Information Flow, Team Coordination, and Shared Knowledge in Integrated Concurrent Engineering

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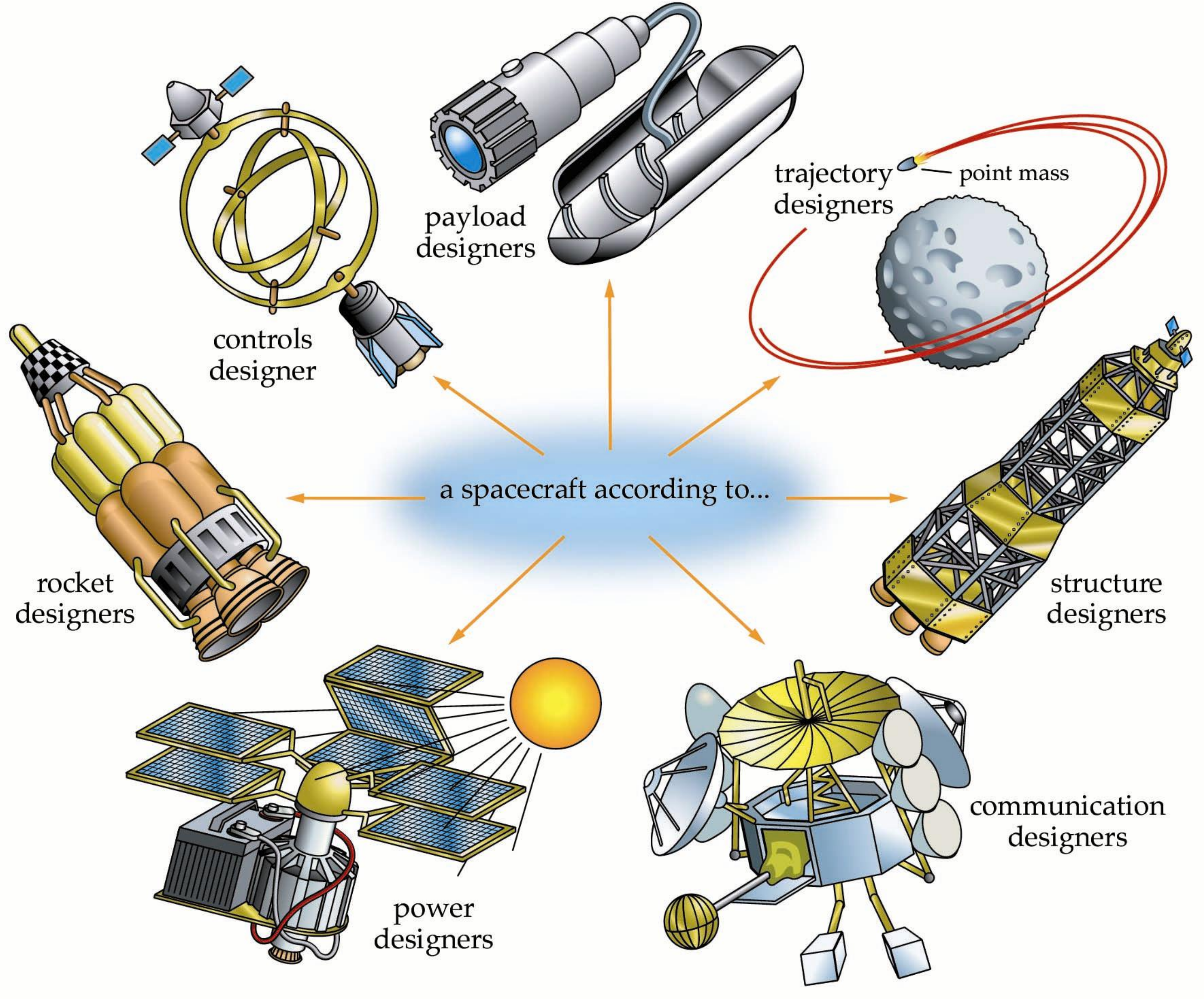
Structure of the Presentation

- Motivation and Research Setting
- Information Flow and Team Coordination
- Shared Knowledge in Systems Engineering
- Research Contributions and Ongoing Work



a spacecraft according to...
controls designer
payload designers
trajectory designers
point mass
rocket designers
structure designers
power designers
communication designers

Literature Review: Design Process Analysis

Design Structure Matrix

Steward (1981a, 1981b) – proposal

Eppinger et al. (1990), Gebala and Eppinger (1991) – reintroduction and algorithm development

Eppinger et al. (1992), Eppinger et al. (1994) – DSM for automobile parts and semiconductors

DSM in Space Systems Design

Rogers (1999) – application of the DSM to conceptual aircraft design

Padula et al. (1989) – early space system model similar to the DSM

Ahmadi et al. (2001) – detailed DSM of the Space Shuttle Main Engine

Organizational Structure and Product Architecture

Baldwin and Clark (2000) – effect of IBM's System/360 on industry structure

McCord and Eppinger (1993) – integration problem in concurrent engineering

Sosa et al. (2003) – design team interactions and product architecture

Cataldo et al. (2008) – socio-technical congruence (STC)

Application of the DSM to Rapid Concurrent Engineering

Avnet and Weigel (2010) – first application to the design of a full space mission

Literature Review: Shared Knowledge in Teams

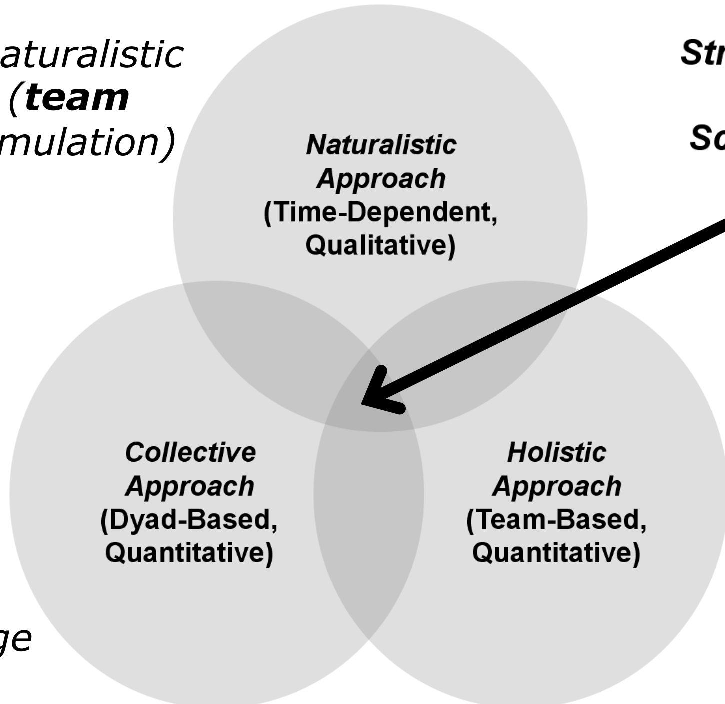
*Klein (1998) – naturalistic decision making (**team mind**, mental simulation)*

Structural Approach (Quantitative, Scalable, Dynamic)

Avnet and Weigel (2013)

*Mathieu et al. (2000) – **shared mental models** in dyads (pairs)*

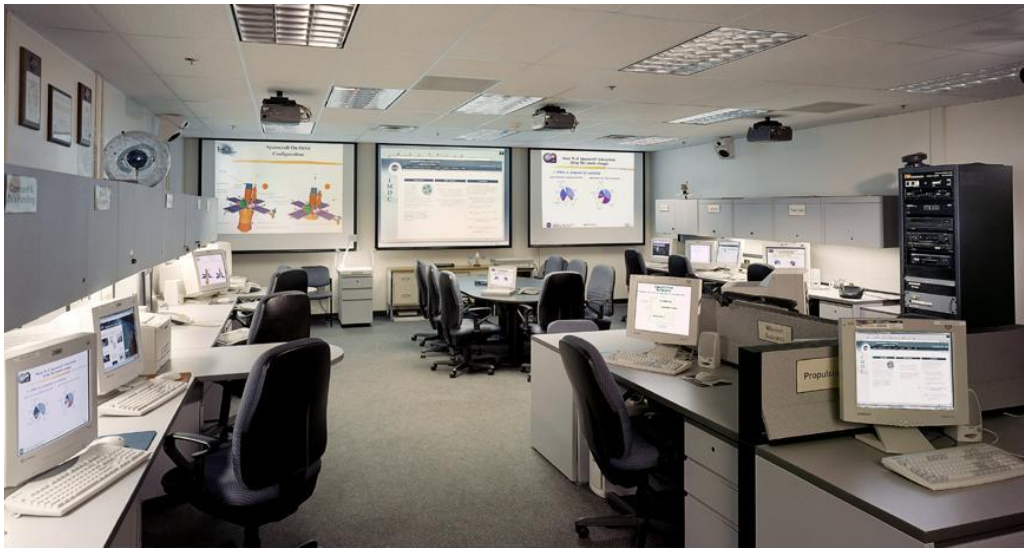
*Lim and Klein (2006) – **team mental model** defined as average among all dyads in a larger team*



*Cooke and Gorman (2006) – **team cognition** inferred from team behavior*

Badke-Schaub et al. (2007) – an exploration of the applicability of shared mental models to design teams

Research Setting:
Integrated Concurrent Engineering (ICE)



Mission Design Laboratory (MDL)
NASA Goddard Space Flight Center (GSFC)

Design Team:

- Team Lead
- Systems Engineer
- Attitude Control
- Avionics
- Communications
- Electrical Power
- Flight Dynamics
- Flight Software
- Integration and Test
- Launch Vehicles
- Mechanical
- Mission Operations
- Orbital Debris
- Parametric Cost
- Propulsion
- Radiation
- Reliability
- Thermal

Customer Team:

- Scientists
- Program Managers
- Systems Engineers
- Discipline Engineers

MDL Design Study Observations

Study	Scientific Objectives	Mission Architecture	Mission Dynamics
1	Planetary	Multiple Spacecraft	Interplanetary
2	Space	Single Spacecraft	Earth Orbit
3	Earth	Single Spacecraft	Earth Orbit
4	Space	Single Spacecraft	Earth Orbit
5	Earth	Single Spacecraft	Earth Orbit
6	Space	Single Spacecraft	Earth Orbit
7	Space	Single Spacecraft	Earth Orbit
8	Space	Costing/Bus Design	Sun-Earth L2
9	Space	Surface Operations	Lunar Surface
10	Planetary	Multiple Spacecraft	Interplanetary
11	Space	Multiple Spacecraft	Heliocentric Orbit
12	Planetary	Single Spacecraft	Interplanetary

"Typical" Studies

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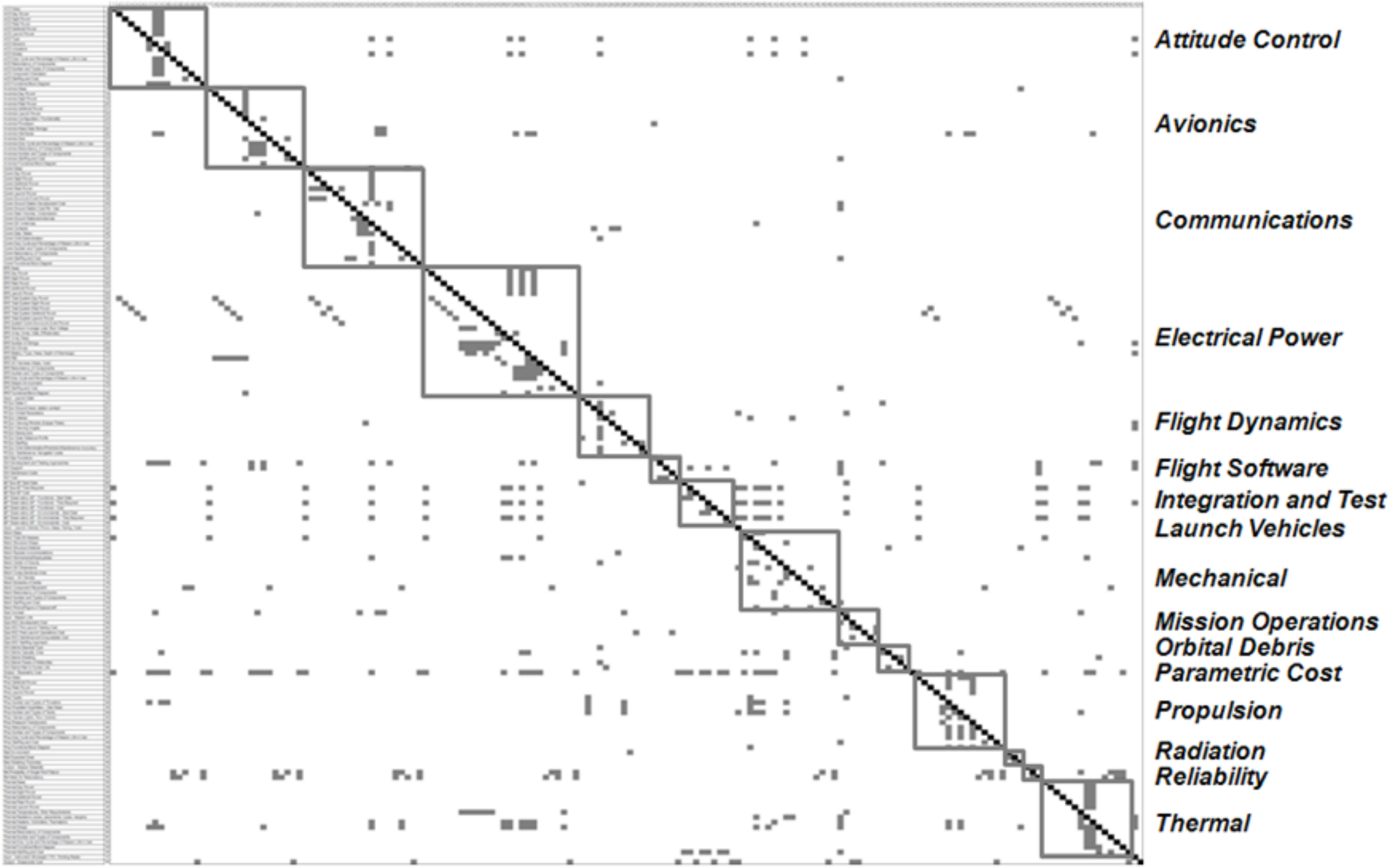
Review of the Design Structure Matrix

	A	B	C	D	E	F	G	H	I	J	K	L
A							X					
B												
C	X	X										
D		X			X			X				
E	X			X				X				
F	X				X		X	X	X			X
G		X										
H					X					X		
I		X					X	X		X		
J	X		X	X								
K	X			X	X							
L			X	X	X		X					

Task A depends on information from Task G

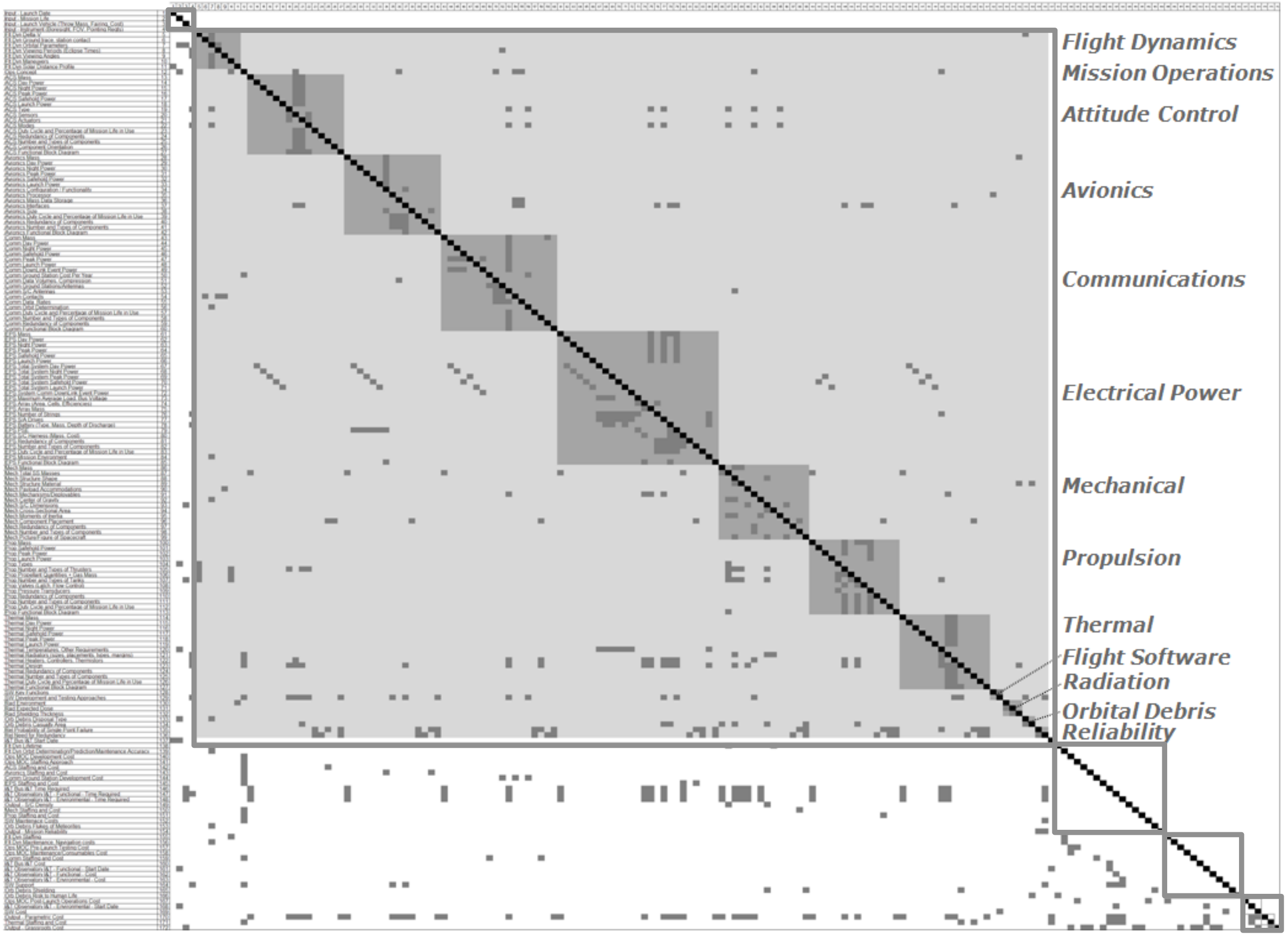
Tasks D and E must be done concurrently

Modeling the ICE Design Process: 172 Parameters and 682 Dependencies



See Avnet and Weigel (2010) for further detail

Partitioning the DSM: The Conceptual Design Life Cycle



Requirements Definition Phase

Engineering Design Phase

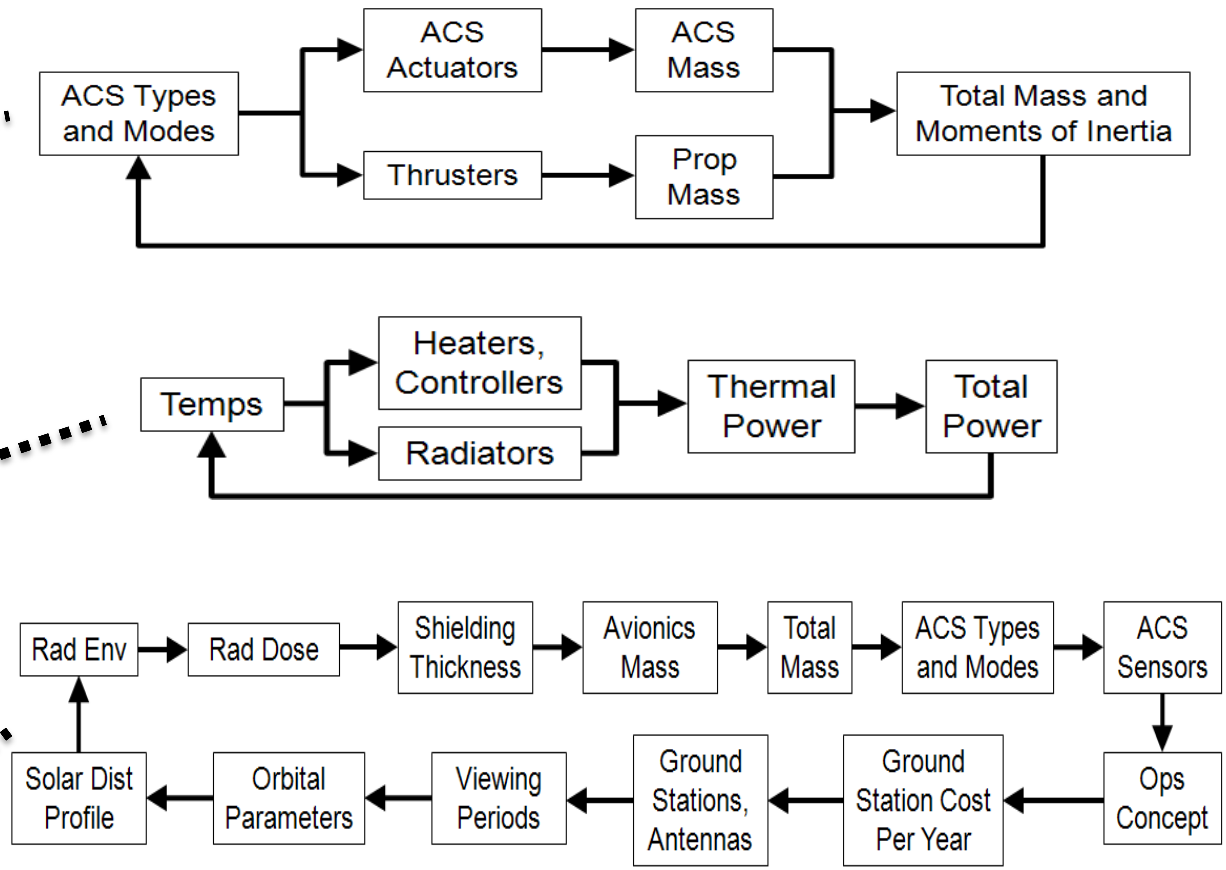
Integration Phase

Maintenance and Support Phase

Costing Phase

Loop Analysis to Determine Critical Design Trades

13 Primary Loop Types
Spacecraft Bus Loop
Propulsion Sizing Loop
Stabilization Loop
Ground Segment Loop
Data Loop
Power System Electronics Loop
Power Loop
Electrical Heating Loop
Propulsion Thermal Control Loop
Radiator Operation Loop
Reentry Loop
Computing Reliability Loop
Radiation Shielding Loop



Measuring Team Coordination

		AC	AV	CM	EP	FD	SW	MC	OP	OD	PR	RD	RL	TM
Attitude Control	AC		O		O	O	O	#			O			
Avionics	AV			#	#		#				O	#		#
Communications	CM		#		O	#		O	#			O		
Electrical Power	EP	O	#	O		O	O	O	O					#
Flight Dynamics	FD	O		X	O						O			
Flight Software	SW	O	#	O									X	O
Mechanical	MC	#	#	O	O					X	#			#
Mission Operations	OP	X	O	#		O	O	X						
Orbital Debris	OD	O			O			#			#			
Propulsion	PR	#				O		#		O				
Radiation	RD		O			X								
Reliability	RL	O	#	O	O	O					O			O
Thermal	TM	O	O	O	#	O	O	#	#		#		O	

Expected Interaction Matrix

Based on Primary Loop Types in the Partitioned DSM

Congruence Matrix

Overlay of Expected and Reported Interactions

Reported Interaction Matrix

Based on Survey Data of Interactions for Each Study (Study 3 Shown Here)

Formalism Developed by Sosa et al. (2003)

		Expected Interactions: YES (32)	Expected Interactions: NO (124)
Actual Interactions	NO (87)	X (6)	(81)
	YES (69)	# (26)	O (43)

χ^2	p
22.4	< 0.001

Socio-Technical Congruence
(Adapted from Cataldo et al. 2008)

$$C_{S-T} = \frac{N_{\#} - N_b}{N}$$

$N_{\#}$ = number of # cells

N_b = number of blank cells

N = total number of cells

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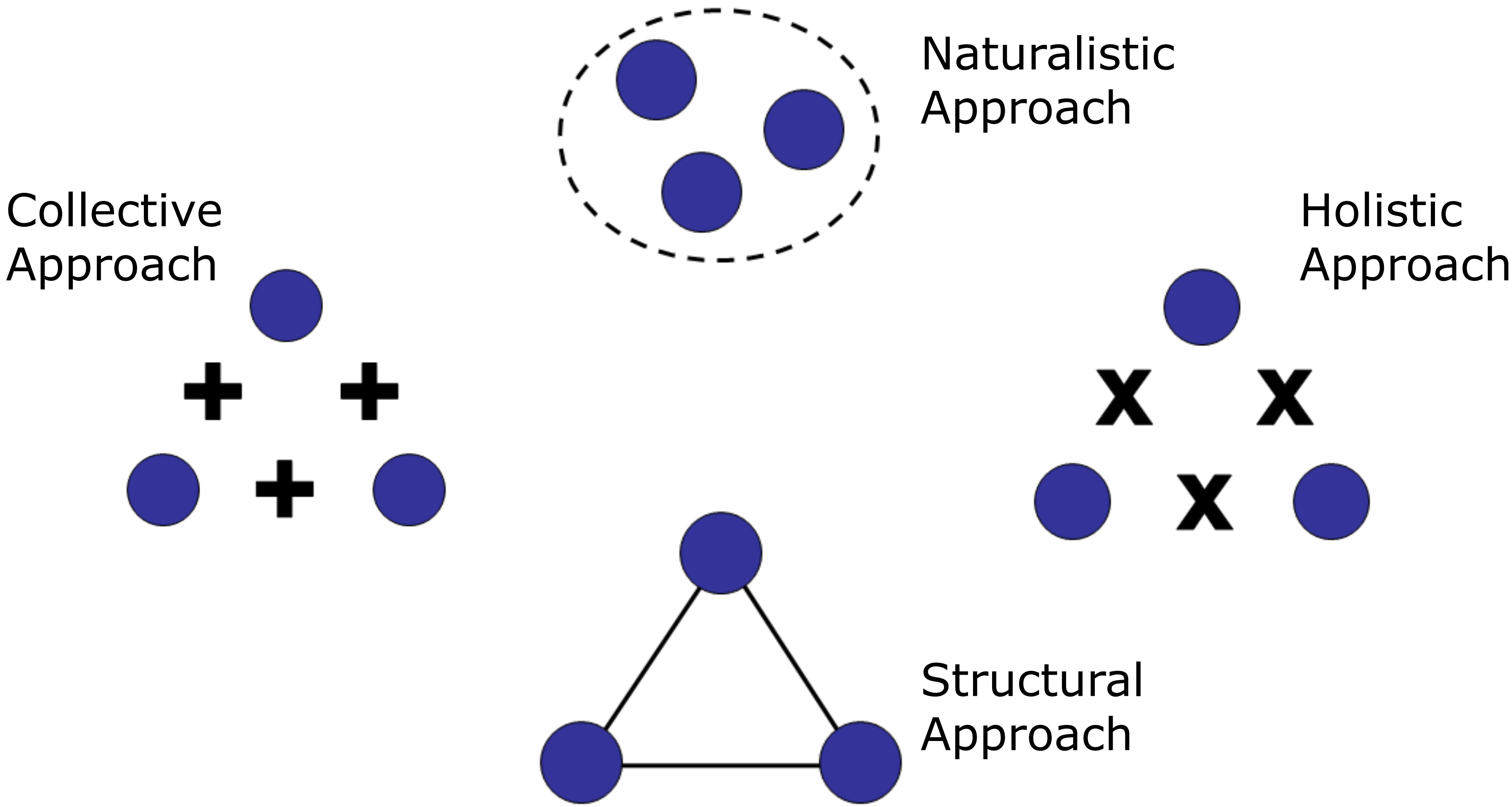
Approaches to Shared Knowledge



Mental Models of the System

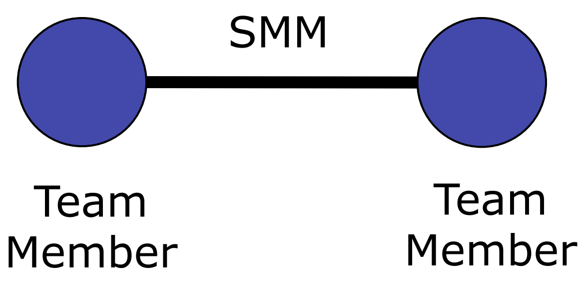
Mental Models

"Mechanisms whereby humans are able to generate descriptions of system purpose and form, explanations of system functioning and observed system states, and predictions of future system states"*

* Rouse, W.B. and N.M. Morris (1986)

Shared Mental Model (SMM)

Condition in which two people utilize mechanisms that lead to similar descriptions, explanations, and predictions



Measuring Mental Models

Survey Question on Major Design Drivers

For the current study only, please check all subsystems or disciplines that are major design drivers for the entire mission.

- ☐ Attitude Control
- ☐ Avionics
- ☐ Communications
- ☐ Contamination
- ☐ Cost
- ☐ Electrical Power
- ☐ Flight Dynamics
- ☐ Flight Software
- ☐ Instrument(s)
- ☐ Integration and Test
- ☐ Launch Vehicles
- ☐ Management
- ☐ Mechanical
- ☐ Mission Operations
- ☐ Orbital Debris
- ☐ Propulsion
- ☐ Radiation
- ☐ Reliability
- ☐ Schedule
- ☐ Thermal
- ☐ Other (please specify)

A Metric for Shared Mental Models

Mental Model Sharedness, $S_{x,y}$, is defined as:

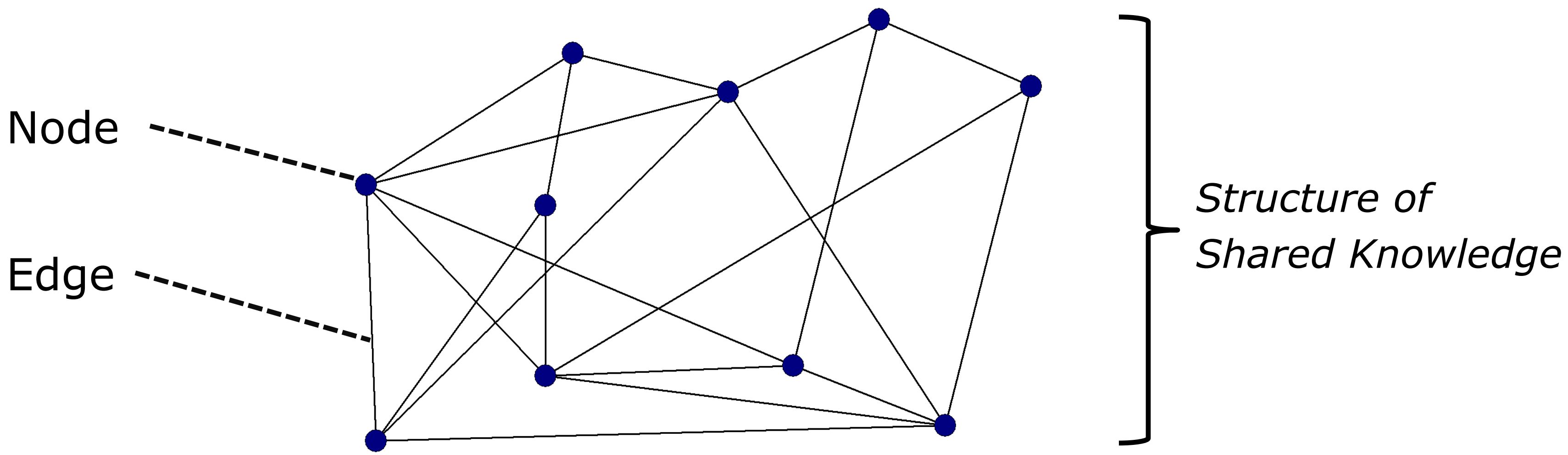
$$S_{x,y} = 2 \times \left(\frac{D_{x,y}}{D_x + D_y} \right)$$

D_x = # of drivers selected by person x
D_y = # of drivers selected by person y
$D_{x,y}$ = # of drivers selected by both x and y

- Ratio of common choices to total choices
- To filter out randomness, values of $S_{x,y}$ converted to $SMM_{x,y}$, a 0-to-4 scale based on the expected value
- Sensitivity analysis conducted to show independence of results to cutoff values in the scale

Social Network Analysis

A set of tools and techniques for analyzing a large group of entities (nodes) and the structure of interactions and/or relationships among them (edges)

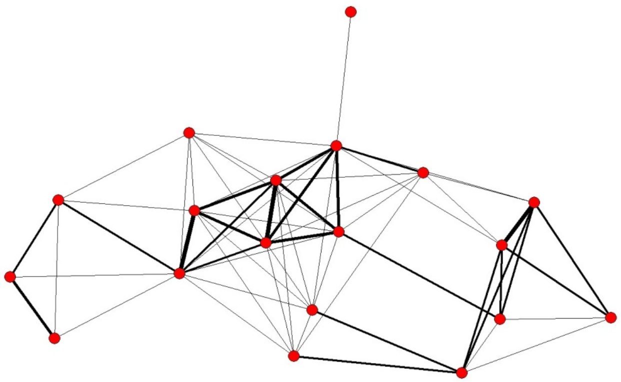


Node = Design Team Member x or y

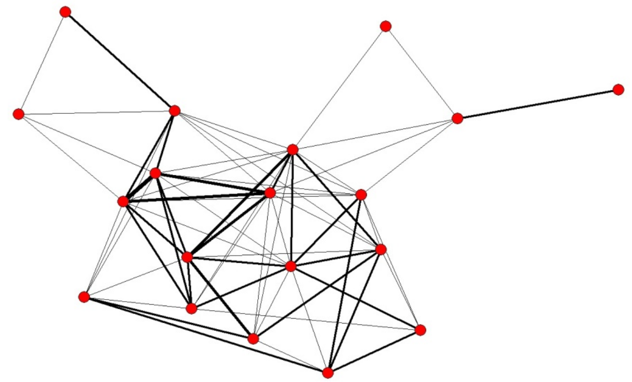
Edge = Shared Knowledge between x and y

Edge Weight = Shared Mental Model, $SMM_{x,y}$

Dynamics of Shared Knowledge



Pre-Session



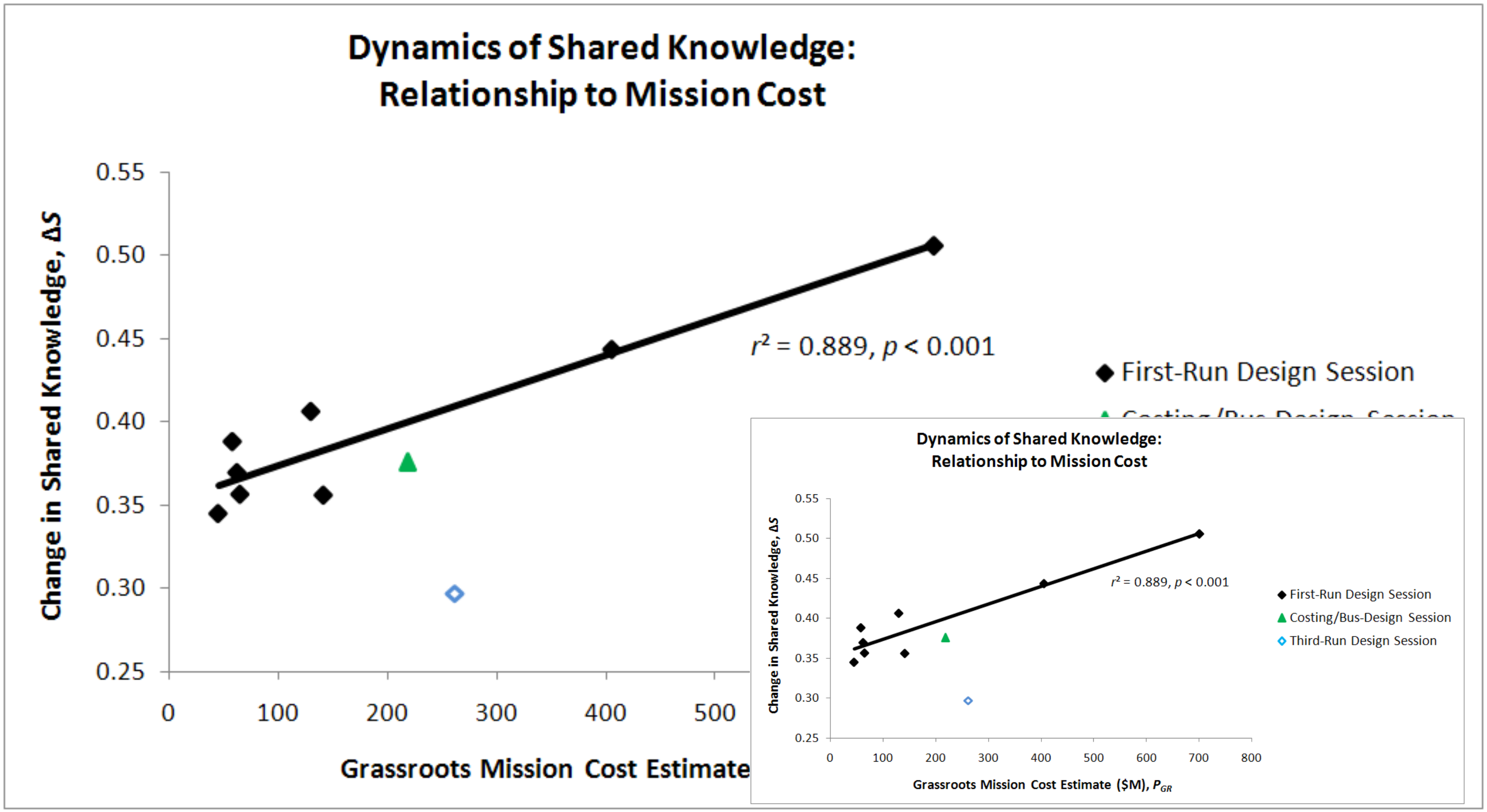
Post-Session

C_{SMM} = structural similarity (edge-by-edge correlation)

Change in Shared Knowledge →

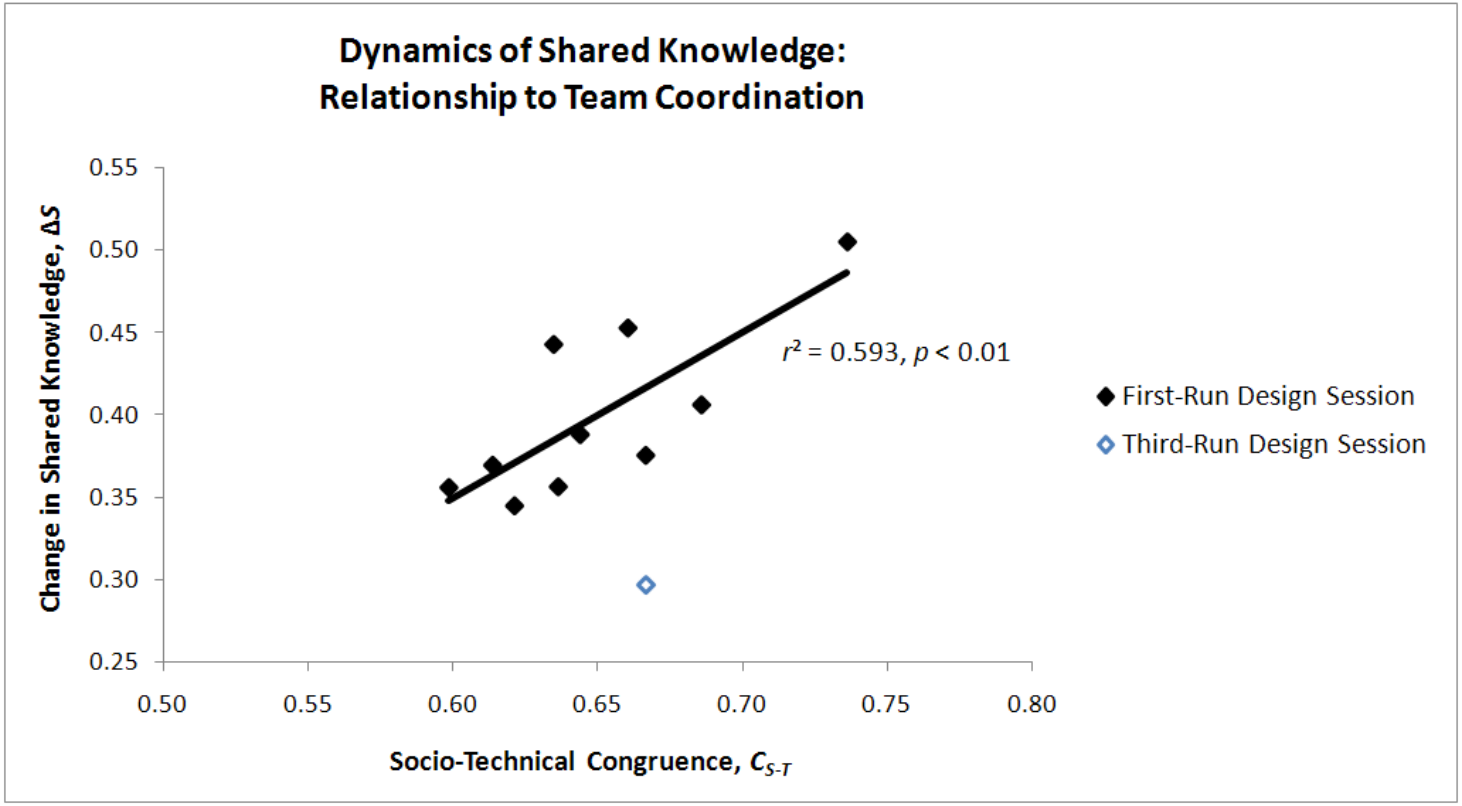
$$\Delta S = \frac{1 - C_{SMM}}{2}$$

Dynamics of Shared Knowledge: Relationship to the Design Product



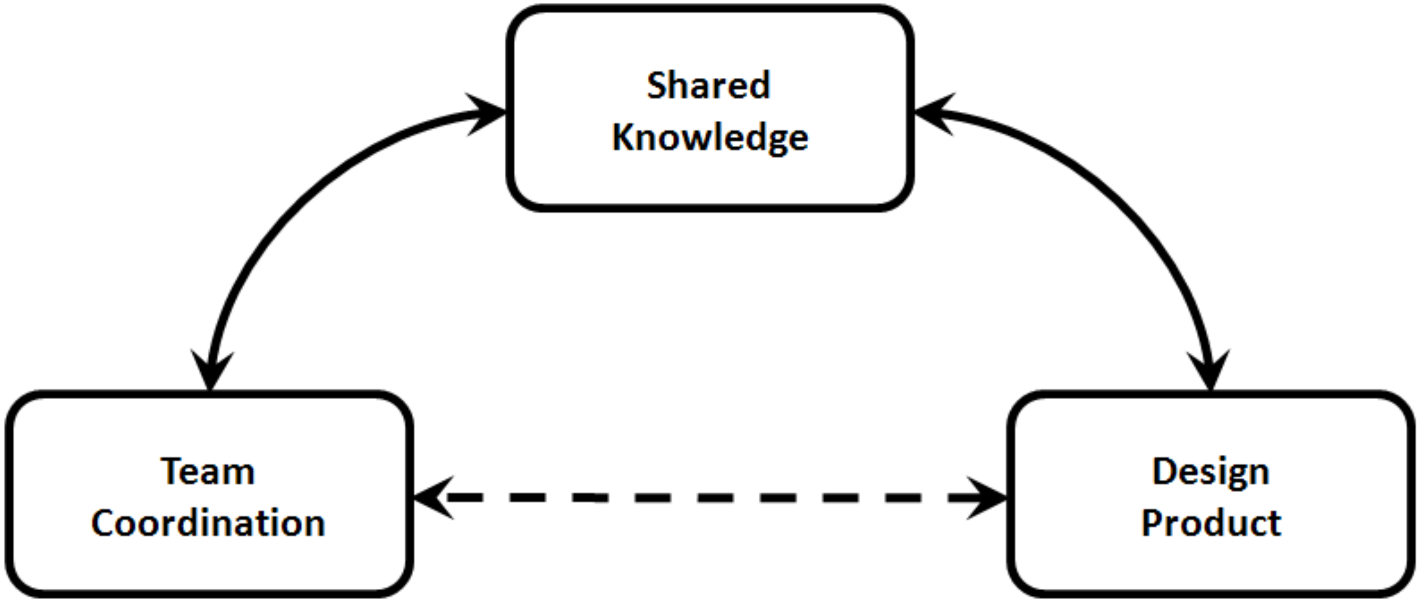
See Avnet and Weigel (2013) for further detail

Dynamics of Shared Knowledge: Relationship to Team Coordination



Change in shared knowledge and team coordination are positively correlated.

The Role of Team Coordination and Shared Knowledge in Engineering Systems Design



Team coordination and the design product are related to change in shared knowledge but are not necessarily related to each other.

Structure of the Presentation

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Research Contributions

- Application of the DSM Methodology to Integrated Concurrent Engineering
- Structural Approach to Shared Knowledge
  - Quantitative, Scalable, and Dynamic
  - Integrates the Advantages of Existing Approaches
- Relationship among Shared Knowledge, Team Coordination, and the Design Product
- Explicit Connection between Organizational/Social Psychology and Systems Engineering
- Framing of an Area for Further Research:
  Socio-Cognitive Analysis of Engineering Systems Design

Ongoing Research on Team Coordination and Shared Knowledge in Other Settings

- **Information Flow in Supply Chain Organizations**
  - Organization(s): Dow Chemical Company
  - Objective: To examine the relationship of socio-technical congruence to supply chain KPIs (e.g., inventory turns, working capital, forecast accuracy, customer lead time, days of sales in inventory, safety stock)

- **Safety Culture and Organizational Learning in the Oil and Gas Industry**
  - Organization(s): A major oil and gas company; a consulting firm; the Mary Kay O'Connor Process Safety Center (MKOPSC) at Texas A&M
  - Objective: To assess the effectiveness of safety initiatives in driving the culture change needed for improved safety practices and outcomes

- **Communication and Cognition in Healthcare Delivery**
  - Organization(s): St. Joseph Regional Health Center, Bryan, TX; Texas A&M University's Center for Health Systems and Design (CHSD)
  - Objective: To study the role of shared knowledge and communication networks among nurses in a critical care unit

Thank You

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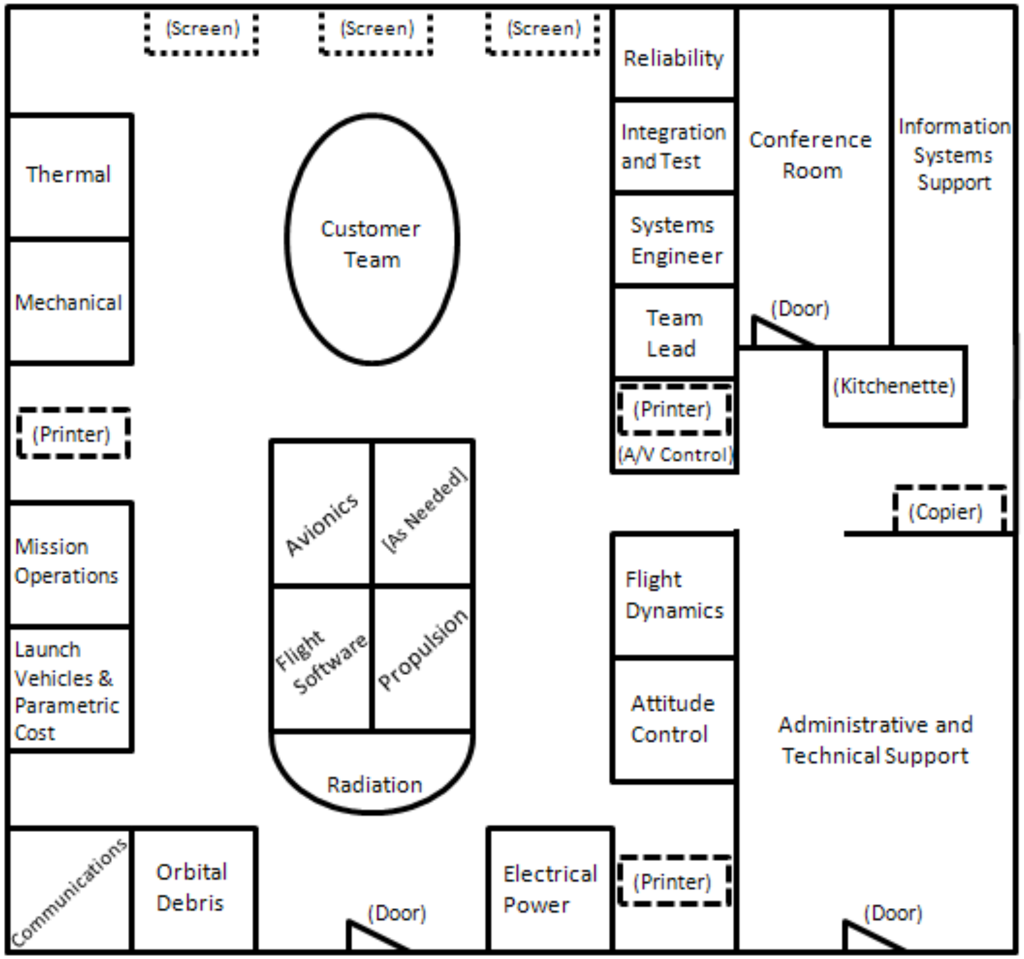
Backup

Layout of the MDL Facility



Overview of DSM Process Analysis

	A	B	C	D	E	F	G	H	I	J	K	L
A	■						X					
B		■										
C	X	X	■									
D		X		■	X			X				
E	X			X	■			X				
F	X				X	■	X	X	X			X
G		X					■					
H					X			■		X		
I		X					X	X	■	X		
J	X		X	X						■		
K	X			X	X						■	
L			X	X	X		X					■

	B	D	G	A	C	E	J	K	L	H	I	F
B	■											
D	X	■				X				X		
G	X		■									
A			X	■								
C	X			X	■							
E		X		X		■				X		
J		X		X	X		■					
K		X		X		X		■				
L		X	X		X	X			■			
H						X	X			■		
I	X		X				X			X	■	
F			X	X		X			X	X	X	■

Parallel
rting
nptions

Tearing

Building the DSM for ICE

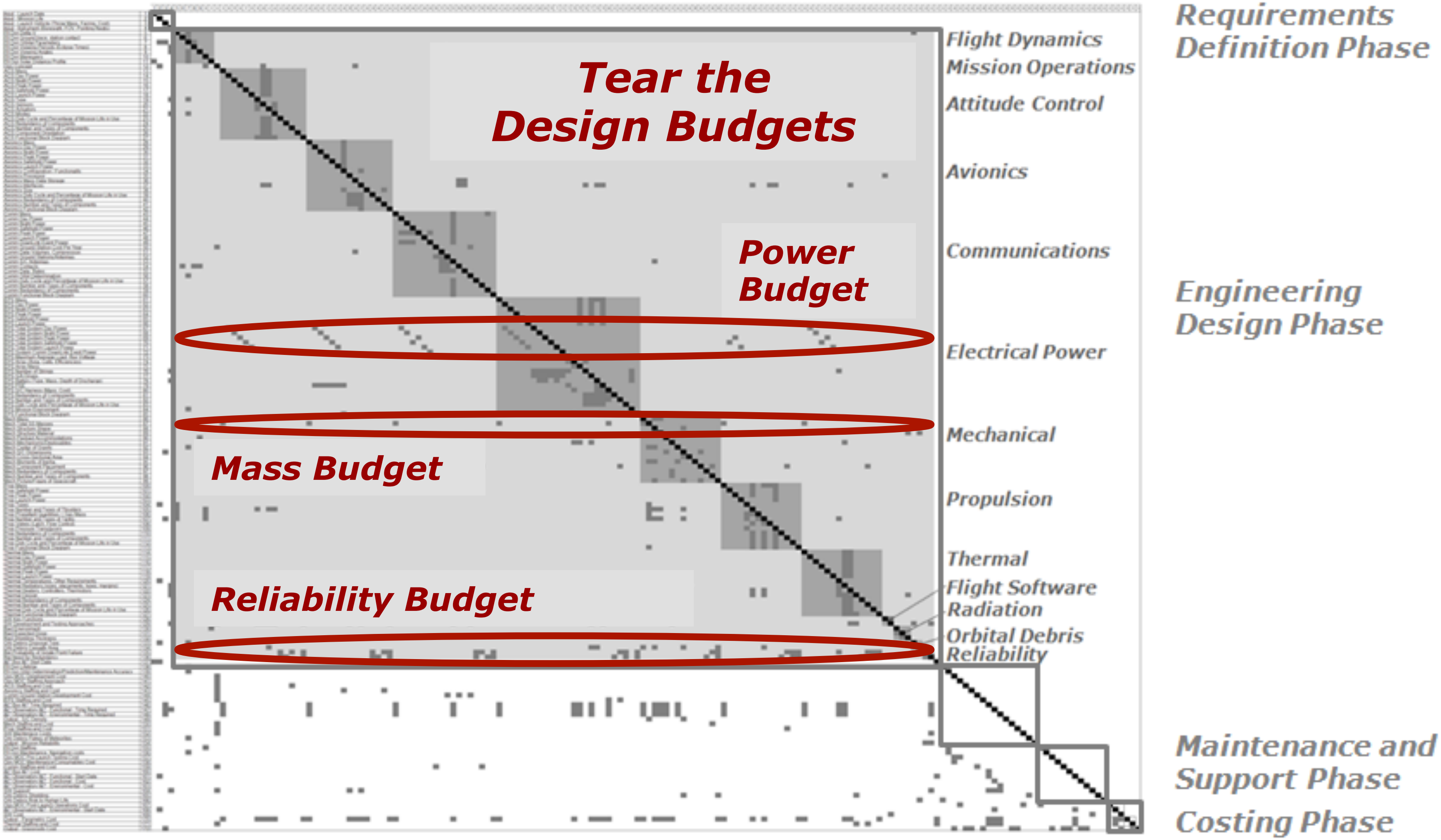
Although collocation accelerates the pace of design activity, it also presents an obstacle to formal analysis and process improvement. DSM construction must account for this.

- Parameter-Based DSM for Conceptual Design
- Steps of DSM Construction in the MDL
  1) Review of Existing Documentation
  2) Surveys on Design Sessions
  3) Structured Interviews
  4) Verification and Validation
- Guiding Principles for DSM Construction in the MDL
  - Document *maximal* flow for a *typical* design session
  - Include only *deliberate* and *purposeful* information flow
  - Abstract two-way *negotiation-type interactions*

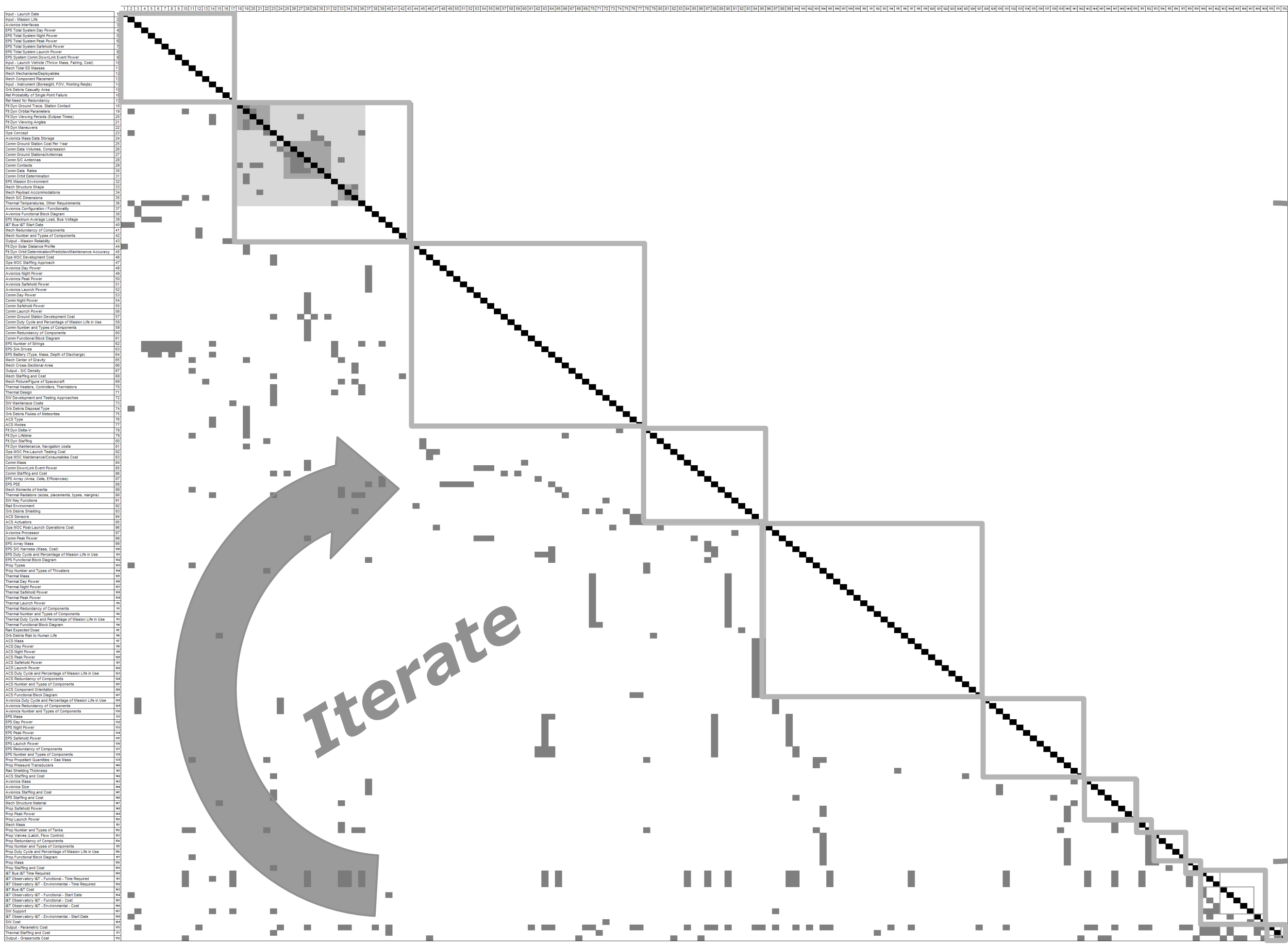
Interdependent Disciplines

		LV	FD	CM	RD	AV	SW	RL	OP	AC	MC	PR	TM	OD	EP	IT	CT
Launch Vehicles	LV																
Flight Dynamics	FD			X													
Communications	CM		X			X			X								
Radiation	RD		X														
Avionics	AV			X	X		X						X		X		
Flight Software	SW					X		X									
Reliability	RL					X											
Mission Operations	OP			X						X	X						
Attitude Control	AC										X						
Mechanical	MC					X				X		X	X	X			
Propulsion	PR									X	X						
Thermal	TM								X		X	X			X		
Orbital Debris	OD										X	X					
Electrical Power	EP					X							X				
Integration and Test	IT																
Parametric Cost	CT																

Tearing the DSM: Identification of Starting Assumptions



The Torn DSM: ICE Process with Starting Assumptions Made



The Core of Interdependent Disciplines

		18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	
Flt Dyn Ground Trace, Station Contact	18		X																		
Flt Dyn Orbital Parameters	19			X																	
Flt Dyn Viewing Periods (Eclipse Times)	20										X										***Flight Dynamics***
Flt Dyn Viewing Angles	21		X																		
Flt Dyn Maneuvers	22		X																		
Ops Concept	23					X							X							X	***Mission Operations***
Avionics Mass Data Storage	24												X	X							***Avionics***
Comm Ground Station Cost Per Year	25						X								X						
Comm Data Volumes, Compression	26							X													
Comm Ground Stations/Antennas	27								X	X											
Comm S/C Antennas	28									X	X						X				***Communications***
Comm Contacts	29	X		X	X					X	X										
Comm Data Rates	30									X	X	X									
Comm Orbit Determination	31		X																		
EPS Mission Environment	32		X																		***Electrical Power***
Mech Structure Shape	33																		X		
Mech Payload Accommodations	34				X																***Mechanical***
Mech S/C Dimensions	35																	X			
Thermal Temperatures, Other Requirements	36															X					***Thermal***

Data Collection on Mental Models

- Survey Data on Major Design Drivers
  - Team members indicate whether each of a set of issues drives the ultimate design.
- Simple Example with Only Four Possible Drivers
  - Cost
  - Schedule
  - Performance
  - Science

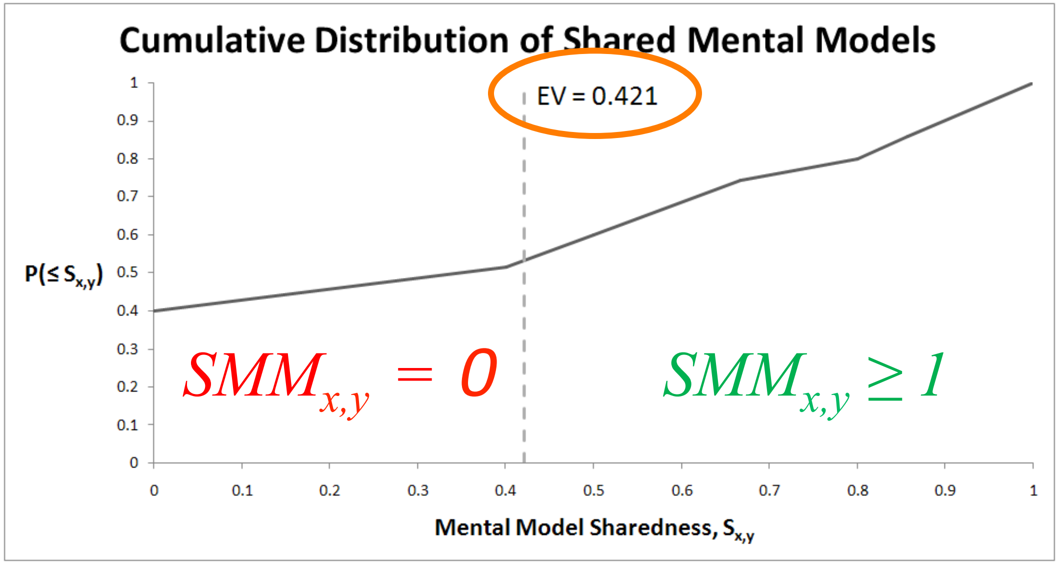
2^4 = 16 Possible Mental Models

	Cost	Schedule	Performance	Science
0	0	0	0	0
1	0	0	0	1
2	0	0	1	0
3	0	0	1	1
4	0	1	0	0
5	0	1	0	1
6	0	1	1	0
7	0	1	1	1
8	1	0	0	0
9	1	0	0	1
10	1	0	1	0
11	1	0	1	1
12	1	1	0	0
13	1	1	0	1
14	1	1	1	0
15	1	1	1	1

Filtering Out Random Responses: A Cutoff For Shared Mental Models

D_x	D_y	$D_{x,y}$	$S_{x,y}$
0	0	0	1.000
0	1	0	0.000
0	2	0	0.000
0	3	0	0.000
0	4	0	0.000
1	0	0	0.000
1	1	0	0.000
1	1	1	1.000
1	2	0	0.000
1	2	1	0.667
1	3	0	0.000
1	3	1	0.500
1	4	1	0.400
2	0	0	0.000
2	1	0	0.000
2	1	1	0.667
2	2	0	0.000
2	2	1	0.500
2	2	2	1.000
2	3	1	0.400
2	3	2	0.800
2	4	2	0.667
3	0	0	0.000
3	1	0	0.000
3	1	1	0.500
3	2	1	0.400
3	2	2	0.800
3	3	2	0.667
3	3	3	1.000
3	4	3	0.857
4	0	0	0.000
4	1	1	0.400
4	2	2	0.667
4	3	3	0.857
4	4	4	1.000

35 Possible SMMs



$S_{x,y} \leq EV$ →

x and y do not share mental models to any greater extent than two people with no prior knowledge of the task answering at random

A Filtered Scale of Shared Mental Models

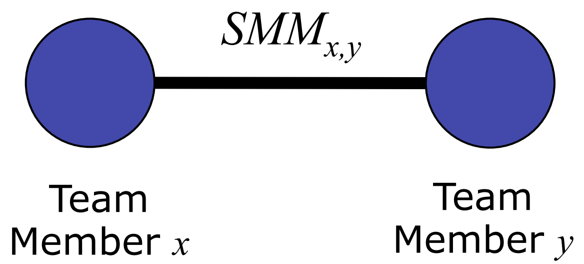
$$SMM_{x,y} = 0: S_{x,y} \leq EV$$

$$SMM_{x,y} = 1: EV + 0.5\sigma \geq S_{x,y} > EV$$

$$SMM_{x,y} = 2: EV + \sigma \geq S_{x,y} > EV + 0.5\sigma$$

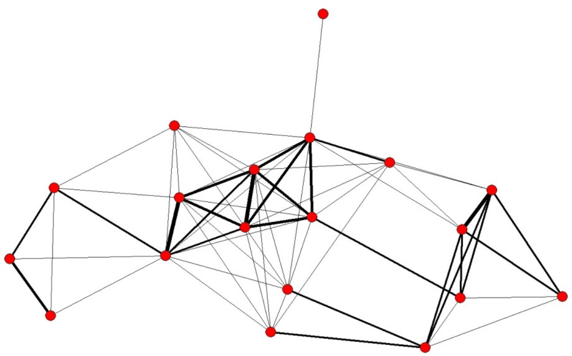
$$SMM_{x,y} = 3: EV + 1.5\sigma \geq S_{x,y} > EV + \sigma$$

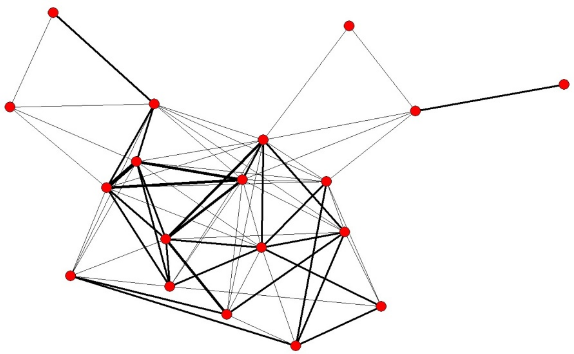
$$SMM_{x,y} = 4: S_{x,y} > EV + 1.5\sigma$$



Sensitivity analysis conducted to show independence of results to cutoff values

Direction of Change in Shared Knowledge





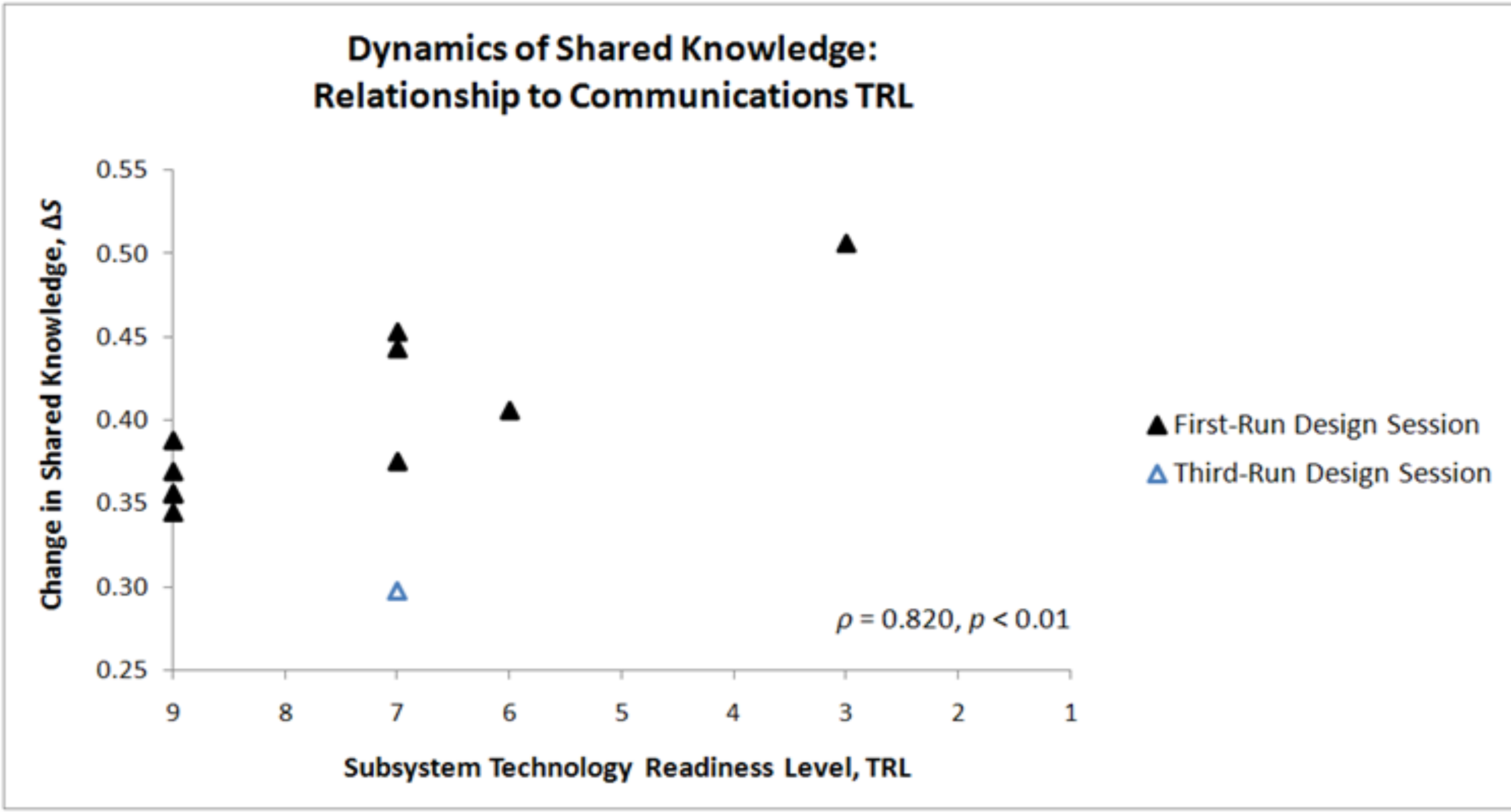
S_{Pre} (Average $S_{x,y}$) $\leq$ S_{Post} (Average $S_{x,y}$)

ΔS = Increase in Shared Knowledge

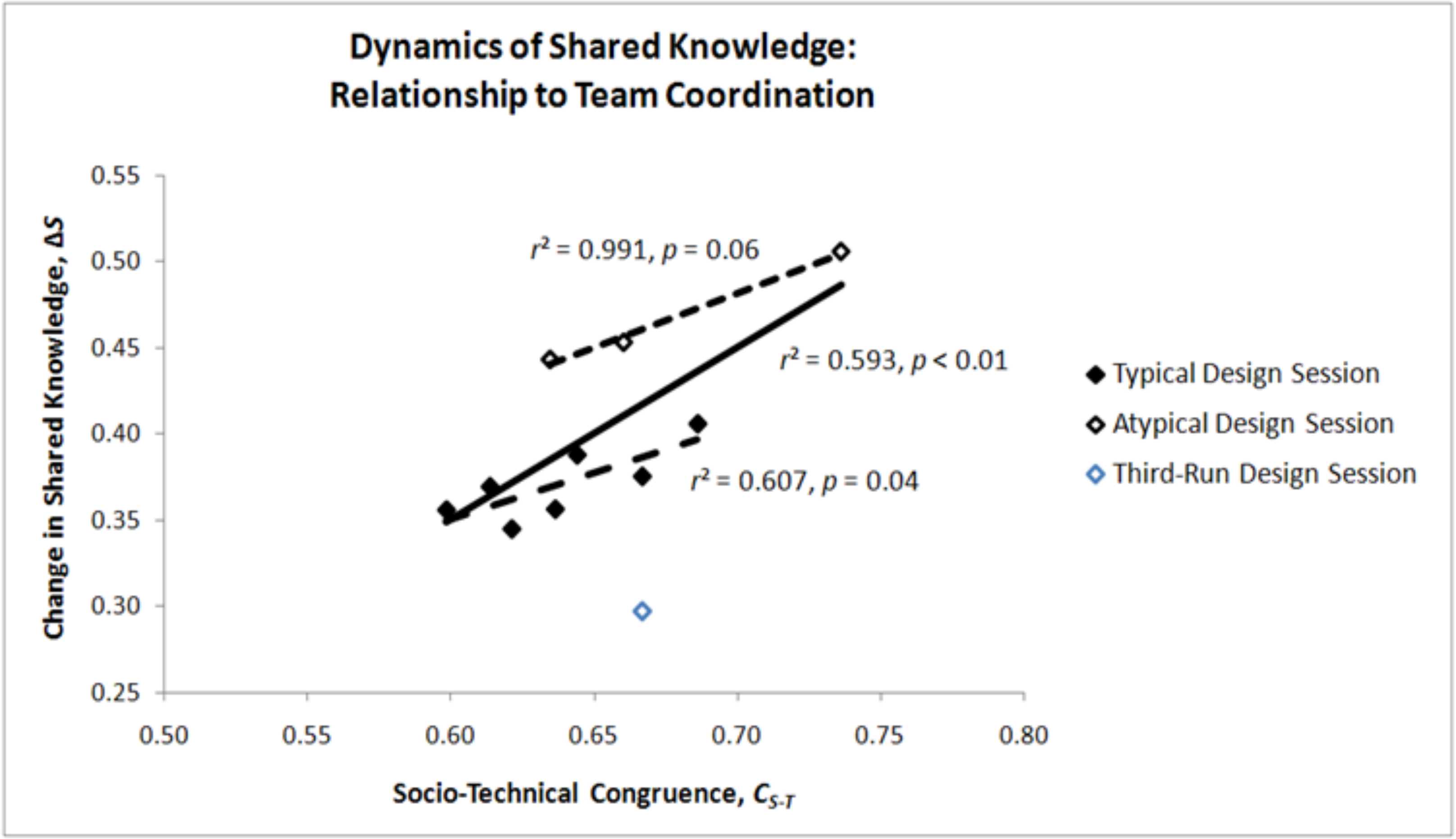
Relationship Among System Attributes

	MTRL		T_L		M_L	
	ρ	p	r	p	r	p
T_L	0.691	0.01	-	-	-	-
M_L	0.728	< 0.01	0.883	< 0.001	-	-
P_{GR}	0.673	0.02	0.649	0.03	0.527	0.10

The Communications Subsystem As an Indicator of Shared Knowledge



Team Coordination and Shared Knowledge in the Team



Recommendations to the MDL

People

Period of learning and consensus building

Sub-teams based on interdependent disciplines

Process

Resolve orbit determination trades

Determine starting assumptions

Design sequentially… then iterate

Tools

DSM-based process automation software

Facility

Lab layout based on interdependent disciplines

Standard Design Process Model for an ICE Laboratory