed using methods and concepts from graph theory:
  - E.g., degree distribution, density, connected components, modularity.
- This approach supports architectural decision making:
  - E.g., dependency allocation, boundary identification, areas of focus and selection between architectures.
- …but it must be deployed with care.

About Me

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  - Motivation
  - Current Approaches
  - Proposed Approach
- Part 2 – Methodology
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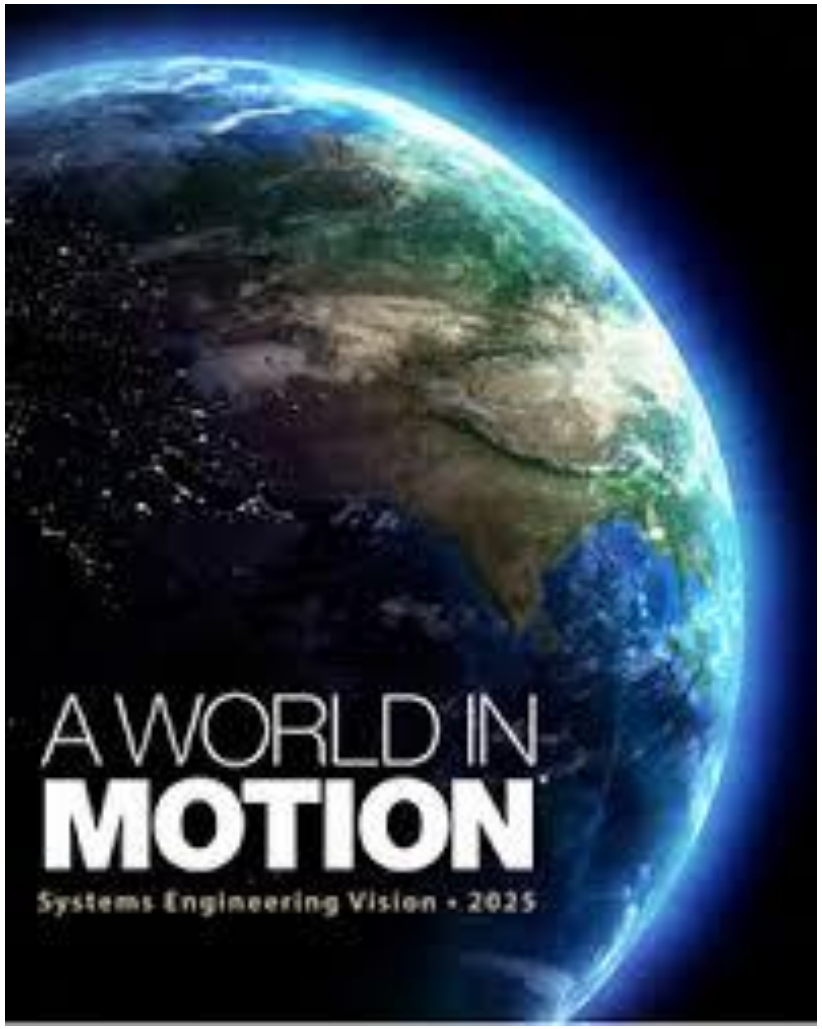
- Part 4 – Discussion
- Part 5 – Conclusions and Further Work

Motivation (1): SoS Design

- System of Systems (SoS) Characteristics:
  - Autonomy
  - Belonging
  - Connectivity
  - Diversity
  - Emergence
- Emergence…the principle that entities exhibit properties which are only meaningful when attributed to the whole, not to its parts [Boardman & Sauser]

INCOSE 2025 Vision



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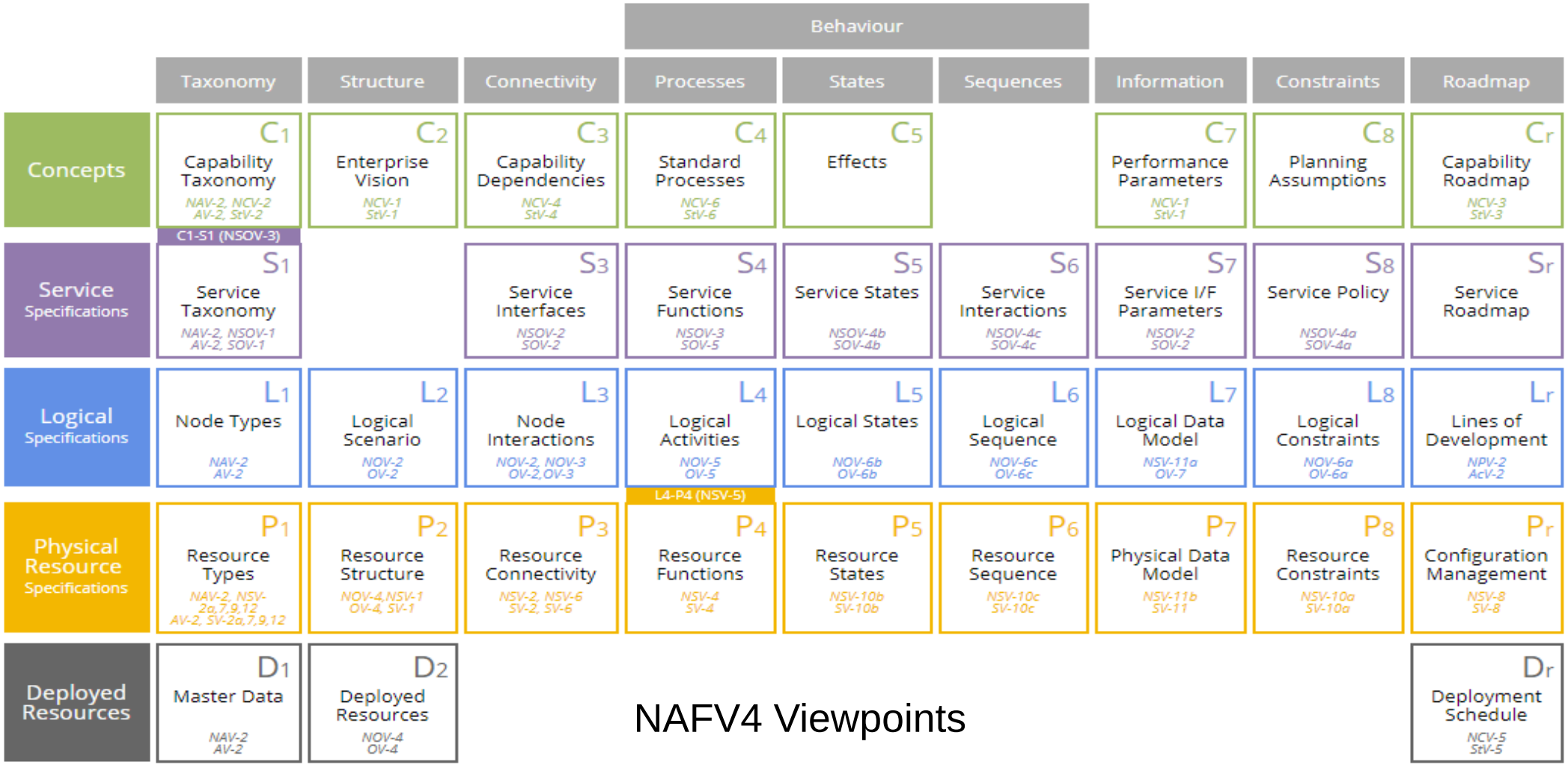
Motivation: System Architecture



NAFV4 Viewpoints

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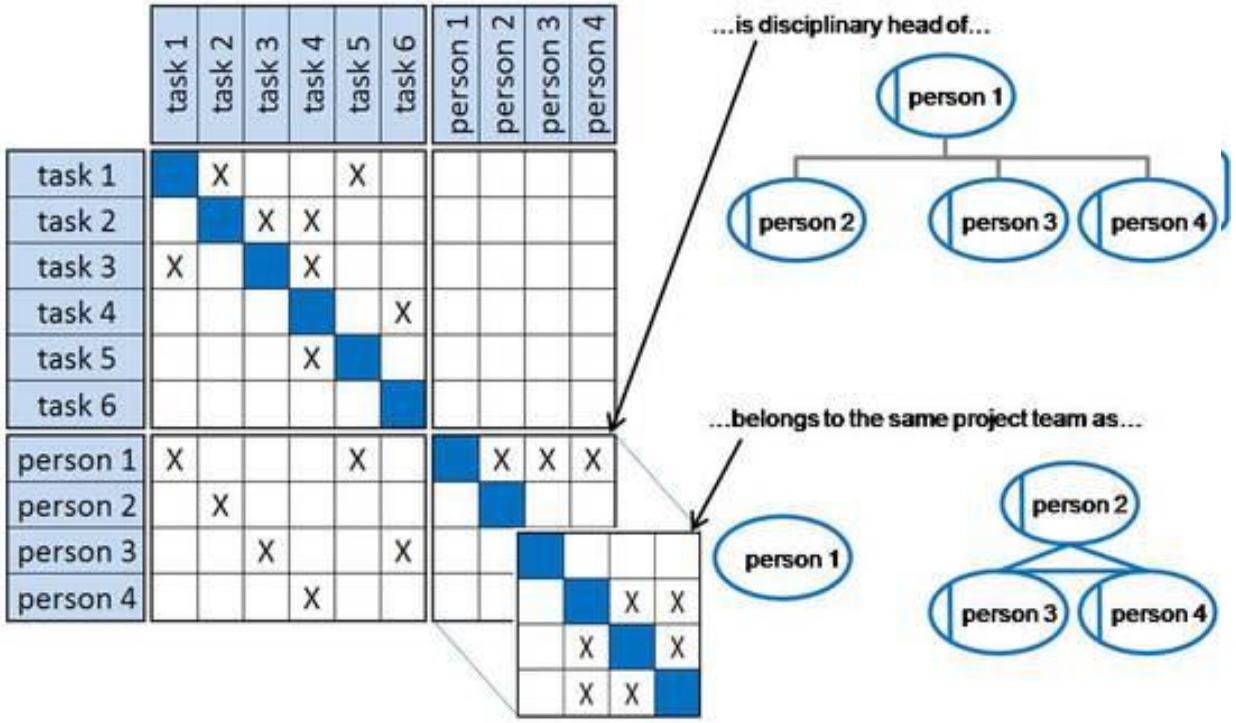
Current Approaches: Matrices

- "A design structure matrix (DSM) provides a simple, compact, and visual representation of a complex system that supports innovative solutions to decomposition and integration problems" [Browning]
- A Domain Mapping Matrix (DMM) include multiple domains
- The two can be combined to create a Multiple-Domain Matrix (MDM)



DSM, DMM & MDM Examples taken from Design Society

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Current Approaches: Matrices

	Environmental Domain	Social Domain	Functional Domain		Technical Domain	Process Domain
	System Drivers	**Stakeholders**	**Objectives**	**Functions**	**Objects**	**Activities**
System Drivers	**System Drivers X System Drivers**	Stakeholders X System Drivers	Objectives X System Drivers	Functions X System Drivers	Objects X System Drivers	Activities X System Drivers
Stakeholders	System Drivers X Stakeholders	**Stakeholders X Stakeholders**	Objectives X Stakeholders	Functions X Stakeholders	Objects X Stakeholders	Activities X Stakeholders
Objectives	System Drivers X Objectives	Stakeholders X Objectives	**Objectives X Objectives**	Functions X Objectives	Objects X Objectives	Activities X Objectives
Functions	System Drivers X Functions	Stakeholders X Functions	Objectives X Functions	**Functions X Functions**	Objects X Functions	Activities X Functions
Objects	System Drivers X Objects	Stakeholders X Objects	Objectives X Objects	Functions X Objects	**Objects X Objects**	Activities X Objects
Activities	System Drivers X Activities	Stakeholders X Activities	Objectives X Activities	Functions X Activities	Objects X Activities	**Activities X Activities**

t_{past}

$t_{present}$

t_{future}

Engineering Systems Matrices taken from Bartolomei et al 2012

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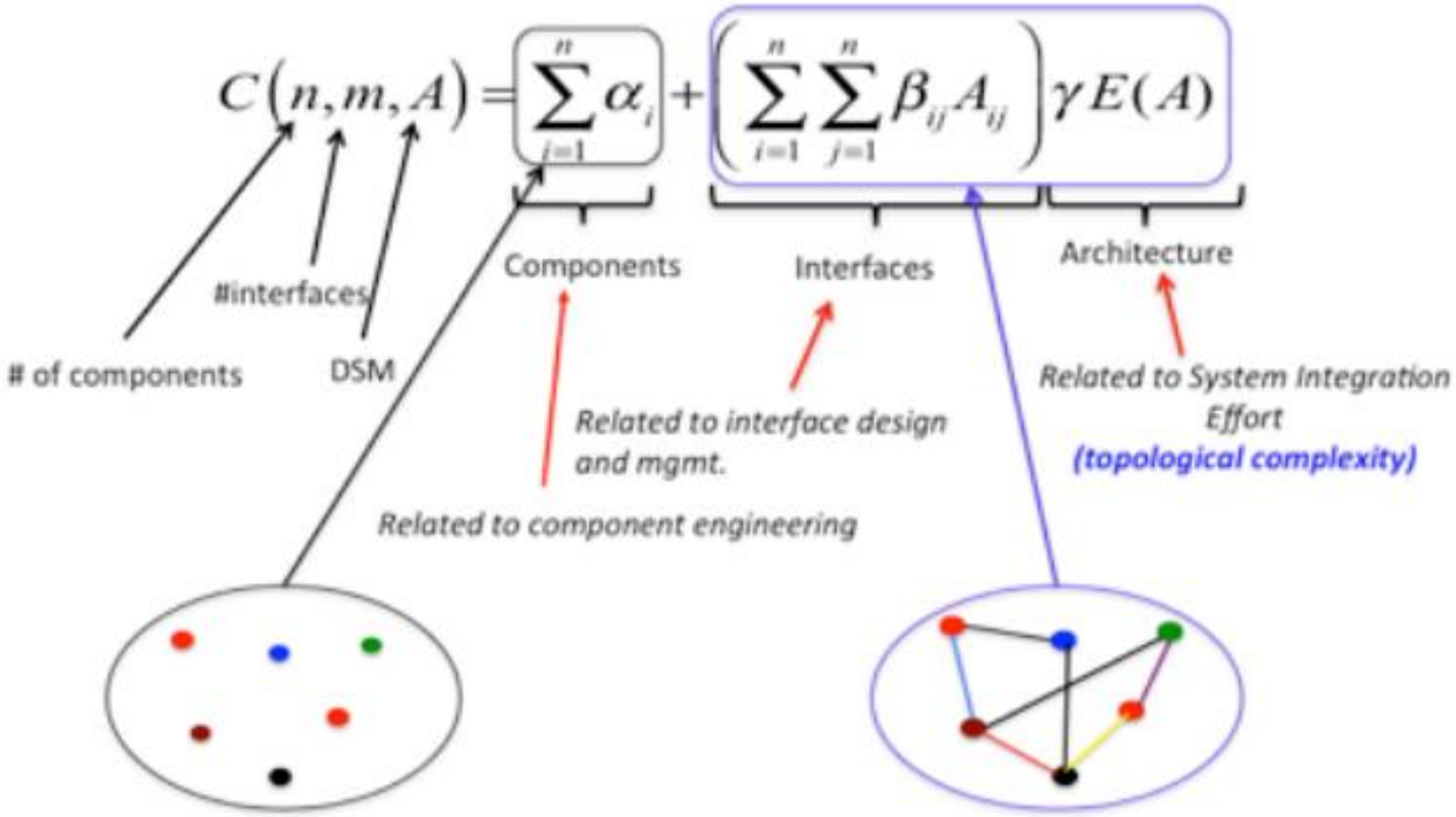
Current Approaches: Graph Theory



Structural Complexity Metric taken from Sinha & De Weck 2013

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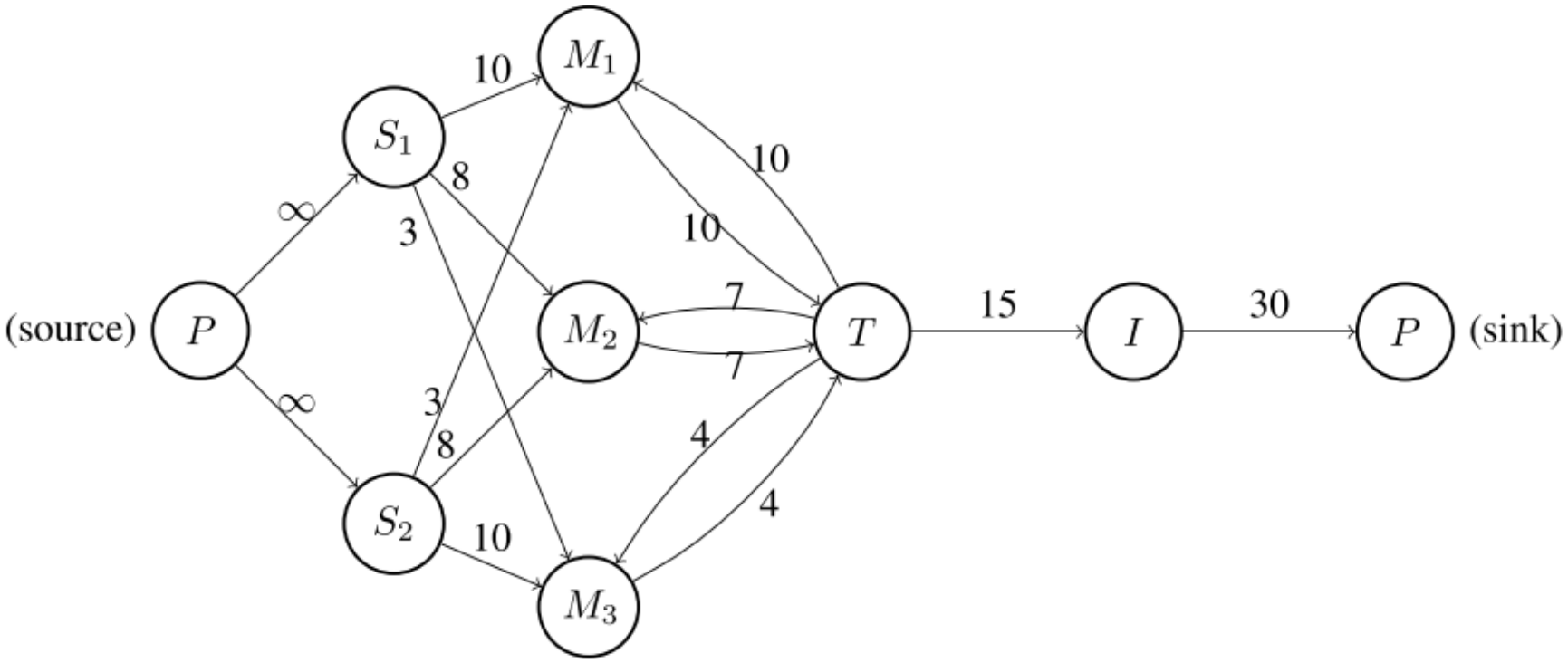
Current Approaches: Graph Theory



Manufacturing System Graph Theoretic Network taken from Harrison 2016

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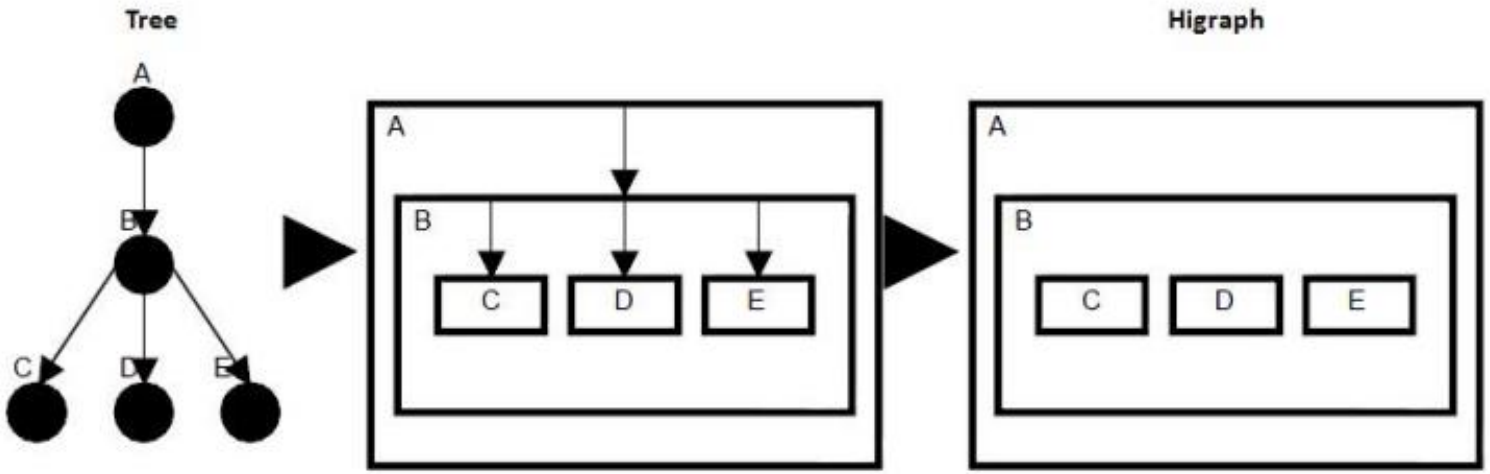
Current Approaches: Graph Theory



Developing a Higraph from a tree taken from Aboutaleb 2017

Current Approaches: Proposed Approach

- Analyse to explore the underlying structure and relationships of a complex SoS architecture
- Support shared understanding
- Support decision making
- Coherent with SoS engineering methodologies and system architecture frameworks

Methodology

- Part 1 - Introduction
- Part 2 – Methodology
  - Problem Characterisation
  - Graph Based Model
- Part 3 – Analysis
- Part 4 – Discussion
- Part 5 – Conclusions & Further Work

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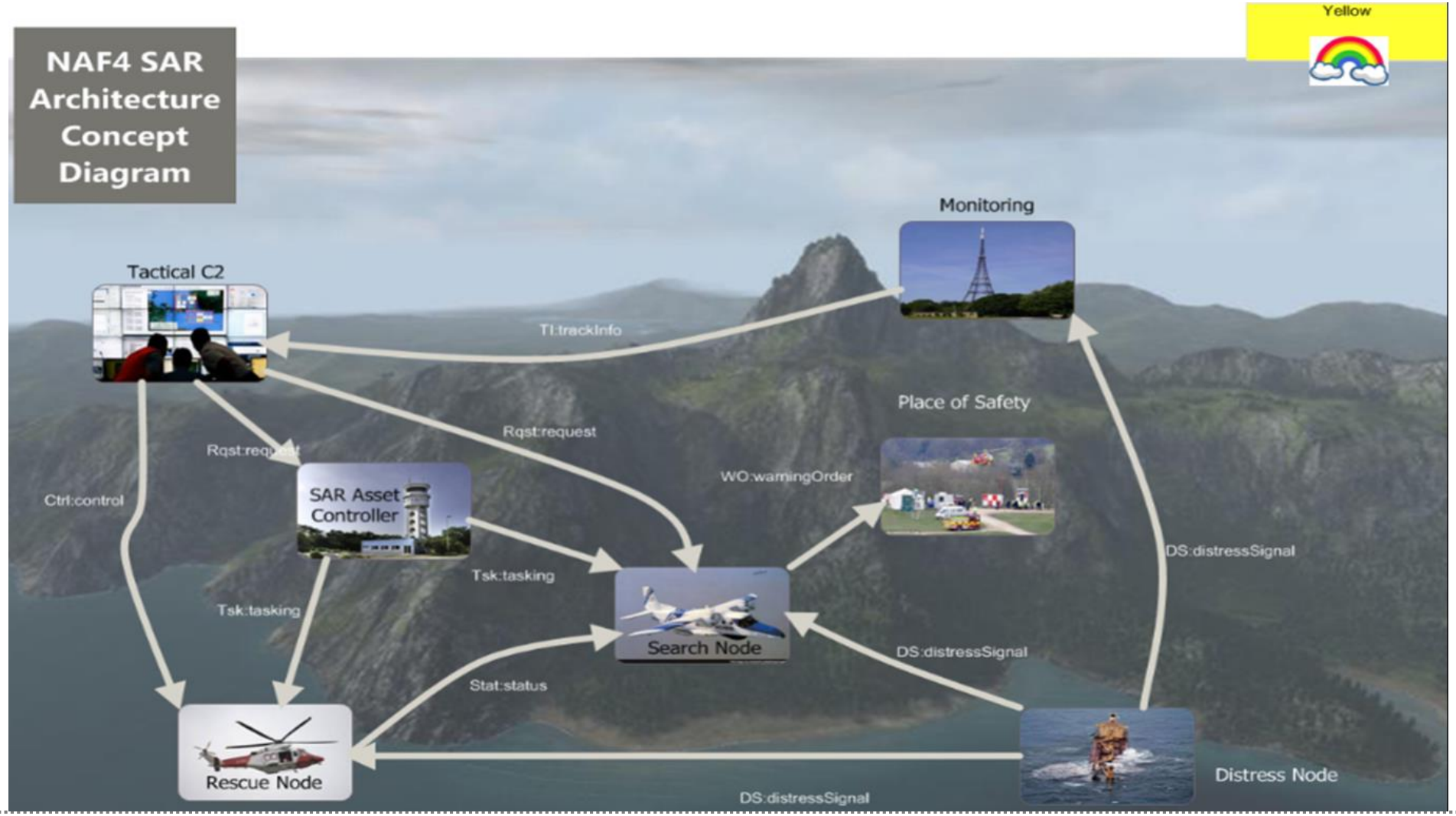
Problem Characterisation



OV1a High Level Operational Concept Graphic View taken from NAFv4 Chapter 2 Example,. Libert & Garnier J-L

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Problem Characterisation

System	Complex System	System of Systems	SAR Use Case Characterisation
Interacting elements [SEBoK, ISO 15288, Checkland, Boardman & Sauser][3-5]	Interconnected components [Bar-Yam, Mitchell, Waldrop]	Interconnected (connectivity) and diverse components or systems [Maier, Boardman & Sauser]	Heterogeneous components and relationships between them
Deliberately brought together [SEBoK, ISO 15288, Checkland, Boardman & Sauser]	Behaviour cannot be inferred from component behaviour [Bar-Yam, Mitchell, Waldrop, Crawley et al]	Constituent systems deliberately brought together (belonging) [Maier, Boardman & Sauser, ISO 15288]	Although aspects of SAR could be conducted by individual systems, a full maritime SAR capability relies on the overall SoS availability.
Defined purpose [ISO 15288]	May be adaptive and self organised (lack of centralised control) [Kaisler & Madey, Miller, Ladyman et al]	Defined purpose [Maier, Jamshidi]	The SAR SoS serves a clear purpose of Search and Rescue in the maritime domain.
May exhibit emergence [Checkland, Boardman & Sauser]	Capacity for emergence [Bar-Yam, Mitchell, Waldrop, Crawley et al]	Operational & managerial independence (including autonomy) [Maier, Jamshidi, Cocks]	Each constituent system is a system in their own right with their own management and operations, brought together for a common purpose.
		Capacity for emergence [Maierer, Boardman & Sauser, Jamshidi, ISO 15288]	Emergent behaviour is the ability of the SoS to effectively coordinate a search operation over a large area for a small, moving object and recover it with precision and speed to a place of safety.

Table of key characteristics for Systems, Complex Systems, System of Systems & the SAR Use Case

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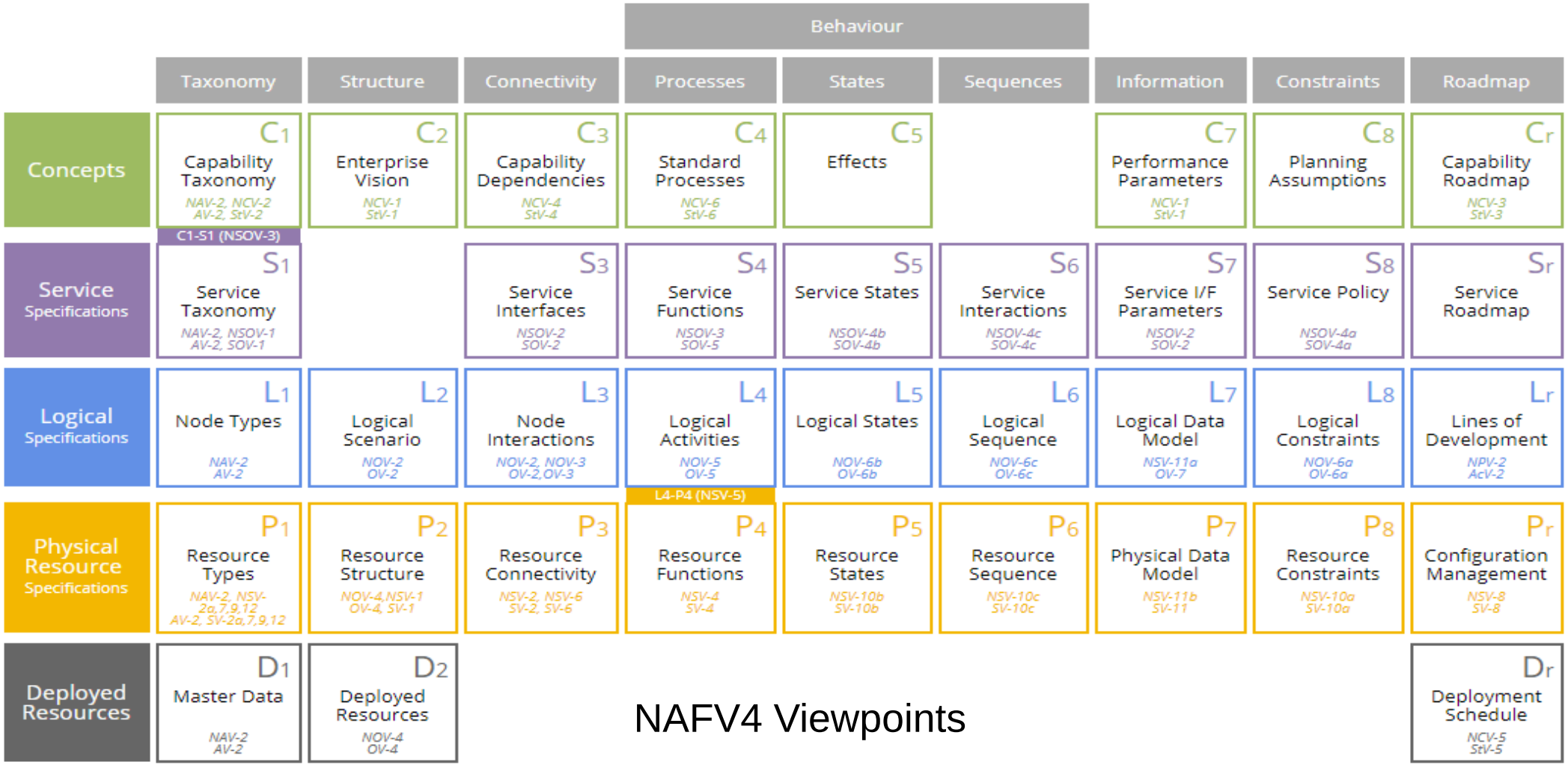
Problem Characterisation



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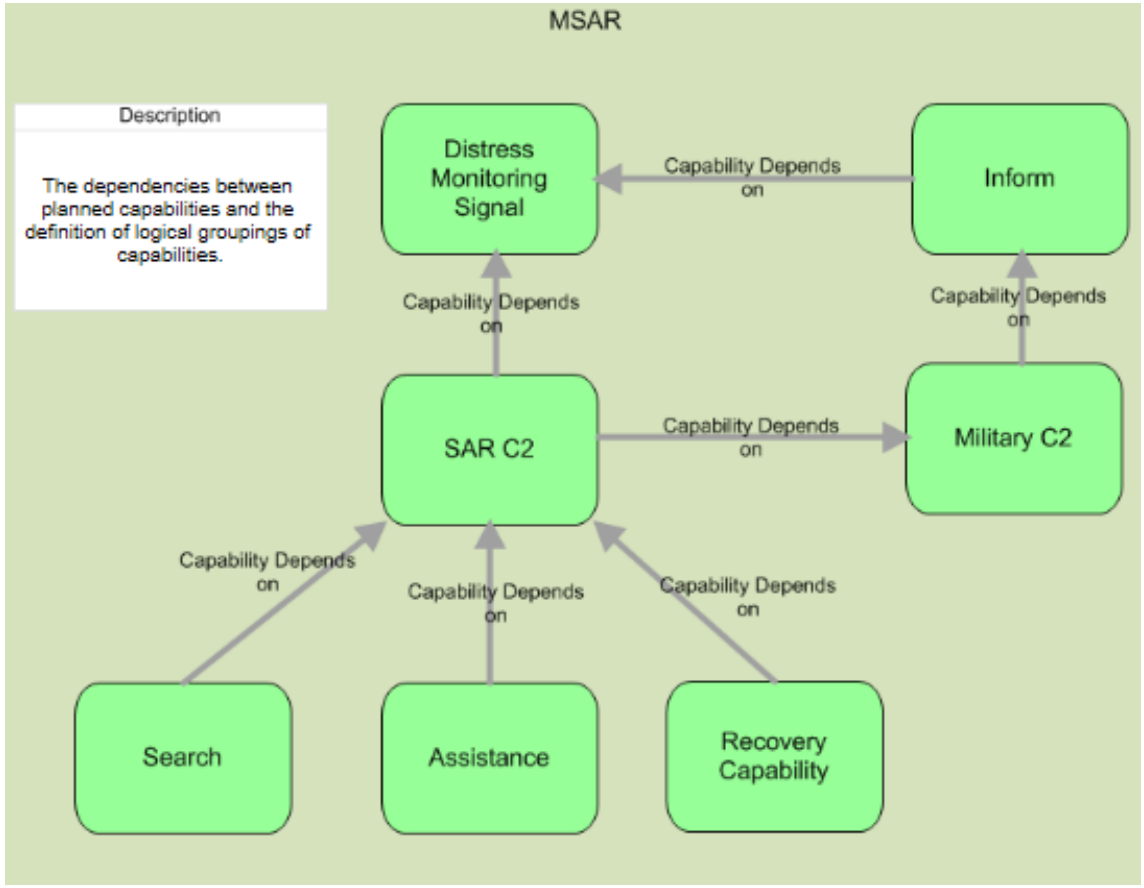
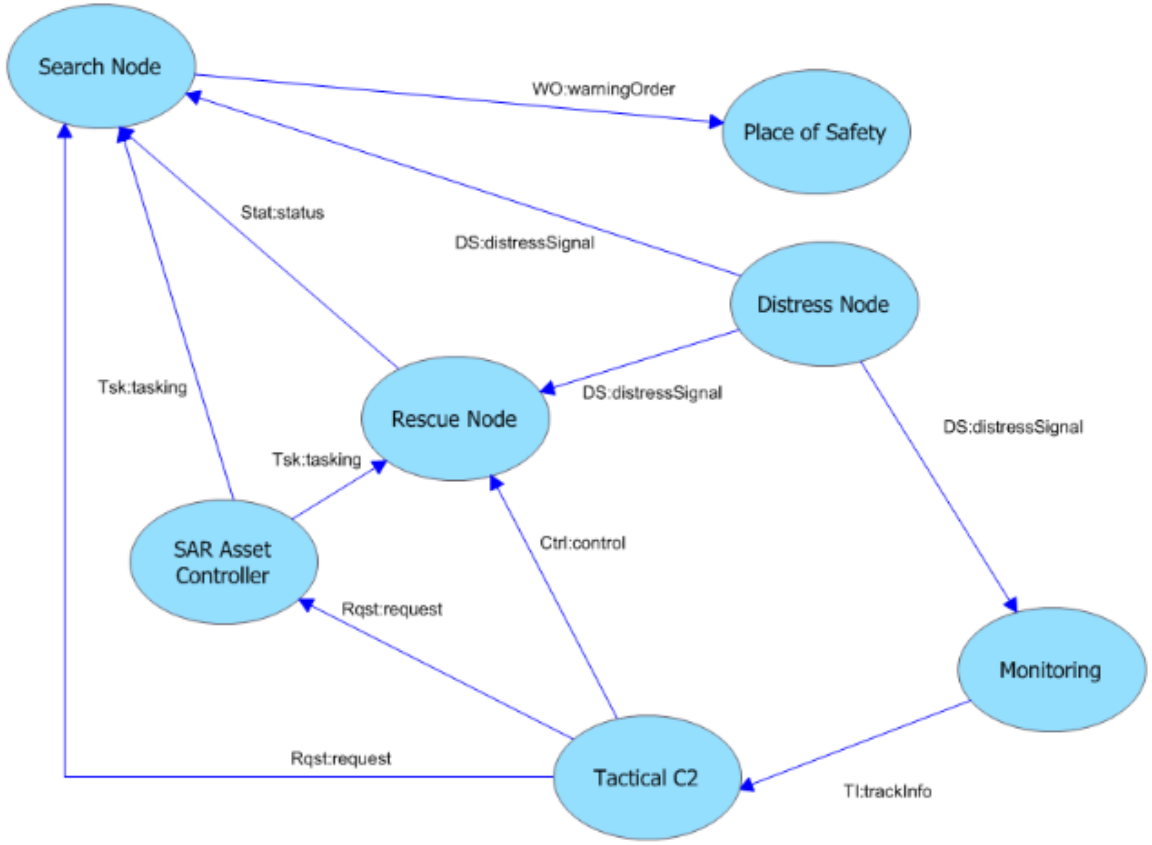
Graph Based Model



Capabilities C1 View



Logical Nodes L1 View

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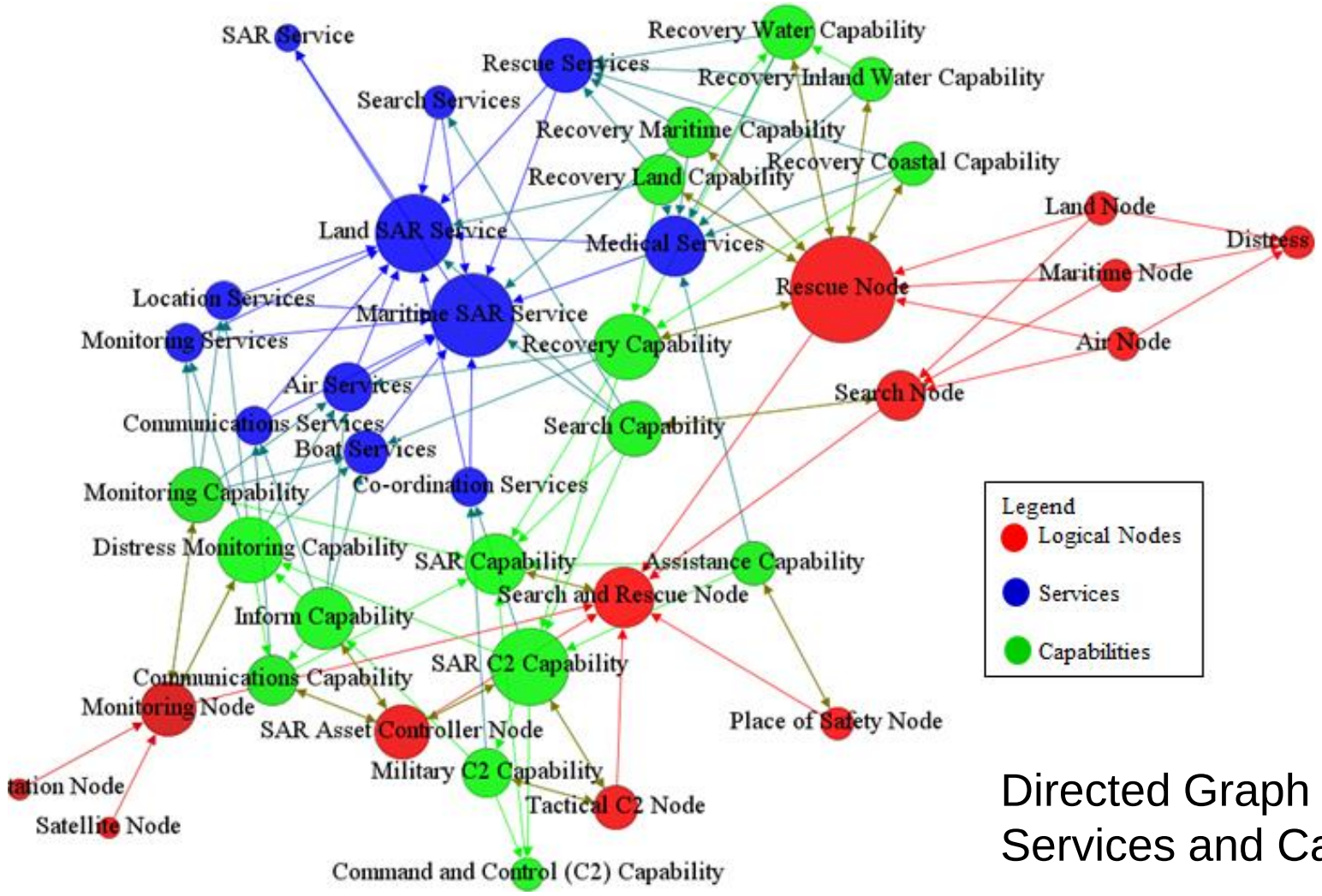
Graph Based Model



Directed Graph of Logical Nodes, Services and Capabilities

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Analysis

- Part 1 - Introduction
- Part 2 – Methodology
- Part 3 – Analysis
  - Degree Distribution
  - Density
  - Strongly Connected Components
  - Community Detection (Modularity)
- Part 4 – Discussion
- Part 5 – Conclusions & Further Work

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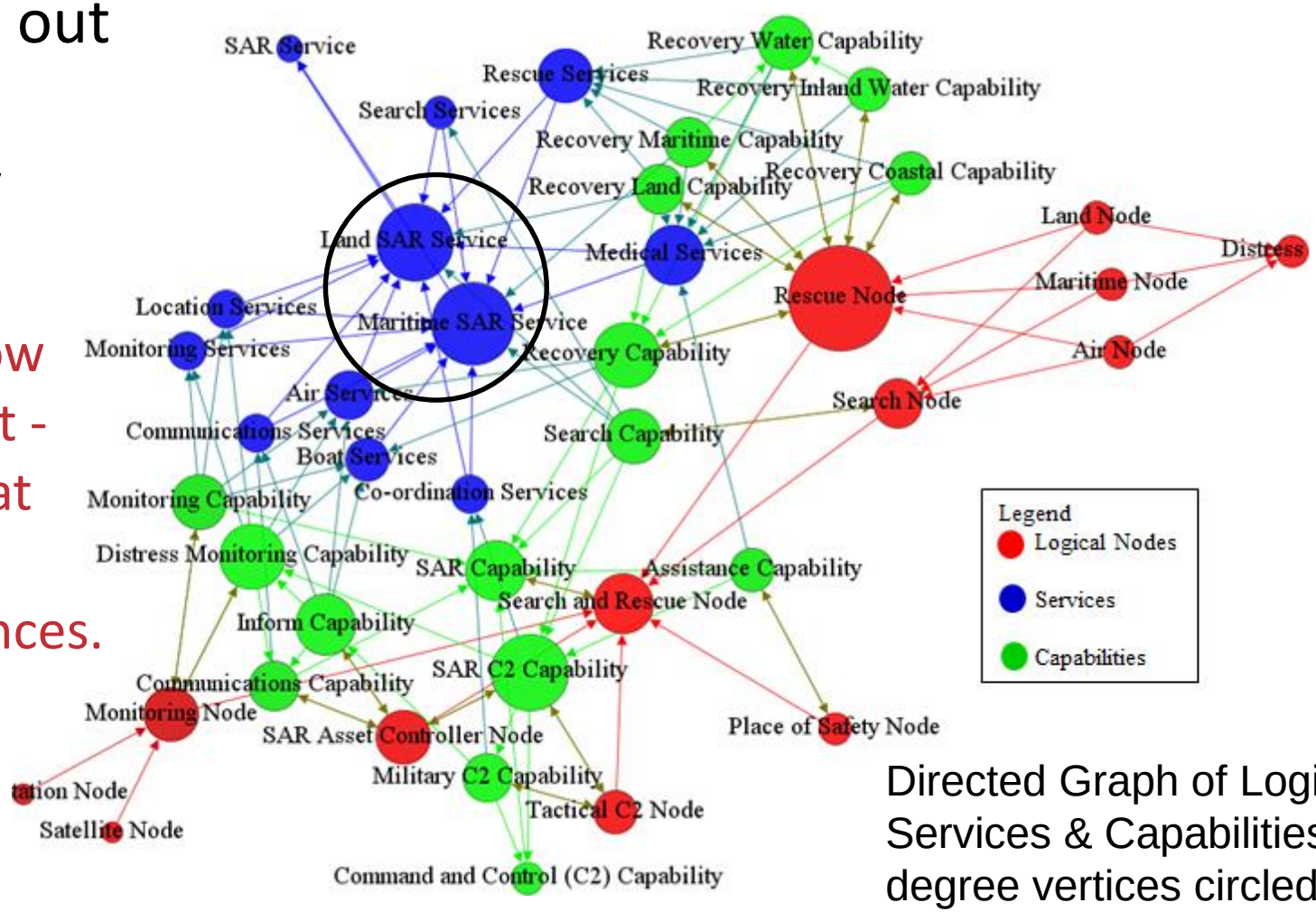
Degree Distribution

- Examining the in and out degree distribution highlights potentially important vertices:
  - High in degree and low out degree of interest - loss or removal of that vertices could have significant consequences.



Directed Graph of Logical Nodes, Services & Capabilities with high degree vertices circled

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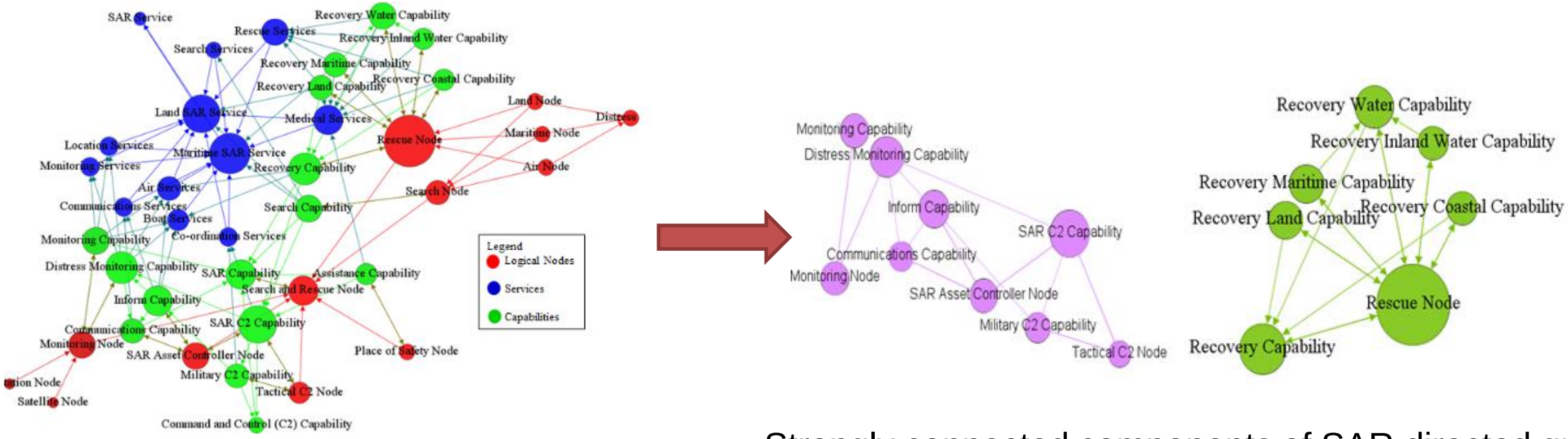
Density

- How densely connected is the graph?
- $$D = \frac{|E|}{|V|\,(|V|-1)} \quad (1)$$
- where D is the graph density, E is the number of edges and V is the number of vertices in the graph
- Hints at integration or dependency management challenge
- Potential to compare architectures

Strongly Connected Components

- Strongly connected if path (distinct sequence of edges connecting vertices) in each direction between each pair of vertices
- Groupings of vertices that can reach other: ‘core’ and ‘periphery’



Strongly connected components of SAR directed graph

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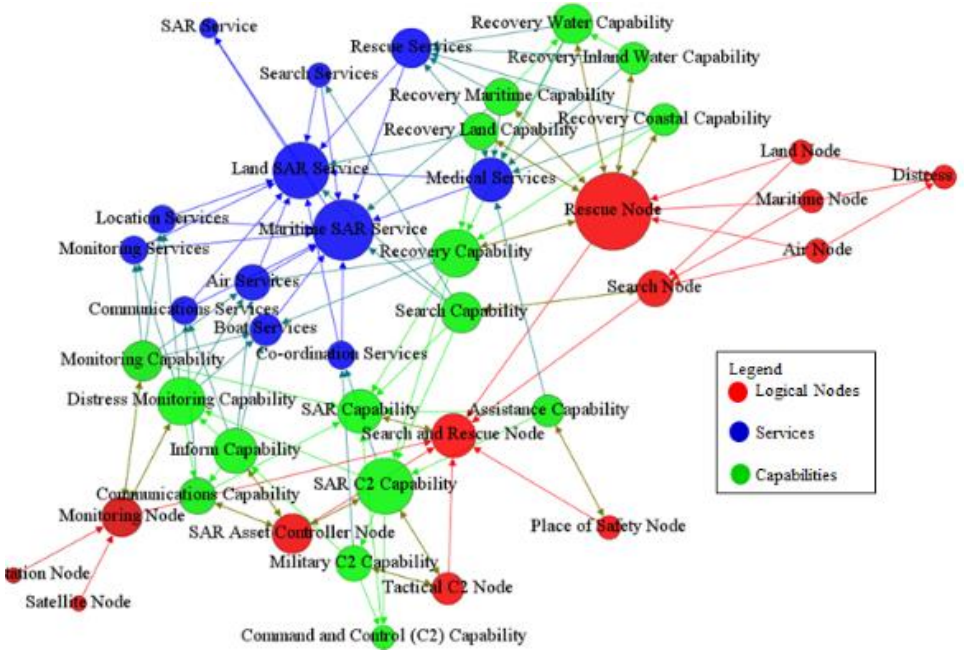
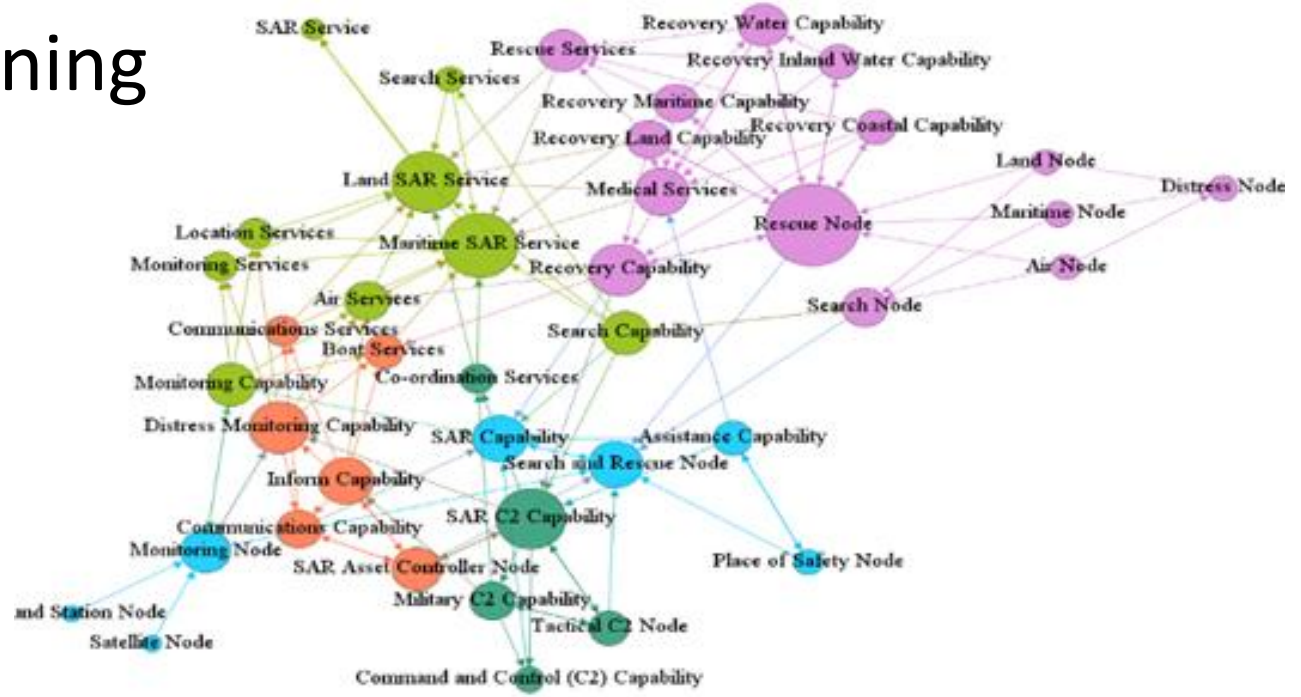
Community Detection (Modularity)

- Communities of vertices with many edges joining vertices of the same community and comparatively few between communities
- Alternative approach to partitioning





Communities detected within SAR directed graph

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Discussion

- Part 1 - Introduction
- Part 2 – Methodology
- Part 3 – Analysis
- Part 4 – Discussion
  - Utilisation
  - Limitations & Cautions
- Part 5 – Conclusions & Further Work

Utilisation

- Enable visualisation of structure and relationships that may remain hidden
- Identify areas to focus attention on
- Alternative approach to partitioning, boundary and dependency allocation
- Metrics in isolation meaningless – require organisational learning

Limitations & Cautions

- Architecture: Art & Science
- Large abstraction - heterogeneous entities and relationships modelled
- Selection of scope for graph based model
- Edge weights could distinguish importance/intensity of connection
- Only explored metrics in one ‘timeframe’
- Metrics in isolation meaningless – require organisational learning
  - Recommendation – use for specific purpose; visualise structure, identify areas of interest, temper decisions

Conclusions and Further Work

- Part 1 - Introduction
- Part 2 – Methodology
- Part 3 – Analysis
- Part 4 – Discussion
- Part 5 – Conclusions & Further Work
  - Further Work
  - Summary
  - Conclusions

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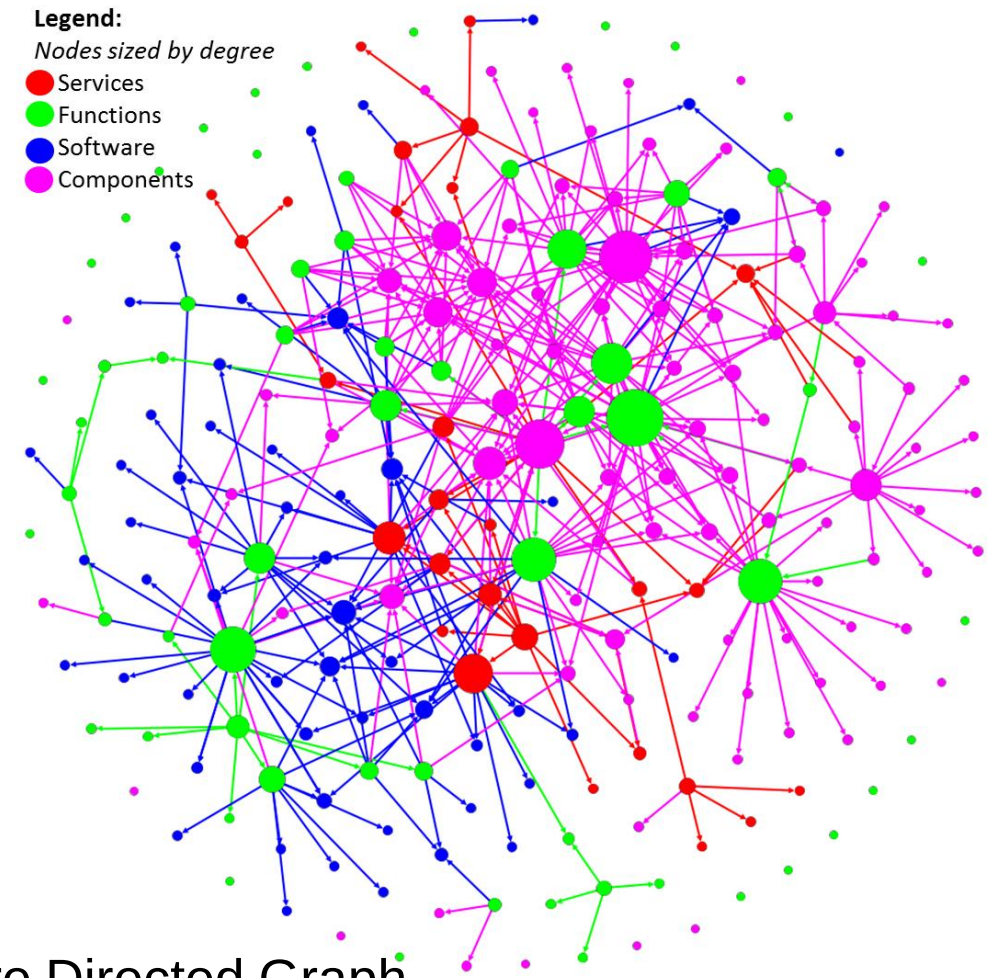
Further Work

- Include edge weights
- Dynamic considerations of relationships
- Additional Use Cases



Tactical Military Communications Enterprise Architecture Directed Graph

Summary

- Challenge: supporting decision making on complex SoS architectures
- Graph based models have been widely used to identify important entities
- Graph based models can be used to explore complex SoS architectures
- Topological properties such as degree distributions, density, strongly connected components and community identification can support investment decisions, boundary selection, a new perspective on partitioning
- Such an approach has several cautions
- Recommended to be used as an additional perspective

Conclusions

- Complimentary view
- Integrate data already available into a single directed graph for analysis
- Potentially important characteristics become tractable
- May support decision making around complex SoS architectures
- Further work needed to qualify the utility of this approach

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Thank you

Any Questions?

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