Programmatic Complexity & Interdependence: Emerging Insights and Predictive Indicators of Development Resource Demand

Authors:

Robert M. Flowe
ODUSD(A&T)/SSE/SI

Maureen Brown
UNC Charlotte

Paul L. Hardin, III
Technomics

To a large extent, the network has become an even more important component of system architectures. Although security concerns remain high, especially within the DoD, there has been a clear trend toward linked systems.

Report of the Defense Science Board Task Force on Defense Software November, 2000

BACKGROUND AND CHALLENGES

- Background
  - Weapon system investments capture a significant share of defense budgets
  - Strong emphasis on Jointness generated by Capstone Concept for Joint Operations (2009)
  - Joint requirements conveyed to systems acquisition process via Joint Capabilities Integration and Development System (JCIDS)
- Challenges
  - To what extent has the focus on joint solutions impacted the acquisition process?
  - What can be done to address the increasingly complex joint capabilities requirements?

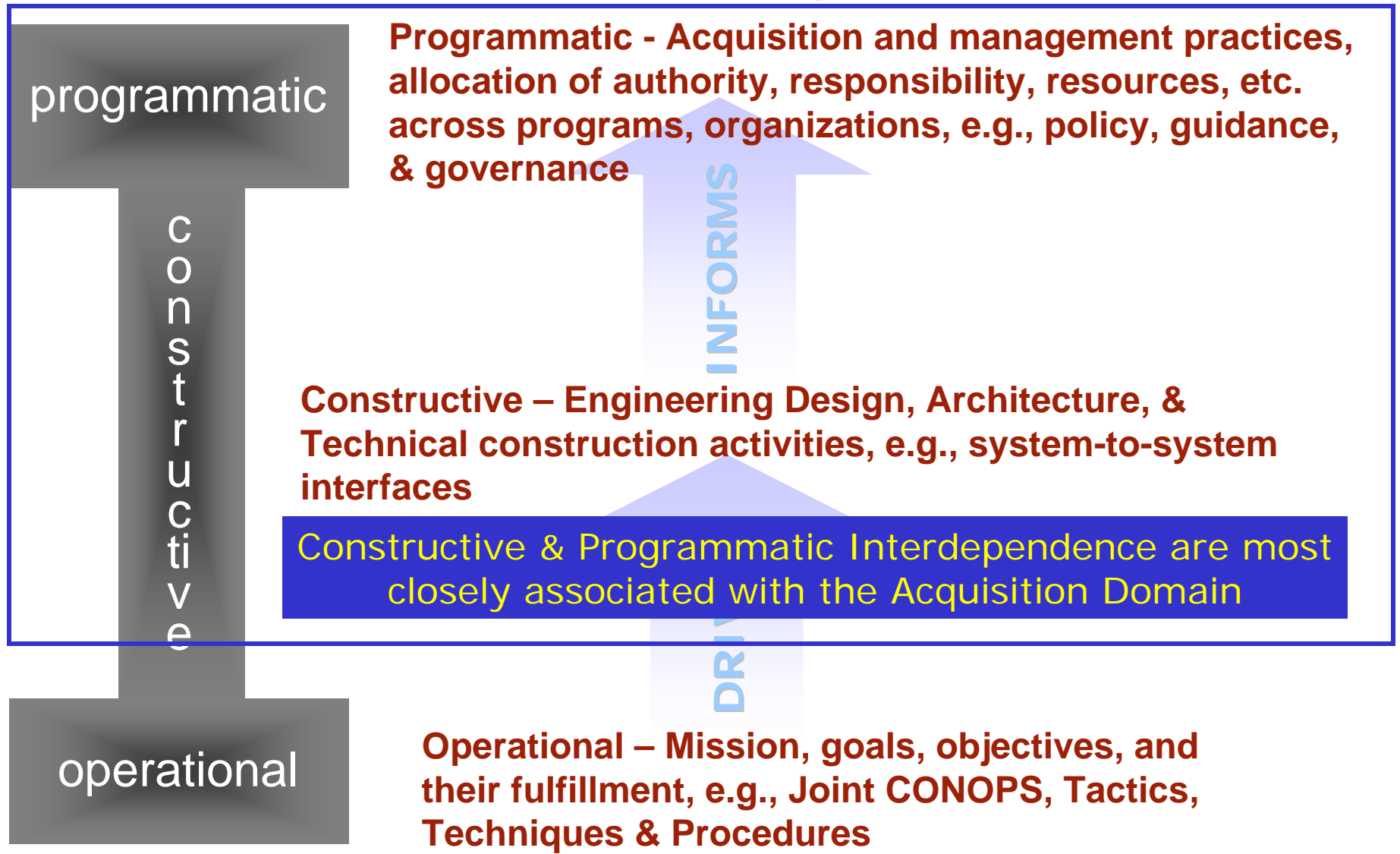# Implications of JCIDS Joint Capabilities Focus in Systems Acquisition

- Emphasis on developing capabilities to support Joint Operations
  - Focus on benefits of multiple systems working together in a 'systems of systems' (SoS) or 'net-centric' context
  - Existing (legacy) and new systems are required to work together towards the capability objective
- In most cases, DoD acquires individual systems
  - Systems, programs defined to fulfill specific requirements, usually in functional, service-specific terms
  - Capability-oriented needs (e.g., net-centric, SoS) may put added demands on systems beyond specified requirements
  - This places additional risks, costs & constraints on program execution
    - Programs impacted by external issues (interdependencies)
    - Difficult to capture in baseline estimates
    - Manifested as cost growth, schedule delay & performance shortfall

Acquiring Defense Capabilities: Nonlinear Scale Effects and Interdependence

- Conventional measures of size no longer predict effort & cost at the extremes
  - Nonlinearity in scaling effects break conventional cost models
  - Fail to account for increased integration & coordination costs
- Extra-programmatic factors confound traditional methods
  - Unpredictable, chaotic nature of program interactions reduce management control
  - Adverse incentives regarding external factors impede proactive planning
- Not just a Joint Program or SoS Problem
  —Any program can be affected
  - Evidence of Interdependence among programs
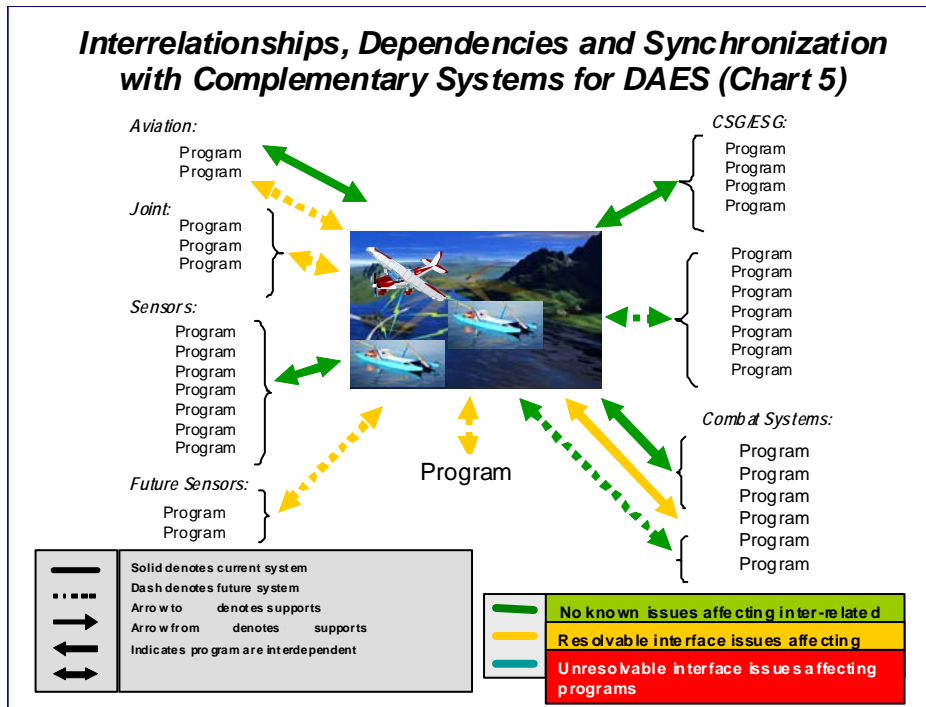 - Explicit (as in SoS) or implicit
  - Can take many forms

Examining interdependence as a distinct feature may provide useful insight into program behaviors

Unpacking Interdependence:
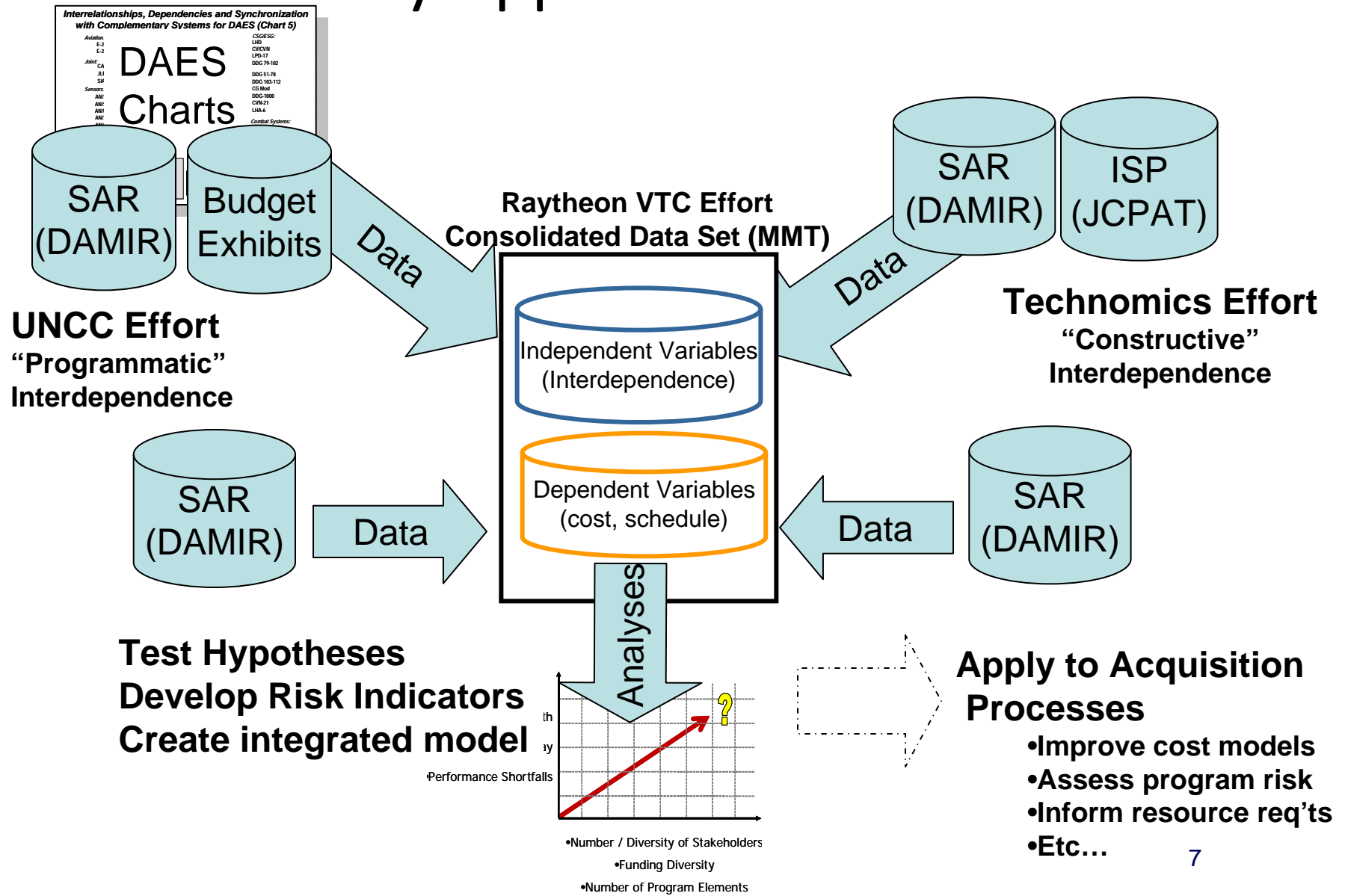# Three Dimensions of Interdependence

programmatic

constructive

operational

Programmatic - Acquisition and management practices, allocation of authority, responsibility, resources, etc. across programs, organizations, e.g., policy, guidance, & governance

INFORMS

Constructive – Engineering Design, Architecture, & Technical construction activities, e.g., system-to-system interfaces

Constructive & Programmatic Interdependence are most closely associated with the Acquisition Domain

DRI

Operational – Mission, goals, objectives, and their fulfillment, e.g., Joint CONOPS, Tactics, Techniques & Procedures

Current Treatment of Interdependence

DAES Depiction of Interdependence (representative)

Interrelationships, Dependencies and Synchronization with Complementary Systems for DAES (Chart 5)

Aviation:
Program
Program

Joint:
Program
Program
Program

Sensors:
Program
Program
Program
Program
Program
Program
Program

Future Sensors:
Program
Program

Program

CSG/ESG:
Program
Program
Program
Program

Program
Program
Program
Program
Program
Program
Program

Combat Systems:
Program
Program
Program
Program
Program
Program

Solid denotes current system
Dash denotes future system
Arrow to denotes supports
Arrow from denotes supports
Indicates program are interdependent

No known issues affecting inter-related

Resolvable interface issues affecting

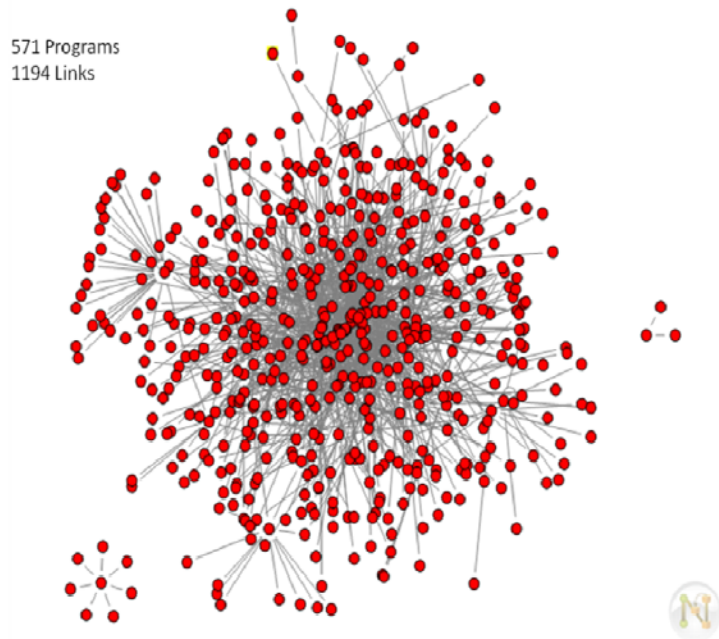Unresolvable interface issues affecting programs

- Current DAES View provides some insight regarding interdependence
- Concern about consistency & objectivity of format
- Most relationships with non-reporting programs
- Hard to assess program risk from this representation

Subjective Insights are Interesting, Objective Measures would be Useful
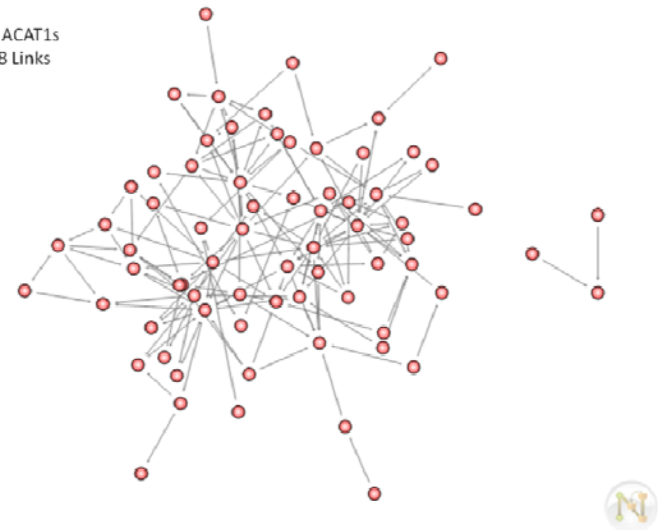
Study Approach Overview

Interrelationships, Dependencies and Synchronization with Complementary Systems for DAES (Chart 5)

DAES Charts

SAR (DAMIR)

Budget Exhibits

Data

UNCC Effort
"Programmatic" Interdependence

SAR (DAMIR)

Data

Raytheon VTC Effort
Consolidated Data Set (MMT)

Independent Variables (Interdependence)

Dependent Variables (cost, schedule)

Data

SAR (DAMIR)

ISP (JCPAT)

Data

Technomics Effort
"Constructive" Interdependence

Data

SAR (DAMIR)

Analyses

Test Hypotheses
Develop Risk Indicators
Create integrated model

•Performance Shortfalls

•Number / Diversity of Stakeholders

•Funding Diversity

•Number of Program Elements

Apply to Acquisition Processes
•Improve cost models
•Assess program risk
•Inform resource req'ts
•Etc...

7

Views of Programmatic Interdependence

571 Programs
1194 Links

65 ACAT1s
238 Links

All Programs

MDAPs Only

Compilation of program dependencies as depicted in 2007 DAES charts

Programmatic Interdependence: Network View
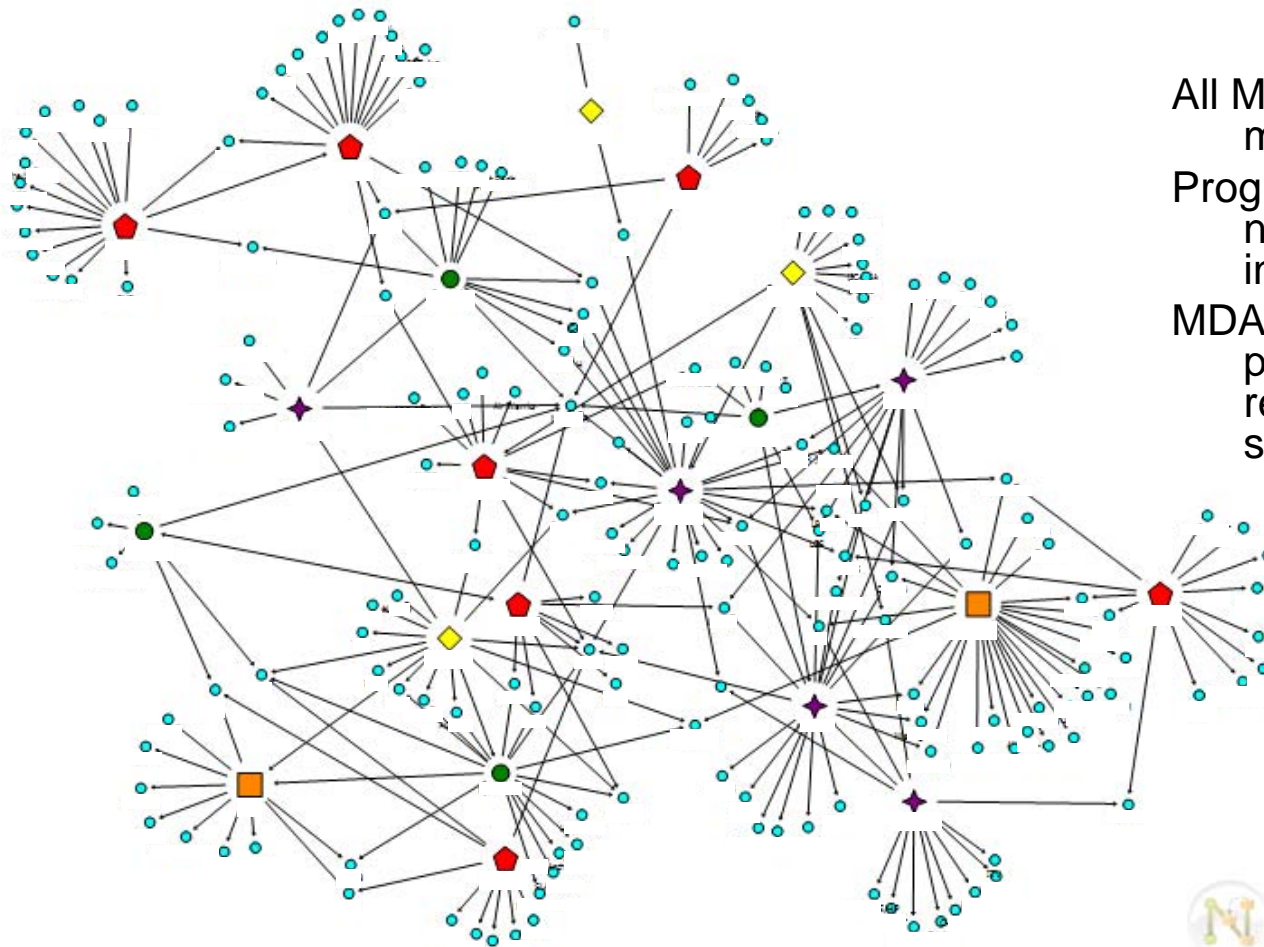
All MDAPs are interdependent in multiple ways

Programs defined as "Joint" are not obviously more interdependent than non-joint.

MDAPs are linked mainly to programs that are not required to report on program status.

Legend:
- ○ Non-MDAP/ Non-Reporting
- ● Net SDD Decrease
- ◇ SDD Growth 1-14%
- ⬠ SDD Growth 15-50%
- ◼ SDD Growth 51-100%
- ✦ SDD Growth > 100%

Interdependencies from DAES charts for programs post M/S-C;

Cost growth data from SAR

Programmatic Interdependence Evolving Over Time

Year	Number of Linkages	Number of MDAPs	Number of Program Elements	Ratio of PE's per MDAP	Number of Links per MDAP	Number of Links per PE
1997	82	24	80	3.3	3.4	1.03
1998	96	26	92	3.5	3.7	1.04
1999	87	26	84	3.2	3.3	1.04
2001	113	31	104	3.4	3.6	1.09
2002	116	35	105	3.0	3.3	1.10
2003	117	37	106	2.9	3.2	1.10
2004	135	44	120	2.7	3.1	1.13
2005	159	50	135	2.7	3.2	1.18
2006	257	92	218	2.4	2.8	1.18
2007	319	95	257	2.7	3.4	1.24

Data from SAR

Number of Links
from MDAPs to Program
Elements increases over
sample period (1997-2007)

Cluster 1 Cluster 2

✦ - MDAP   ● - Program Element
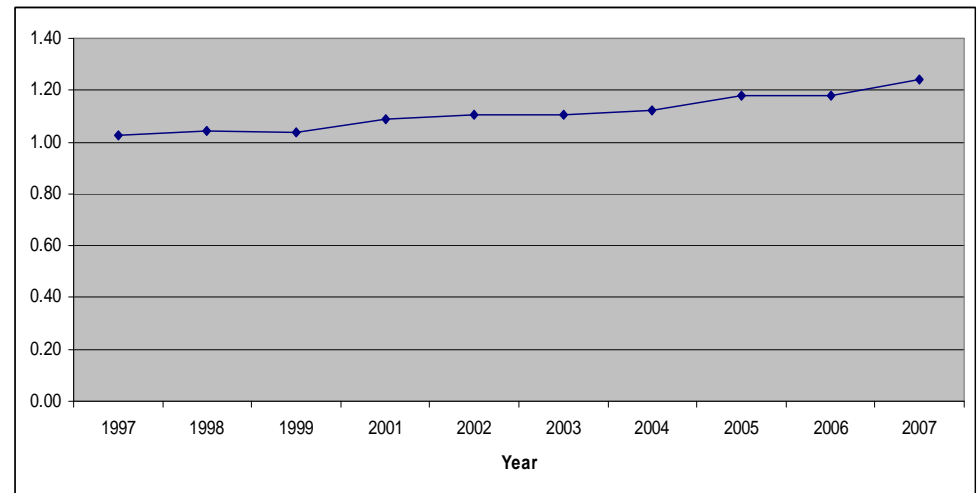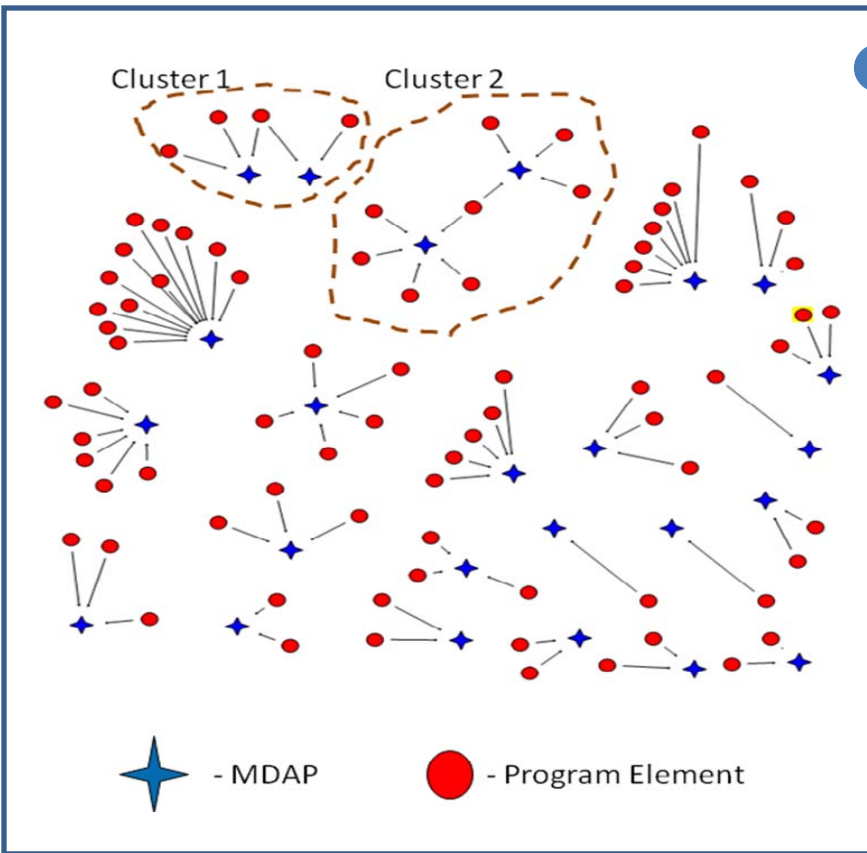
2004

Suggests program
interdependence emerges as
clusters of collaborating programs

Data from SAR

Program Funding
Relationships :
Multi-Program Clusters
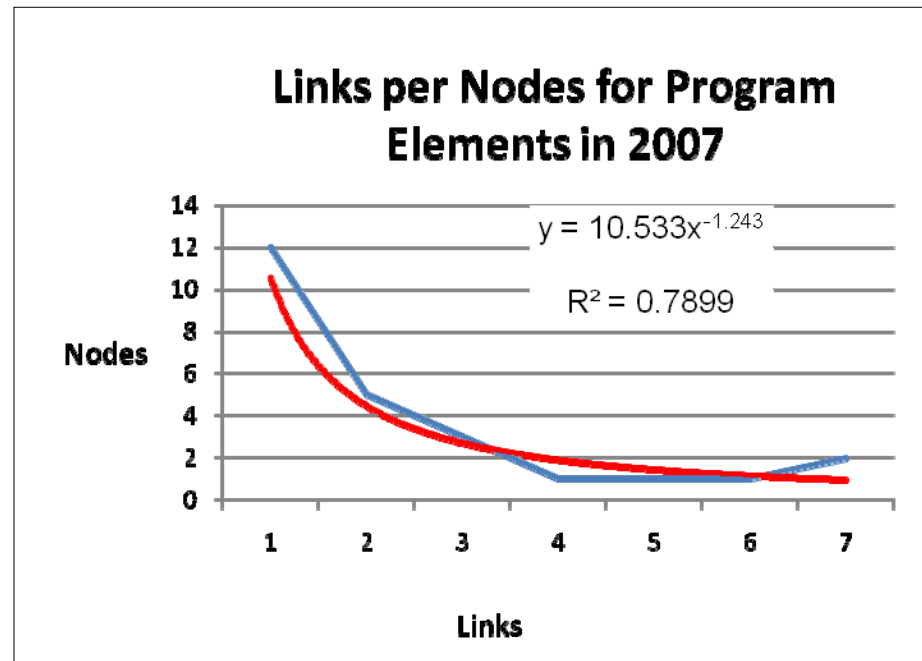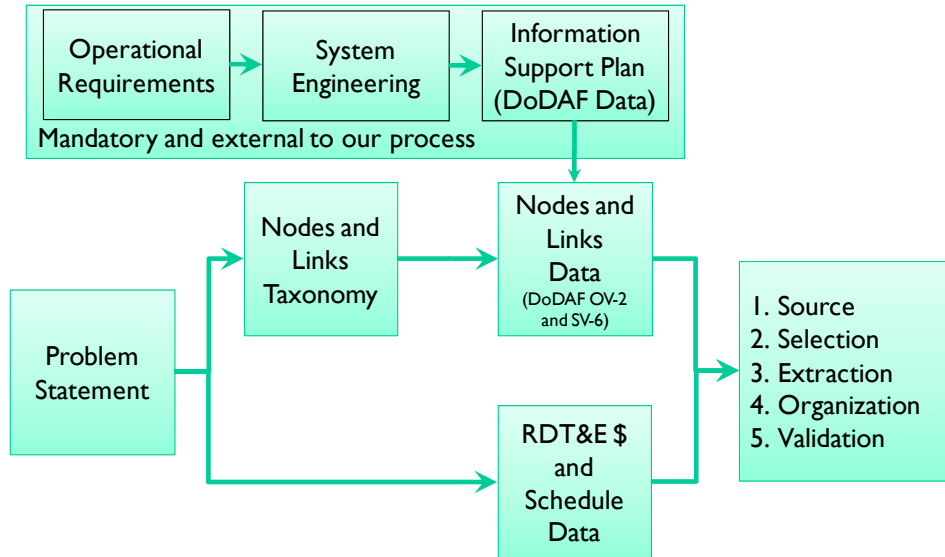have proliferated and
expanded

2007

Cluster 2

Cluster 1

✦ - MDAP   ● - Program Element
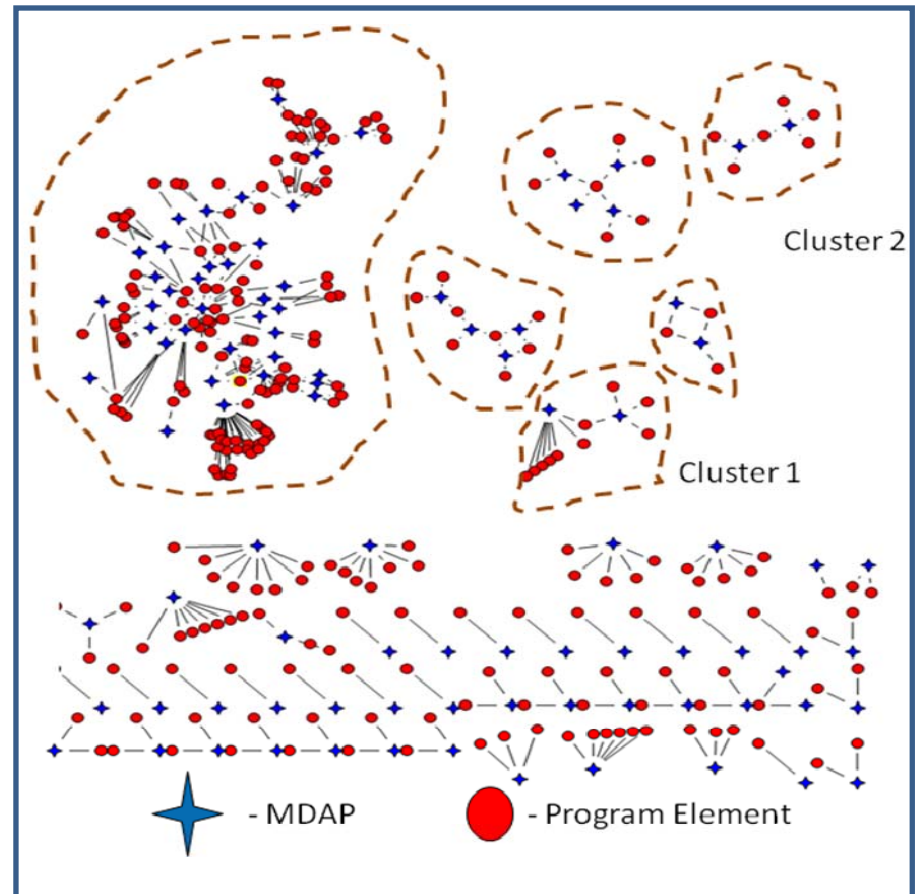
Resource Sharing Among Programs

Average Network Degree by Year for MDAP - PE Relationships
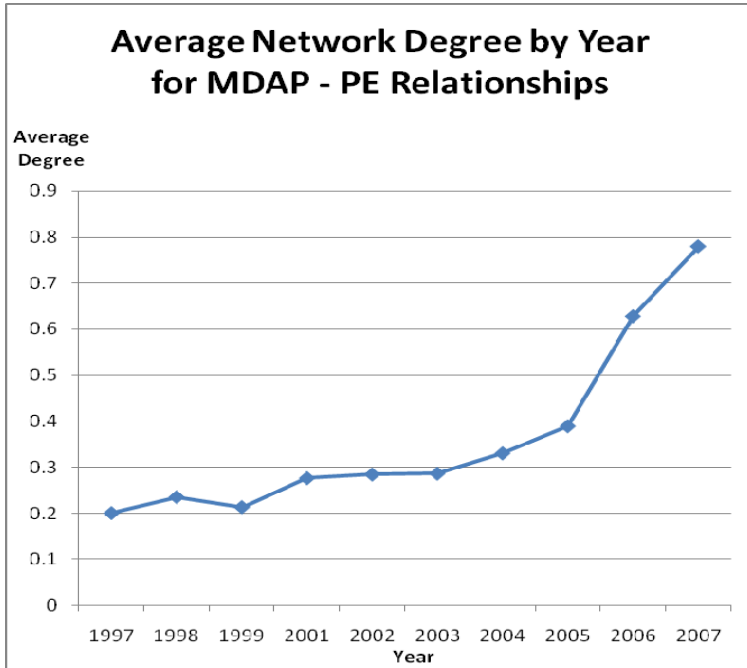
Increasing "connectivity" among programs via their funding program elements…

…suggests programs are becoming more interdependent through shared resources

Data from SAR

Links per Nodes for Program Elements in 2007

$y = 10.533x^{-1.243}$

$R^2 = 0.7899$

Constructive Interdependence: Methodology

Operational Requirements → System Engineering → Information Support Plan (DoDAF Data)

Mandatory and external to our process

Problem Statement

Nodes and Links Taxonomy

Nodes and Links Data (DoDAF OV-2 and SV-6)

RDT&E $ and Schedule Data

1. Source
2. Selection
3. Extraction
4. Organization
5. Validation

Information Support Plans and DoDAF Artifacts provide insight into the "constructive" dimension of interdependence

Simple counting rules create objective measures of interdependence and complexity

Systems Node, N1

Ns/r L1   N2 Ns/r

L4   L5   L2

Ns/r L3 Nr

N3   N4

Link ←→   Potential Link →
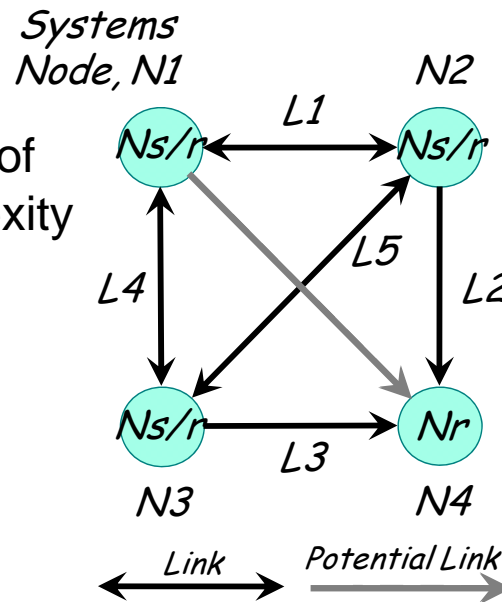
Item	Value
Systems Nodes, N	
Send/Receive, Ns/r	3
Send, Ns	0
Receive, Nr	1
Total, Nt	4
Links, L	
Uni- directional, Lud	2
Bi- directional, Lbd	3
Total, Lt	5
Metcalfe Number, $LtMax$	6
Integration Density, $Lt/LtMax$	5/6
Links per Node, Lt/Nt	5/4

Constructive Interdependence: Emerging Patterns

Integration density within MDAPs shows remarkable consistency over a wide range of programs
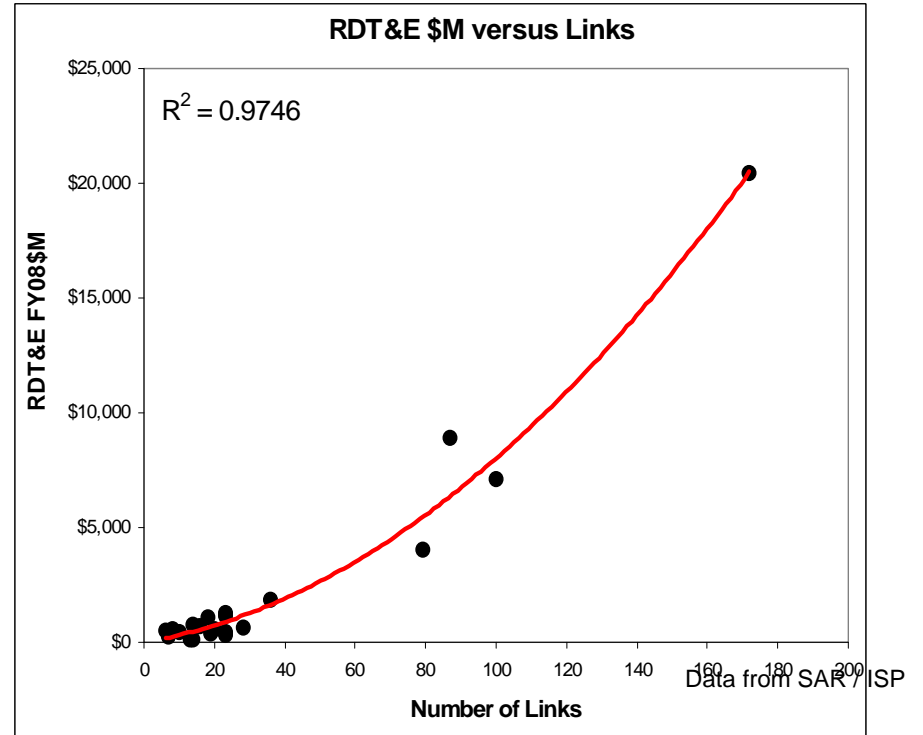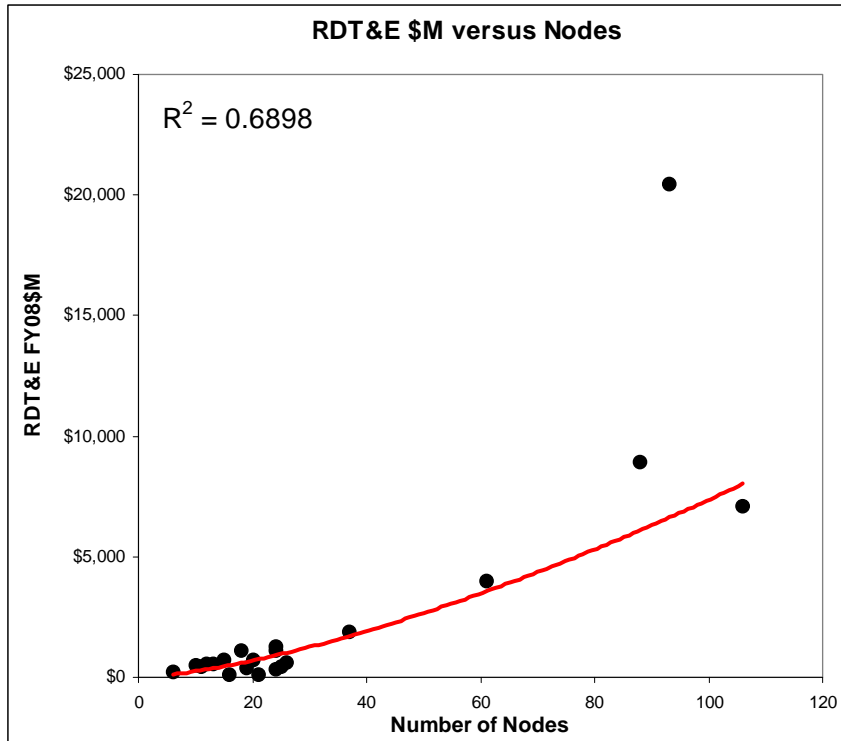
Suggests some underlying principle guides the evolution of complex systems

Relationship has practical utility for inferring development effort with respect to scale
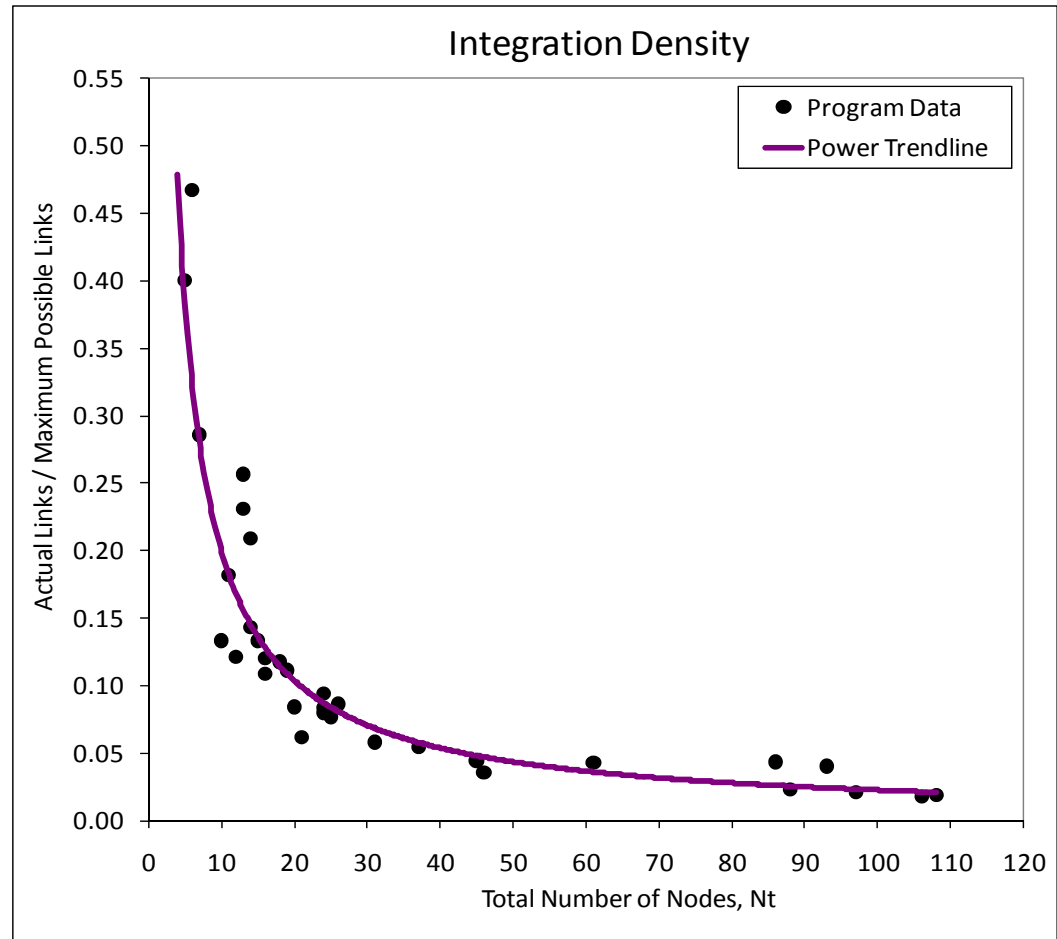

Data from SAR / ISP

Correlation with Resource Demand

Data suggest a nonlinear relationship between measures of interdependence & complexity and development resource demand (measured in RDTE $)

Stronger correlation between Links consistent with the notion of interdependence being a key driver

Formulating a Model

Simple relationship between numbers of nodes and links does not account for the following effects:
- Send / Receive nodes are more complex than Send-only or Receive-Only;
- Send-only nodes are more complex than Receive-Only
- Nodes that have more links are more complex than nodes with fewer links.
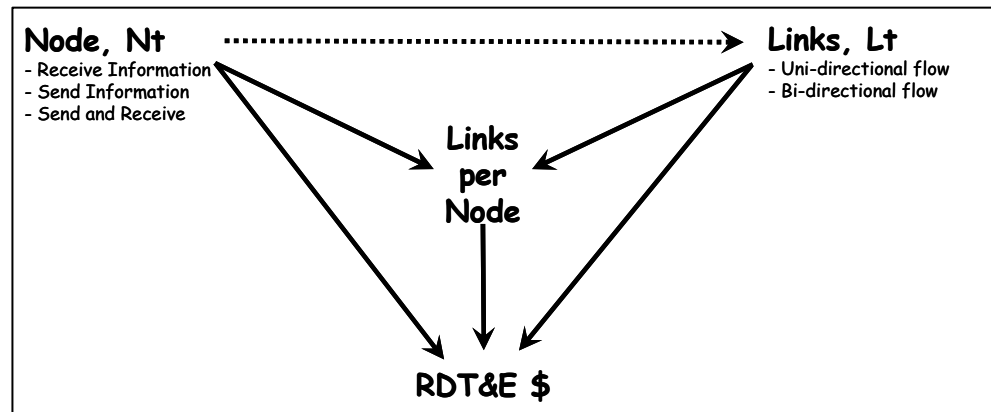
$$N_e = (dN_{s/r} + gN_s + hN_r)\left(\frac{L_t/N_t}{avg\left(L_t/N_t\right)}\right)^c$$

"Effective Nodes" formulation to account for relative node complexity…

$$RDT\&E\$ = aN_e^b$$

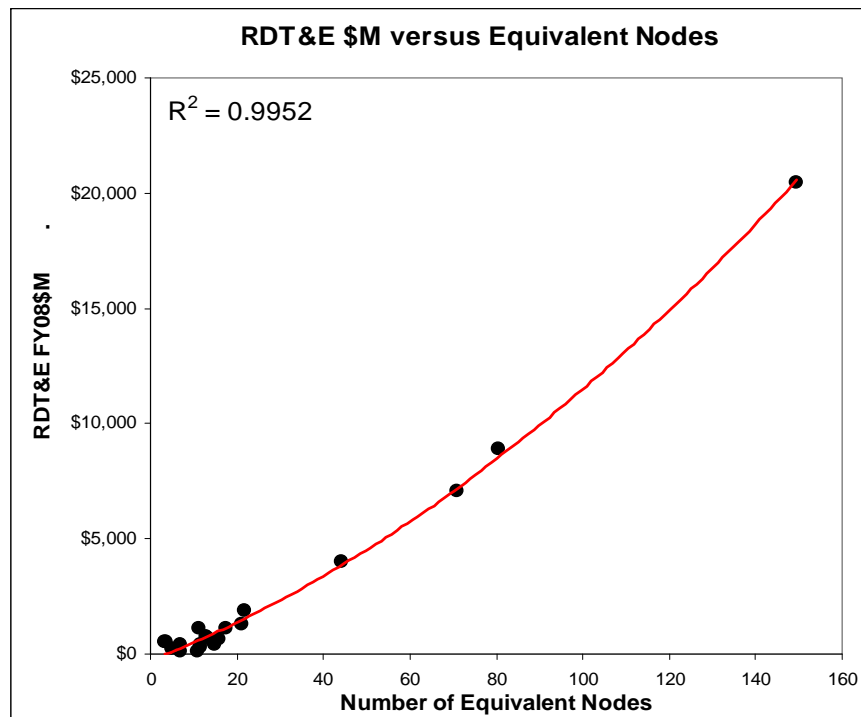…"plugs in" to a simple nonlinear relationship for RDTE\$ in terms of "Effective Nodes"

Refining the Model

$$N_e = (N_{s/r} + 0.5N_s + 0.29N_r)\left(\frac{L_t/N_t}{1.02}\right)^{1.22}$$

Model parameters resolved through optimization against MDAP data set

$$RDT\&E\ FY08\$M = 20.7N_e^{1.38}$$

Significant correlation over large range of MDAP size / complexity

Model provides method to translate measures of interdependence derived from authoritative data into estimates of development resource demand

This correlation may be of significant utility for assessing program development needs or risk

RDT&E $M versus Equivalent Nodes

$R^2 = 0.9952$

Data from SAR / ISP

Findings/Implications

1) Interdependence is pervasive among systems. Limiting consideration of interdependence to programs designated as joint or part of SoS is insufficient.
2) Interdependence among programs is increasing, possibly spontaneously to address increasing demands for joint capabilities.
3) traditional methods of analyzing risk, while important, need to be supplemented with network analysis techniques to reveal the true scope of the effects of interdependencies.
4) Existing data resources, even the relatively aggregate SAR data and the often-disparaged DoDAF artifacts, when combined in an analytically rigorous manner over a sufficiently large sample, can provide significant insights into program behaviors.
5) Continued exploration into the nature and effects of interdependence is likely to yield further insights and benefits

For the paper and/or data set, please contact
Rob Flowe at (703) 602-0851 x121; robert.flowe@osd.mil