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Robustness of decentralized decision-making architectures in command and control systems

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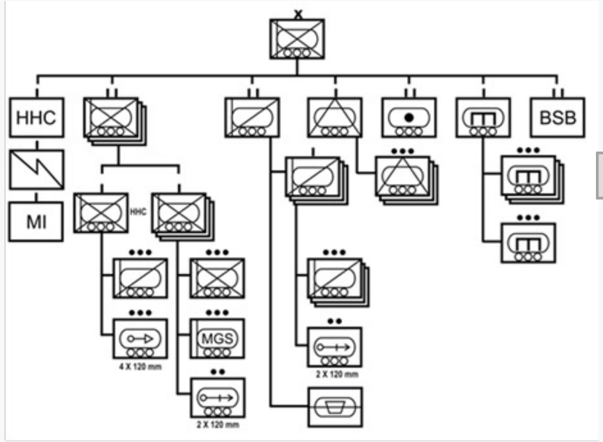
SERC DOCTORAL STUDENT FORUM 2022

Motivation

- Operation Anaconda[1], 2002
  - ➢ Initial use of "big Army" forces in OEF
  - ➢ Unclear delineation of authorities across hierarchy
  - ➢ CENTCOM approval for some tactical actions
  - ➢ Modern ICT ≠ clear, concise communication



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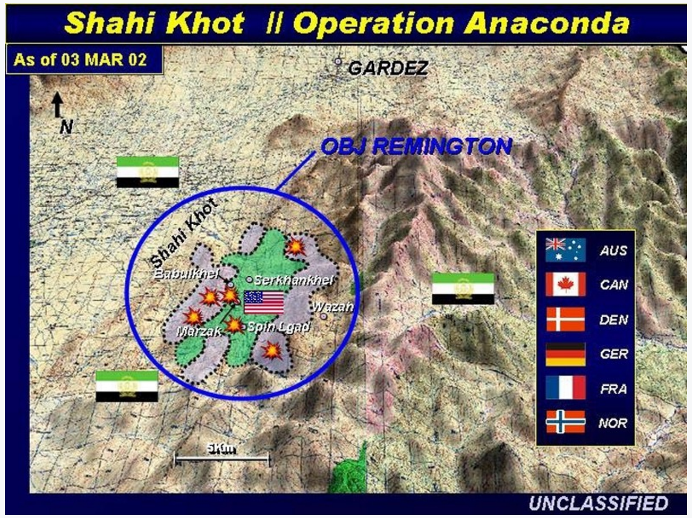
Traditional, centralized structure lacked robust performance



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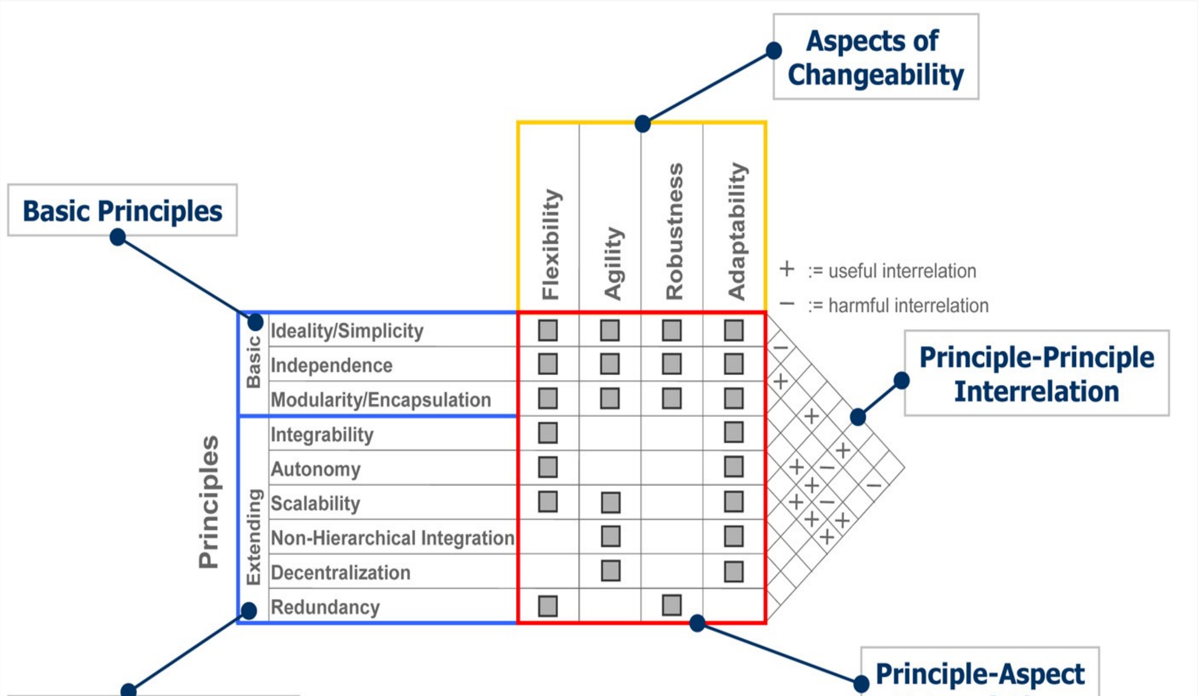
Literature

Decentralization and the "-ilities"

- Tied to
  - Agility, Adaptability[2-3]
  - Flexibility[4-6]
  - Scalability[7-8]
  - Evolvability[9-11]

Decentralized Architecture

- Not frequently explored in isolation from other related principles
  - Non-hierarchical Integration[4-6]
  - Modularity[9-11]



Frick & Schulz[2]

Research Question

- How does *decentralization* in a system's decision-making architecture influence the system's performance *robustness*?

Methodology

- Model a C2 system capable of adopting a range of decision architectures, from centralized to decentralized
- Simulate an operating environment sufficiently diverse and dynamic to stress the system
- Observe performance and robustness characteristics (Experiment 1)
- Explore decentralization schemes to improve robustness (Experiment 2)

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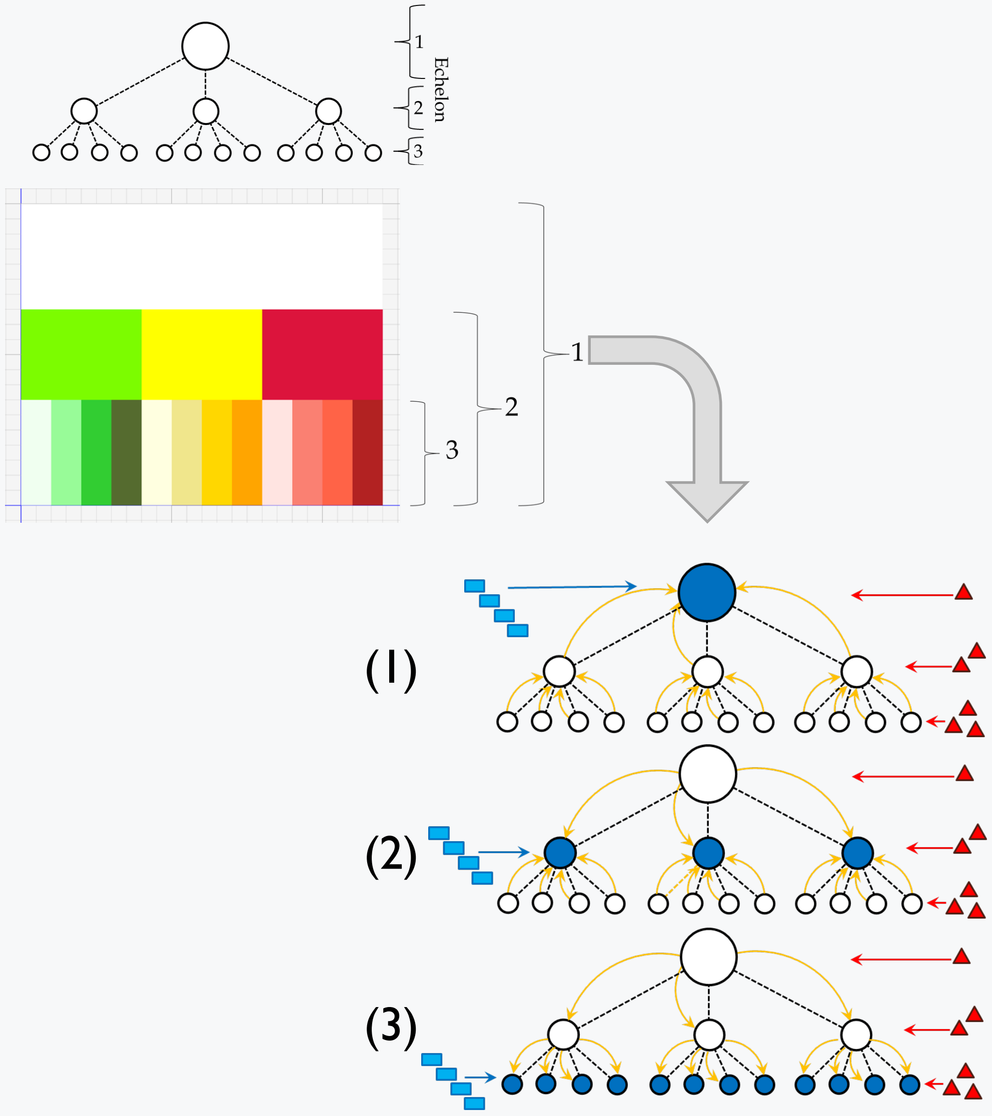
System Description

- Theater Air Control System
  - ➢ Directs combat aircraft to neutralize targets
  - ➢ Consists of decision *agents*
  - ➢ Connected though hierarchical relationships
- System Functions
  - ➢ Detects targets across battlespace
  - ➢ Distributes information to decision-makers
  - ➢ Decides how to use assets to neutralize targets
- Decision-making
  - ➢ Control is consolidated at single echelon (1, 2, or 3)



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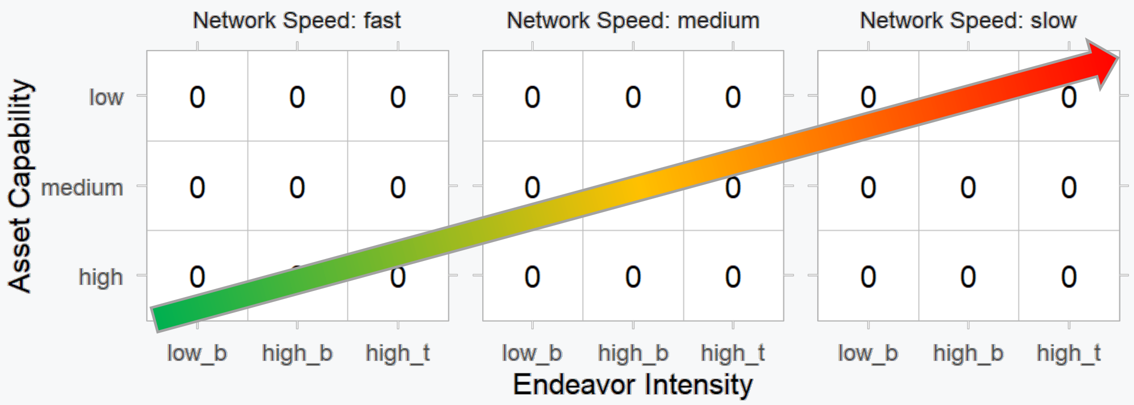
Environment Description

- 3 dimensions, 3 discrete treatment levels
  - Intensity – amount of targets, assets
  - Network Speed – message propagation delay
  - Asset Capability – how fast, far aircraft can travel
- 3^3 discrete "circumstances" from which to assess robustness



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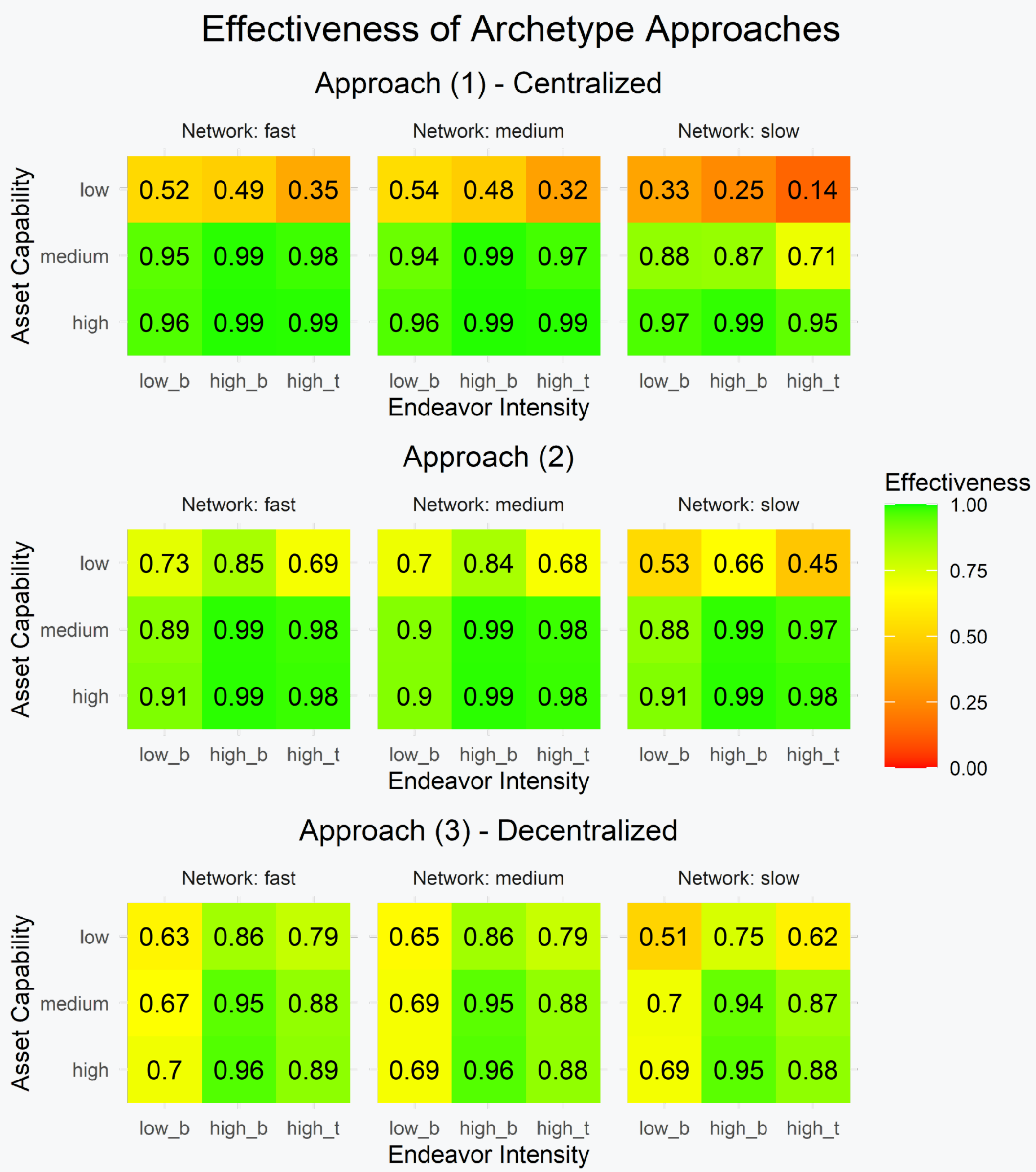
Experiment 1 - Effectiveness

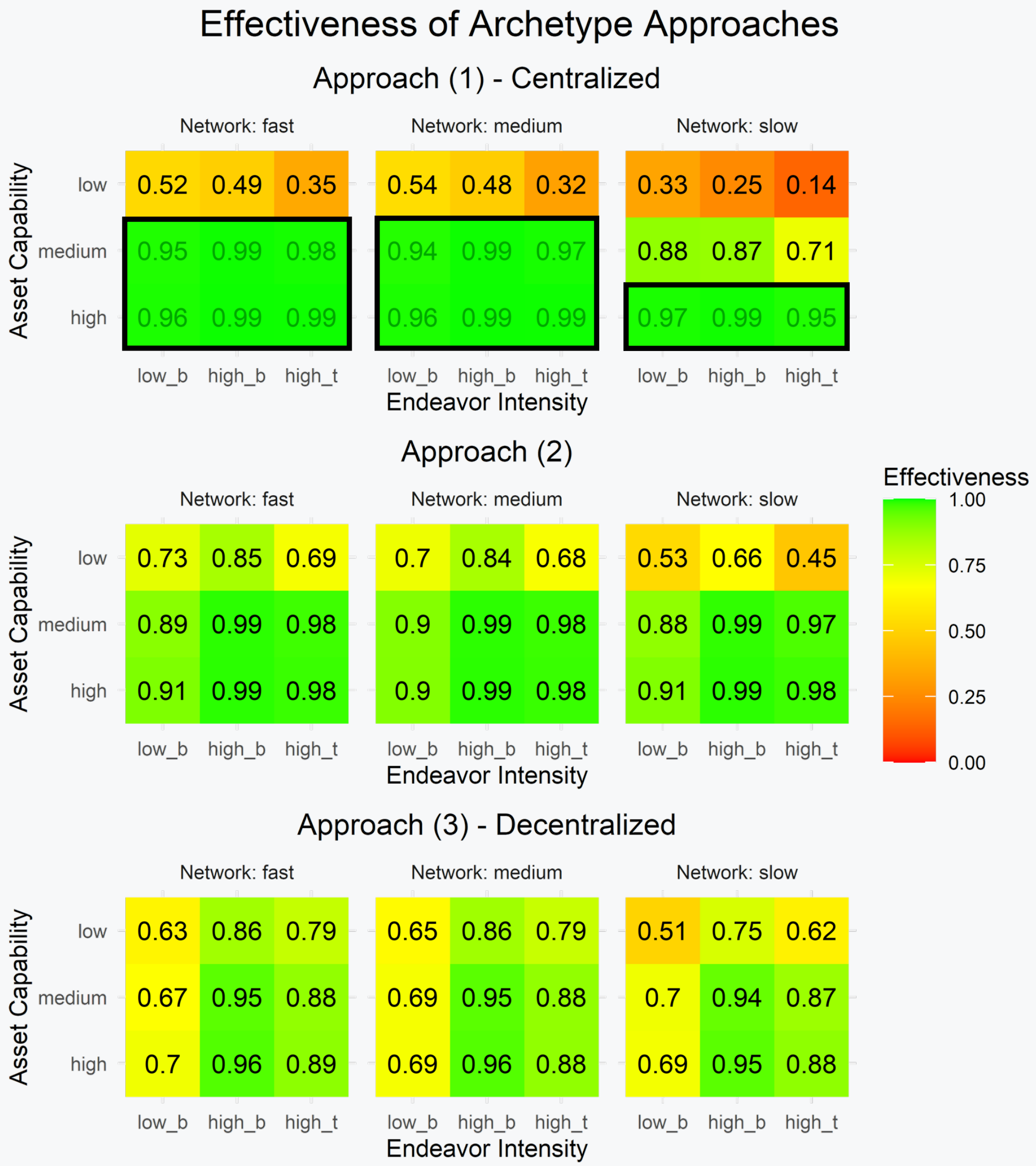
- Effectiveness = % targets neutralized

- No “one size fits all” architecture
- Centralized (1)
  - ➢ High performance
  - ➢ Significant degradation in challenging conditions
- Decentralized (3)
  - ➢ Lower, more stable performance
  - ➢ Inhibited by low intensity



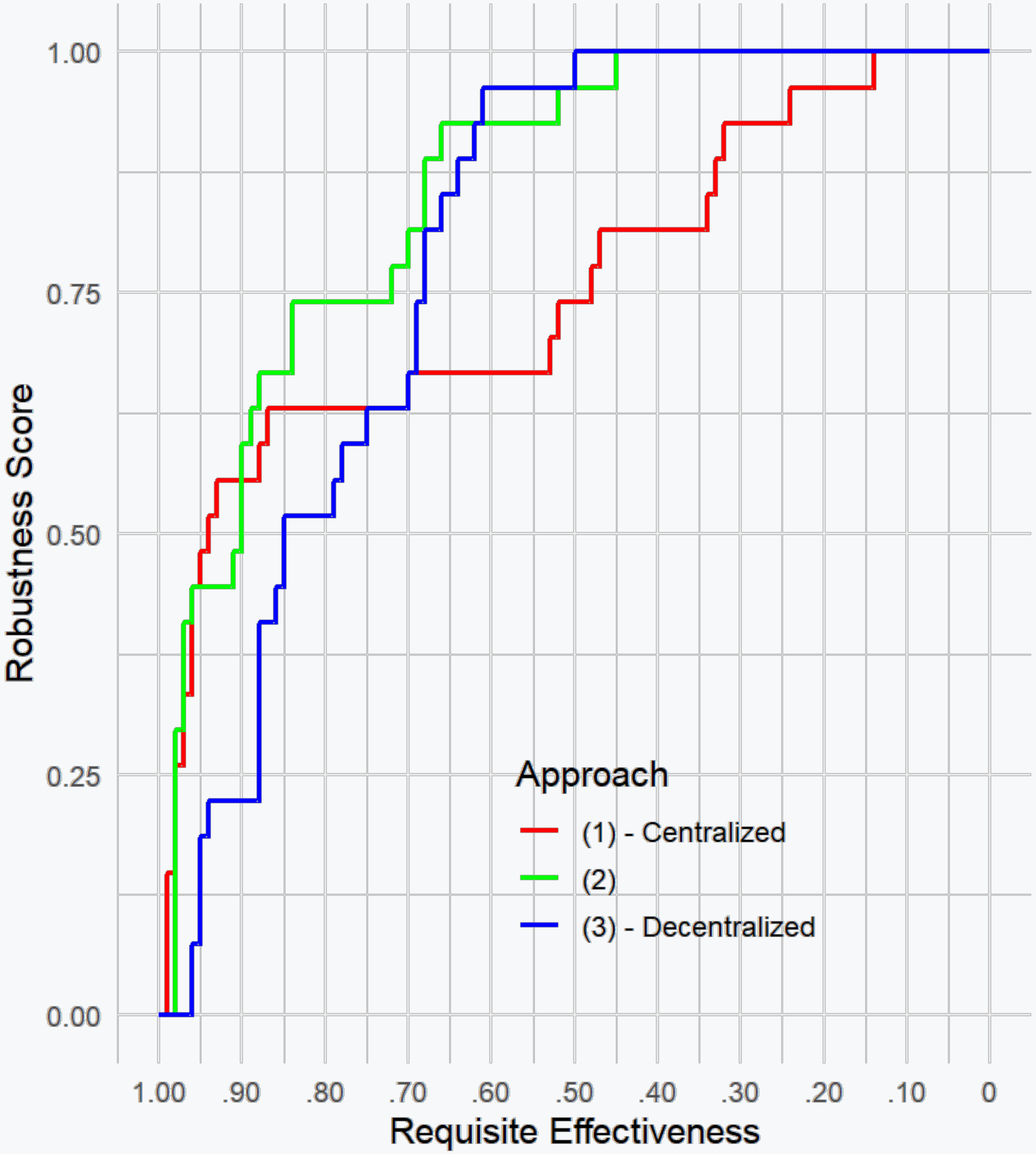
Experiment 1 - Robustness

- How effectively the system maintains capability[12]
  - Portion of circumstances where system maintains adequate effectiveness
- e.g. Requirement: 90% eff.
  - (1) Robustness: ${}^{15}/_{27} = \ .55$
- Robustness depends on the performance requirement



Experiment 1 - Robustness

- Still no “one size fits all” architecture
- Each architecture is best, worst, middle
- Centralized (1)
  - ➢ Higher expected robustness at high levels of required performance
- Decentralized (3)
  - ➢ Highest expected robustness only at modest performance requirement



Insights on Decentralization

- Decentralized
  - Agents spend significant time waiting for assets, or wasting assets waiting for targets
  - Performance dependent on
    - right number of assets
    - right agent
    - right time
- Centralized
  - Very little waste…never an idle asset so long as the agent knows about a target
  - Information takes time to propagate when the comm network is degraded
  - Large geographic scope requires high asset capability

Methodology

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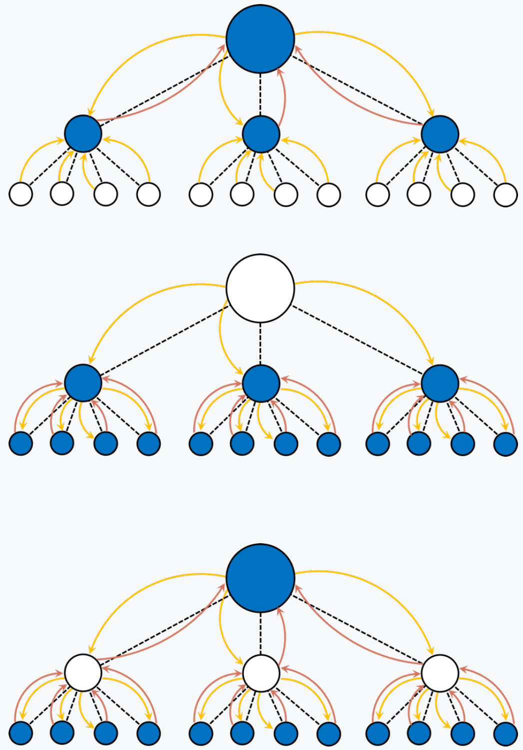
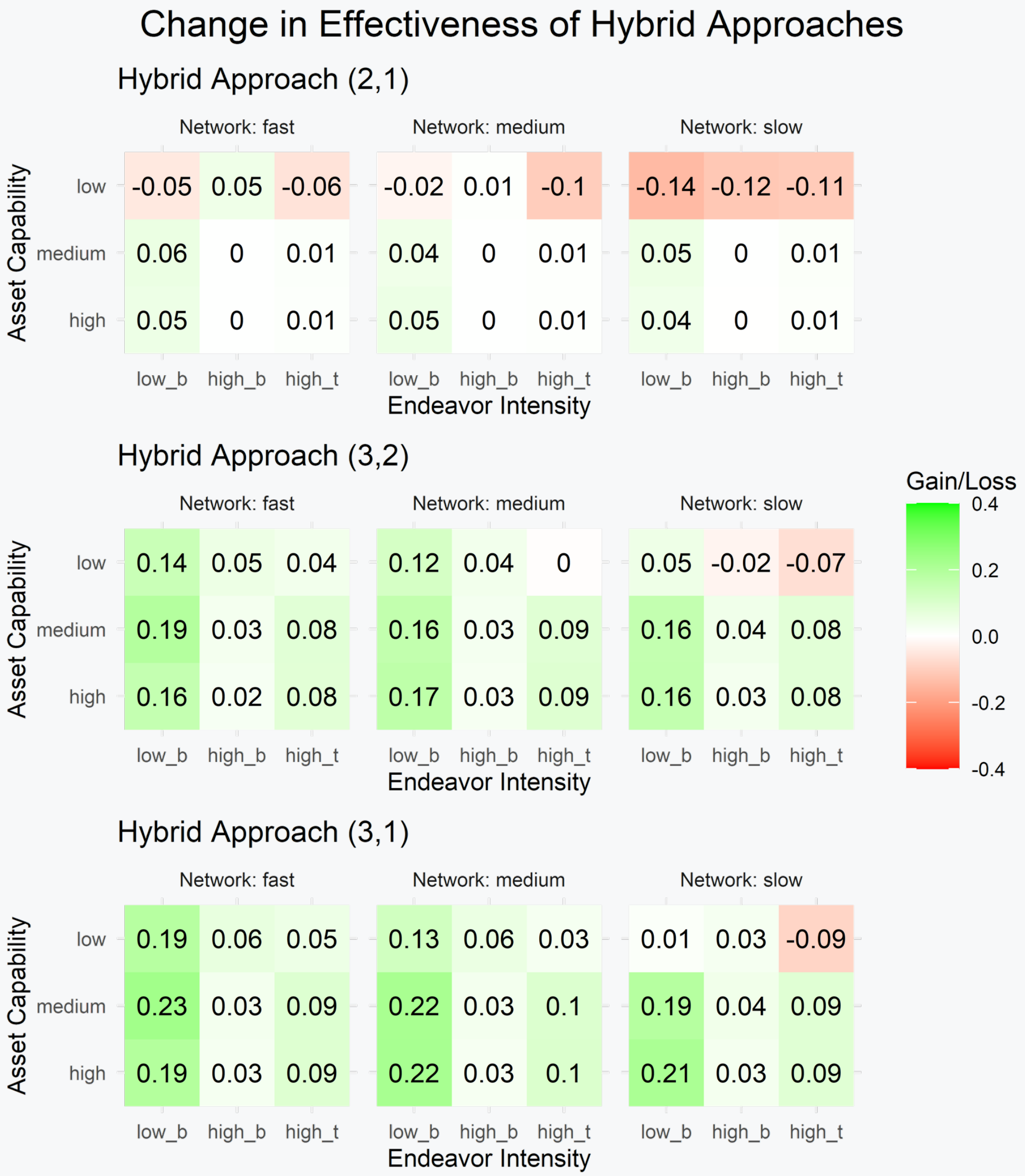
Experiment 2 – Hybrid Architectures

- Decentralized routine, local decision-making (directing assets to targets)
- Centralized asset *allocation*
- Three alternative architectures:
  - (2,1) – Allocate at echelon 1, direct at echelon 2
  - (3,2) – Allocate at echelon 2, direct at echelon 3
  - (3,1) – Allocate at echelon 1, direct at echelon 3



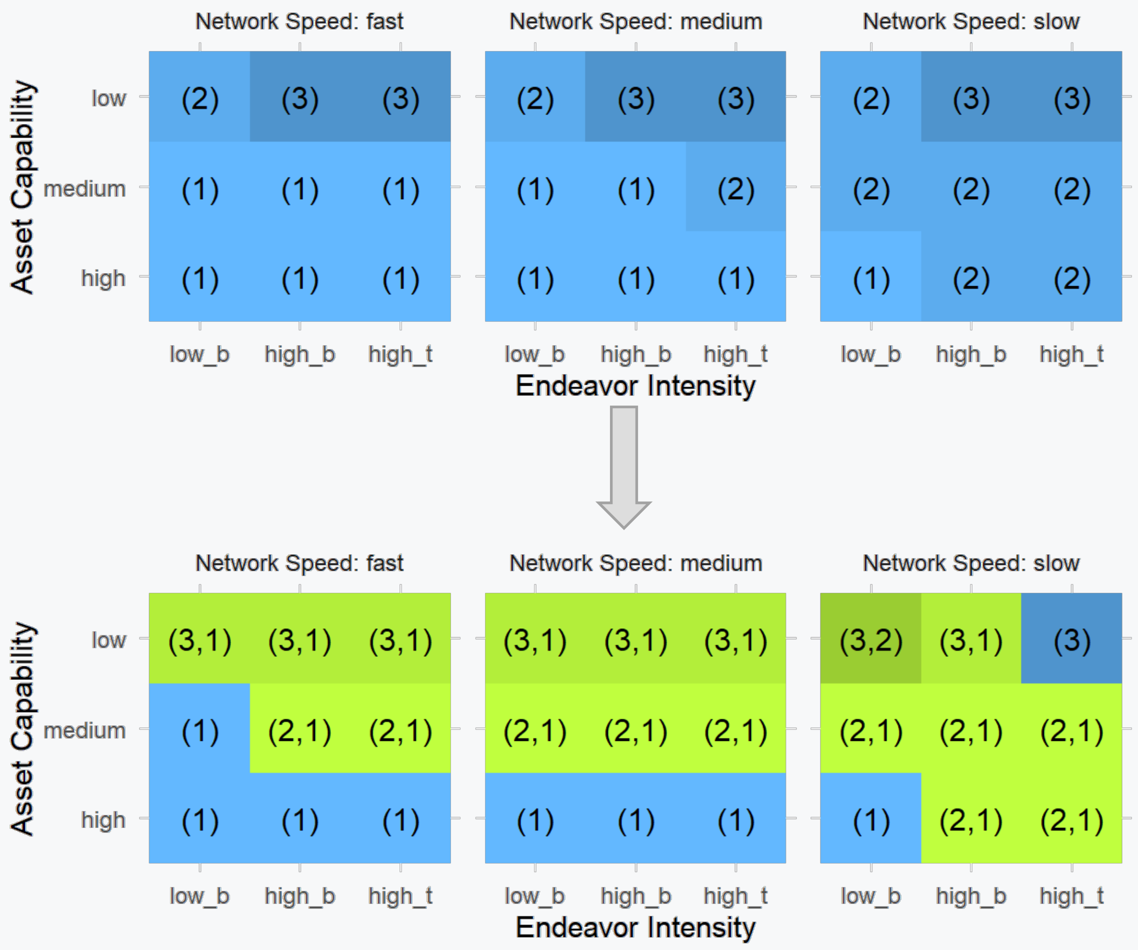
Experiment 2 - Effectiveness

- Performance +/- over their associated archetype
  - ➢ (2) → (2,1)
  - ➢ (3) → (3,2) (3,1)
- Highest performance gains across the most challenging contexts
  - ➢ Low intensity
- Losses where network is slow
  - ➢ Delayed info → poor allocation



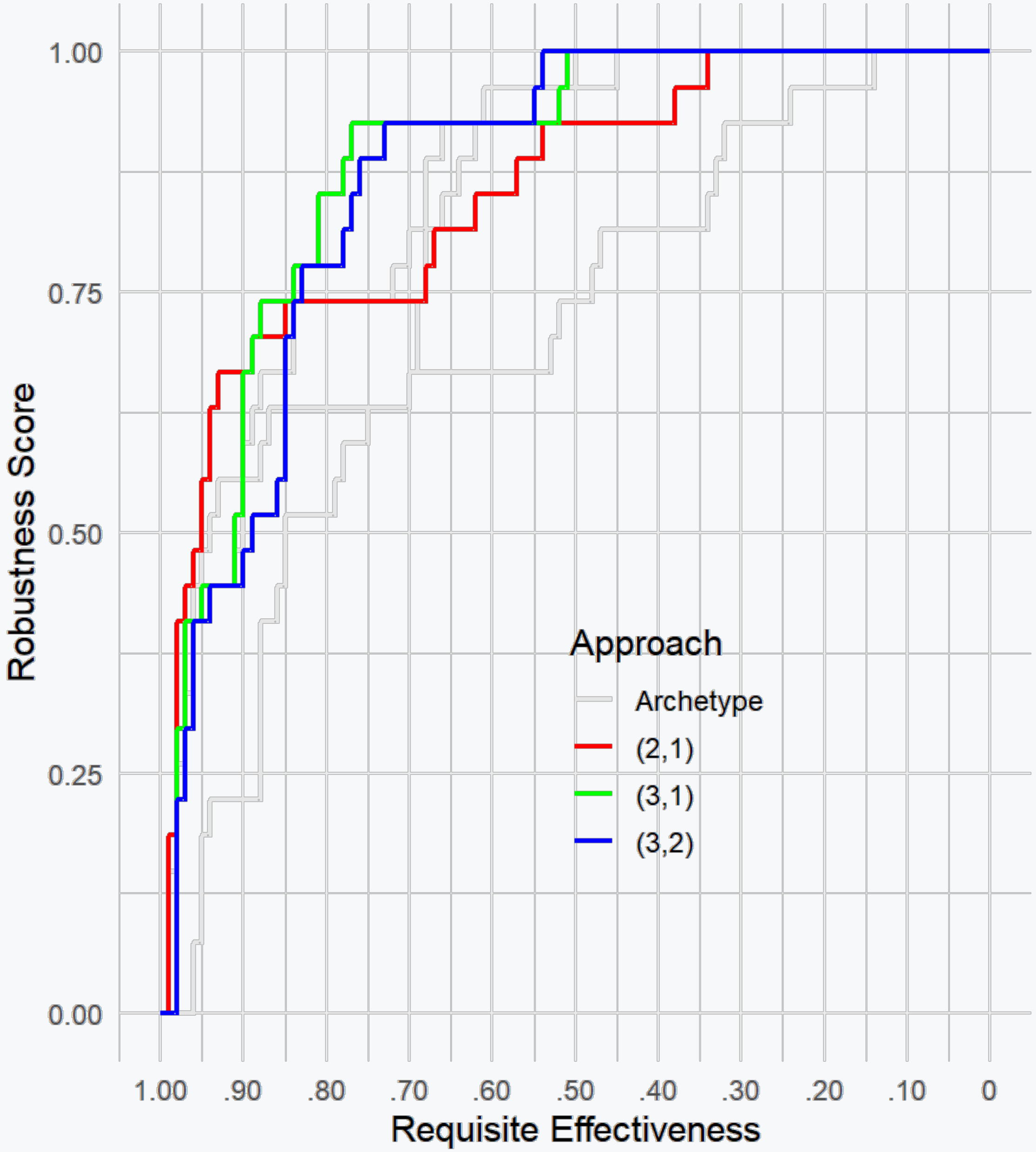
Comparison of "Best" Architectures per Circumstance

- Fully centralized archetype still dominates "most ideal" circumstances
- Fully decentralized archetype outperforms in "worst" conditions
- Most of the middle ground now "bested" by hybrid architectures



Experiment 2 - Robustness

- Architectures (2,1), (3,1), and (3,2) more robust than archetypes
- Still no "most robust" architecture
  - ➢ Performance requirement informs desired architecture



Conclusion

- There is no best degree of decentralization
- Centralized archetype
  - Capable of very high performance under ideal conditions
  - "Most robust" only while requisite performance is high
- Decentralized architecture
  - Lower, but more stable performance
  - Exhibited high expected robustness only at modest requisite performance
- The most-robust architecture depends on the required performance of the system
- Centralizing system-consequential functions while decentralizing repetitive, "local" functions improved performance, robustness over archetypes

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