Socio-Cognitive Analysis of Engineering Systems Design

Shared Knowledge, Process, and Product

Second International Engineering Systems Symposium

Mark S. Avnet
June 17, 2009
Research Motivation: Perspectives on Space Systems Design

Research Approach

**Technical Analysis**

Design process modeling and analysis using the Design Structure Matrix (DSM)

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**Social Analysis**

A network model of shared knowledge in real-world engineering design teams

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**Socio-Technical Analysis**

Integrated model revealing the relationship among shared knowledge, process, and product
Research Setting: Integrated Concurrent Engineering (ICE)

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

Five-Day Conceptual Design Sessions of Scientific Spacecraft and Surrounding Mission Architectures

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
1. Analysis of the Design Process

2. A Model of Shared Knowledge

3. Integrated Analysis: People and Process
Part 1

1. Analysis of the Design Process
2. A Model of Shared Knowledge
3. Integrated Analysis: People and Process

Analysis of the Design Process
Review of the Design Structure Matrix

Task A depends on information from Task G

Tasks D and E must be done concurrently
Overview of DSM Process Analysis

Tearing
Parameter-Based DSM of the Typical ICE Design Process
Partitioning the DSM: The Conceptual Design Life Cycle
Critical Design Trades and Interdependent Disciplines
Tearing the DSM: Identification of Starting Assumptions

- Power Budget
- Mass Budget
- Reliability Budget

Requirements
Definition Phase

Engineering Design Phase

Maintenance and Support Phase
Costing Phase
The Torn DSM: ICE Process with Starting Assumptions Made

Requirements and Assumptions Phase

Orbit Determination Phase

Sequential Engineering Design Phases

Integration Phase

Costing Phase

Iterate
The Core of Interdependent Disciplines

- Flight Dynamics
- Mission Operations
- Avionics
- Communications
- Electrical Power
- Mechanical
- Thermal
Part 2

1. Analysis of the Design Process

2. A Model of Shared Knowledge

3. Integrated Analysis: People and Process

A Model of 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”*


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

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

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

Ratio of common choices to total choices

$D_x = \# \text{ of drivers selected by person } x$

$D_y = \# \text{ of drivers selected by person } y$

$D_{x,y} = \# \text{ of drivers selected by both } x \text{ and } y$
**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

\[ C_{SMM} = \text{structural similarity (edge-by-edge correlation)} \]

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

Change in Shared Knowledge
Dynamics of Shared Knowledge: Relationship to the Design Product

- **1) Mission Concept Maturity Based on Technology Readiness Level (TRL), a 1-to-9 Ordinal Scale**
- **2) System Development Time Number of Years from Design Session to Launch**
- **3) Launch Mass Total Mass of the System**
- **4) Mission Cost Grassroots Estimate**

**Dynamics of Shared Knowledge:**

- Relationship to the Design Product

![Graph showing the relationship between change in shared knowledge and grassroots mission cost estimate](image)

\[ r^2 = 0.677, \ p = 0.02 \quad r^2 = 0.889, \ p < 0.001 \]

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Part 3

1. Analysis of the Design Process

2. A Model of Shared Knowledge

3. Integrated Analysis: People and Process

Integrated Analysis: People and Process
# Measuring Team Coordination

## Congruence Matrix

Overlay of Expected and Reported Interactions

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

### Formalism Developed by Sosa et al. (2003)

### Expected Interaction Matrix

Based on Design Trades in the Partitioned DSM

### Reported Interaction Matrix

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

### N
- $N_{\#}$: number of # cells
- $N_b$: number of blank cells
- $N$: total number of cells

### X
- Actual Interactions
  - NO (87)
  - YES (69)
- Expected Interactions
  - YES (32)
  - NO (124)
Dynamics of Shared Knowledge: Relationship to Team Coordination

Change in Shared Knowledge and Team Coordination are Positively Correlated.

$r^2 = 0.593, p < 0.01$
The Role of Shared Knowledge in Engineering Systems Design
1. Analysis of the Design Process

2. A Model of Shared Knowledge

3. Integrated Analysis: People and Process
Research Contributions

• First DSM Representation of ICE and of the Full Space Mission Design Process

• A New Approach to Shared Knowledge in Teams
  — 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
Thank You
References (1)


References (2)


References (3)


Backup
## Map of the Thesis

<table>
<thead>
<tr>
<th>Part</th>
<th>Purpose</th>
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<th>Chapter Content</th>
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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
- Sosa et al. (2003) – design team interactions and product architecture
- Cataldo et al. (2008) – socio-technical congruence (STC)
Literature Review: Shared Knowledge in Teams

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

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

Lim and Klein (2006) – average among all dyads in a larger team

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

Shared Knowledge in Engineering Design

Badke-Schaub et al. (2007) – an exploration of the applicability of shared mental models to design teams
Layout of the MDL Facility
## MDL Design Study Observations

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Critical Design Trades and Interdependent Disciplines
Approaches to Shared Knowledge

- Naturalistic Approach
- Collective Approach
- Holistic Approach
- Structural Approach
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

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Filtering Out Random Responses: A Cutoff For Shared Mental Models

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35 Possible SMMs

Cumulative Distribution of Shared Mental Models

$S_{x,y} \leq EV$

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

$S_{x,y} = 0, S_{x,y} \geq 1$

$EV = 0.421$
Insights from the Structural Approach to Shared Knowledge

\[ \Delta S = \text{Increase in Shared Knowledge} \]

Let

\[ S_{\text{Pre}} \leq S_{\text{Post}} \]

(Average \( S_{x,y} \))

\[ (\text{Average } S_{x,y}) \]

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Interrelated System Attributes
Communications is central to both the design process and the development of shared knowledge.

The Communications Subsystem: An Indicator of Shared Knowledge

Dynamics of Shared Knowledge: Relationship to Communications TRL

Change in Shared Knowledge, ΔS

Subsystem Technology Readiness Level, TRL

Δ First-Run Design Session
Δ Third-Run Design Session

ρ = 0.820, ρ < 0.01
Measuring Team Coordination

**Congruence Matrix**

Overlay of Expected and Actual Interactions

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

Formalism Developed by Sosa et al. (2003)
Team Coordination and Shared Knowledge in the Team

Dynamics of Shared Knowledge: Relationship to Team Coordination

- $r^2 = 0.991$, $p = 0.06$
- $r^2 = 0.593$, $p < 0.01$
- $r^2 = 0.607$, $p = 0.04$

Change in Shared Knowledge, $\Delta S$

Socio-Technical Congruence, $C_{S,T}$
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

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Engineering Systems Symposium
June 17, 2009
Standard Design Process Model
Future Work

- Design Process Analysis
  - Build the DSM to Include Types and Strengths of Dependencies
  - Apply to Other ICE Design Centers

- Shared Knowledge in Teams
  - Measure Shared Mental Models in Other Ways
  - Time-Series Analysis to Determine How and When Shared Knowledge Changes
  - Analysis of Each Network to Reveal Details of the Structure of Shared Knowledge

- Shared Knowledge, Team Coordination, and Performance
  - Explore the Direct Relationship between Team Coordination and Design Product
  - Determine Metrics of Design Product Quality

- Socio-Cognitive Analysis of *Other* Engineering Systems Design