Computational Enterprise Modeling and Simulation

Enabling Enterprise Performance Improvement, Modernization and Transformation

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Problem Context

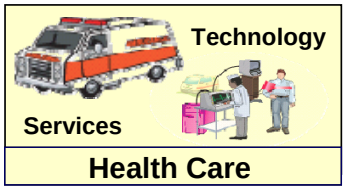
Conventional analytical tools and methods supporting enterprise performance improvement, modernization and transformation are manifestly inadequate to deal effectively with the complexity of enterprise dynamics

- **Unacceptable performance or failure of large acquisition programs with multi-billion dollar implications**
  - Cost overruns, schedule delays, performance shortfalls
  - Traditional systems engineering thinking and methodology no longer adequate
- **Chronic problems of agency modernization efforts; limited benefits resulting from many continuous process improvement initiatives**
  - Frustrated by pre-existing structural constraints; decision cycles & lags
  - Stymied by enterprise complexity and dynamics; multiple pathologies
- **Failure or slow pace of enterprise transformation efforts**
  - Incremental improvement often does not scale up to systemic enterprise change and transformation; "messy" multiscale complexity
  - Lacking: Holistic enterprise systems thinking, structured methods, and tools

Civil Aviation Transformation (NextGen)

IRS Modernization

Net-Centric Warfare
Customs Modernization
Border Control



Health Care Info. Systems

U.S. AIR FORCE

Vantage Point
MITRE-MIT ESD Collaborative Project

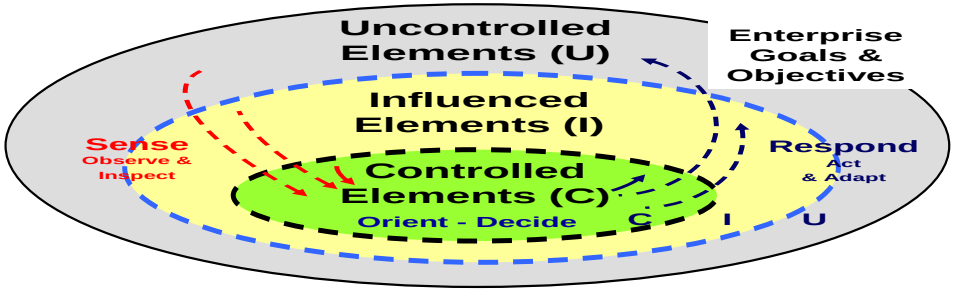
- **MITRE-sponsored research project, now in its third year**
- **Title: Enterprise Dynamics -- Architecture-based, Decision-Driven Approach**
- **MITRE Principal Investigator: Dr Kenneth Hoffman**

  MIT Principal Investigators: Dr Kirkor Bozdogan; Co-PI: Prof Joseph Sussman
- **Purpose:** Develop concepts, models and tools for managing the complexity of enterprise dynamics in an emerging network-centric environment
- **Focus:** ***Computational enterprise modeling and simulation for designing and evolving "next-generation" enterprises that are flexible, adaptive and robust (FAR)***
  - Develop "proof-of-concept" enterprise modeling and simulation capability
  - Contribute to creation of *complex enterprise systems engineering* -- a new discipline
- **Interim Results:**
  - Developed conceptual framework guiding enterprise transformation efforts
  - Made progress in modeling enterprise interactions to achieve better integration
  - **Book in-process:** ***Complex Enterprise Systems Modeling and Engineering for Operational Excellence: Concepts, Models and Applications*** **--** Kenneth Hoffman [MITRE] *and* Kirkor Bozdogan [MIT], Co-editors.

Working Hypothesis: Viewing Enterprises as *Purposeful Complex Adaptive Systems*

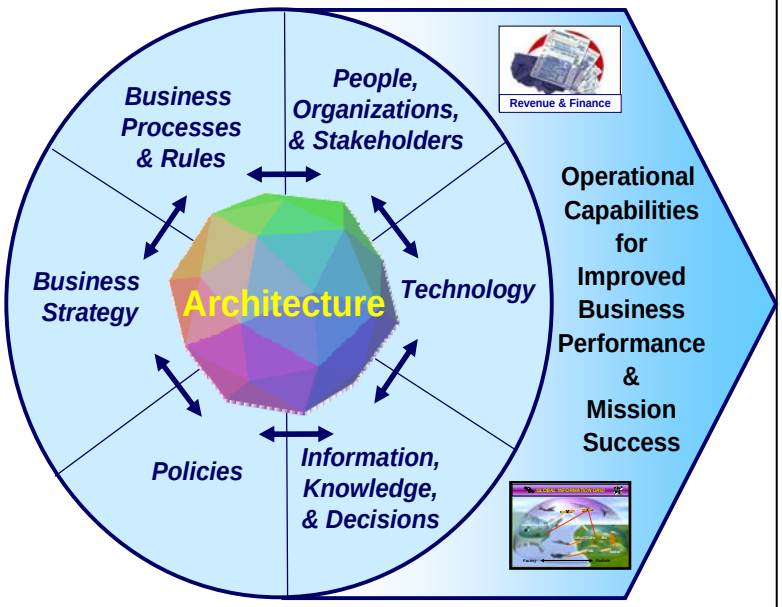
Working definition: Enterprises are goal-directed complex adaptive socio-technical systems organized to create value for their multiple stakeholders by performing their defined missions, functions or businesses*

- **Open systems --** Multilevel two-way interactions with the external environment
- **Nonlinear interactions --** Both internally and externally
- **Interdependence --** Large number of interconnected parts
- **Dynamic change --** The system changes over time, as environment changes
- **Adaptive behavior (*but with intentionality, strategic choice, foresight, unlike in natural systems)* --** How the system learns and adjusts to external changes shapes its evolution (survival, extinction)
- **Emergence --** Collective behavior at a given level (scale) cannot be understood from studying microstructure and behavior at a lower level (scale)
- **Self-organization --** Interaction between system's structure & emergence can create a new structure



* Enterprises: Networked entities sharing a common purpose spanning multiple organizational units (program enterprises, divisions, multi-division companies, agencies)

Mastering the Complexity of Enterprise Dynamics-
New Concepts and Approaches



Multidisciplinary Methods
- **Performance engineering**
- **Computational organization science**
- **Behavioral economics**
- **Complex adaptive systems**
- **Network science**
- **Evolutionary biology**
- **Design engineering; mfg. systems**
- **Computer science**
- **Mathematics; operations research**

- **Enterprise architecture --** Abstract representation of an enterprise's holistic design as a purposeful complex adaptive system-- the main source of its sustained competitive advantage (business architecture).
- **Enterprise architecture model --** Formal computational model of the enterprise's dynamic architecture, through application of theory-based concepts, principles, and modeling & simulation techniques (descriptive, explanatory, predictive, "what-if" analysis)
- **Enterprise architecture design (enterprise architecting):** On-going, modeling-enabled, process of proactively designing the dynamic future evolution of enterprise architecture for continuous improvement, modernization and transformation
- **Enterprise science --** Create basic unifying principles and conceptual frameworks governing enterprise structure and behavioral dynamics, supporting complex enterprise systems engineering (CESE), by integrating knowledge from multiple streams, such as:

Emphasis on Computational Enterprise Modeling and Simulation

- **An emerging interdisciplinary field dedicated to discovering general principles of organization and the conditions under which these principles do or do not apply**
- **Concerned with developing and using formal theory-grounded mathematical and computational models and tools that can be used to:**
  - Develop improved understanding of the structural, behavioral and evolutionary properties of enterprises (organizations)
  - Conceptualize and capture essential features of an organization's current design (architecture); design and evaluate alternative future-state architecture designs
  - Test alternative hypotheses; develop new concepts, theories and knowledge about enterprises
- **Models can be designed to contain varying levels of detail at multiple levels of abstraction in order to:**
  - Simulate interactions among different entities (individuals, teams, units, organizations) that exhibit collective enterprise-level (system-level) properties
  - Conceptualize and capture essential features of an organization's current design (architecture); design and evaluate alternative future-state architecture designs
- **Grounded in existing theory; serves as a forcing function to integrate knowledge from multiple streams that remains highly fragmented**

How Can Computational Enterprise Modeling and Simulation Help?

Computational enterprise modeling and simulation can help managers avoid costly mistakes based on hunch, common sense, or trial and error

- **Serves several important practical purposes**
  - **"Big picture" --** Enables shared mental model of the enterprise's holistic design (gestalt) to meet the "design-transform" challenge
  - **Descriptive --** Defines "current-state"; helps to get everyone on the same page on current picture
  - **Diagnostic --** Indicates quick near-term improvement opportunities
  - **Prescriptive --** Identifies performance gaps and "must do" future decision/action priorities
  - **Explanatory --** Generates new insight into critical relationships shaping outcomes (understanding)
  - **Serious gaming --** Provides "what-if" capability to evaluate alternative decision options in virtual real-time interactive laboratory environment
  - **Education --** Serves as a training tool on how the enterprise works
  - **Summary:** Harnesses power of modern modeling & simulation technology to make informed decisions
- **Provides a whole new way of "doing science"**
  - Allows conducting virtual experiments to test new hypotheses
  - Helps accelerate creation of new knowledge

Quick Background: Virtually Explosive Growth in Modeling "Technology"

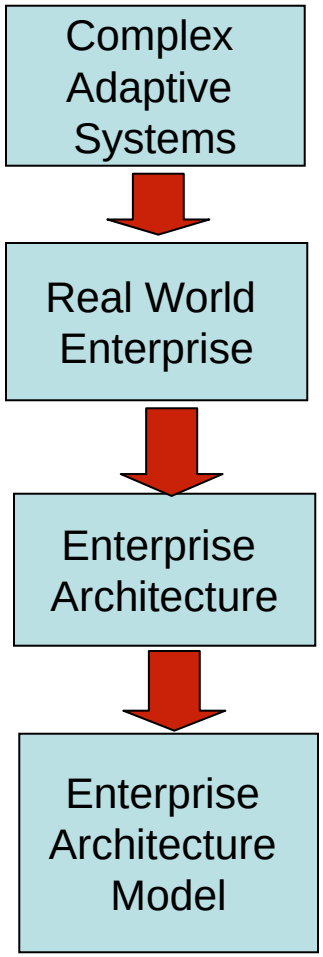
- **There has been a virtual explosion in modeling "technology" (theory, techniques, tools) in recent years -- (right panel)**
- **This growing interest in modeling has been spurred by big "pull" to meet emerging needs as well as by "push" from academic world**
  - Enterprise transformation
  - Organizational adaptation
  - Business process improvement
  - Product development
  - Supply chain optimization
  - Intelligent manufacturing systems
  - Defense simulation
- **Much of this recent growth in modeling "technology" reflects inadequacy of traditional mathematical closed-from solutions to deal effectively with today's complexity**
  - New perspectives and tools provided by recent advances in complexity theory and network science
  - Examples include biologically-inspired computing approaches (e.g., genetic algorithms, multi-agent systems)

- **System dynamics**
- **Agent-based modeling**
- **Discrete event simulation**
- **NK modeling**
- **Network analysis**
- **Highly optimized tolerance (HOT)**
- **Econometric modeling**
- **Neural networks**
- **Bayesian networks**
- **Boolean networks**
- **Petri-nets**
- **Evolutionary multi-objective optimization**
- **Real options**
- **Optimal control**
- **Cellular automata**
- **Genetic algorithms**

Examples of Recent Developments in Computational (Enterprise) Modeling

- **System Dynamics:** (Ford & Sterman 1998; Sterman 2000; Sastry 2001; Sgouridis 2007)
  - **Models dynamic causal loop structure and behavior of complex systems; top-down approach**
  - **Illustrative applications: market dynamics of technology-based product (Birdseye 1996), product development processes (Ford and Sterman 1998); symbiotic strategies in enterprise ecology (Sgouridis 2007)**
- **Agent-based Modeling:** (Carley & Svoboda 1996; Epstein 2003; Chang & Harrington 2006)
  - **Assumes simple behavioral rules (logic) for agent interactions; bottom up approach**
  - **Explores for emergent behavior at a higher (aggregated) level**
  - **Illustrative applications: growing of organization (Epstein 2003); organizational design and search (Rivkin & Siggelkow 2003)**
- **NK modeling:** (Kauffman,1993; Levinthal 1997; Levinthal & Warglien 1999; Rivkin & Siggelkow 2003; Ethiraj & Levinthal 2004; Ethiraj & Levinthal 2004)
  - **Originated from evolutionary biology; focus on analyzing internal and external interactions; provides computational model for simulating adaptive enterprise search and adaptation in enterprise's fitness landscape**
  - **Illustrative applications: Design of fitness landscapes (Levinthal & Warglien 1999);firm organization in complex and uncertain environments (Barr & Hananki 2006)**
- **Network Analysis:** (Carley, 2000, 2001; Krackhardt 1992, 1995; Wasserman & Galaskiewics 1994; Carley & Gasser 1999)
- **Multidisciplinary Design Optimization** (AIAA MDO White Paper, 1991)
  - **Originated and established in aerospace systems design (aerodynamics, structure, and control).**
  - **Multiple objectives in nature: performance, cost, schedule, and quality**
  - **Example of applications: Satellite constellations (de Weck, *et al.,* 2004), automotive product platform (de Weck 2005)**
- **Others: There have been many modeling methods employed, often in pursuit of the challenge of organizational evolution and adaptability:**
  - **Genetic Algorithms: (Miller 2001)**
  - **Neural Networks (Barr and Saraceno 2002; Barr & Saraceno 2005)**

Main Ideas Driving Computational Enterprise Modeling and Simulation



Complex adaptive systems have an underlying architecture that can be discovered, analyzed, understood

Real world enterprises represent a class of complex adaptive systems (goal-directed socio-technical systems)

The architecture of the complexity characterizing real-world enterprises, too, can be discovered, analyzed, understood

Computational enterprise modeling and simulation makes it possible for us to capture, quantify, analyze and "manipulate" enterprise architecture to achieve performance improvements, change and transformation to "grow" more effective future enterprises

Linking Modeling to Context: Enterprise Change Regimes, Architecture Domains, and Decision Issues

What is the enterprise change regime or context requiring planned action?

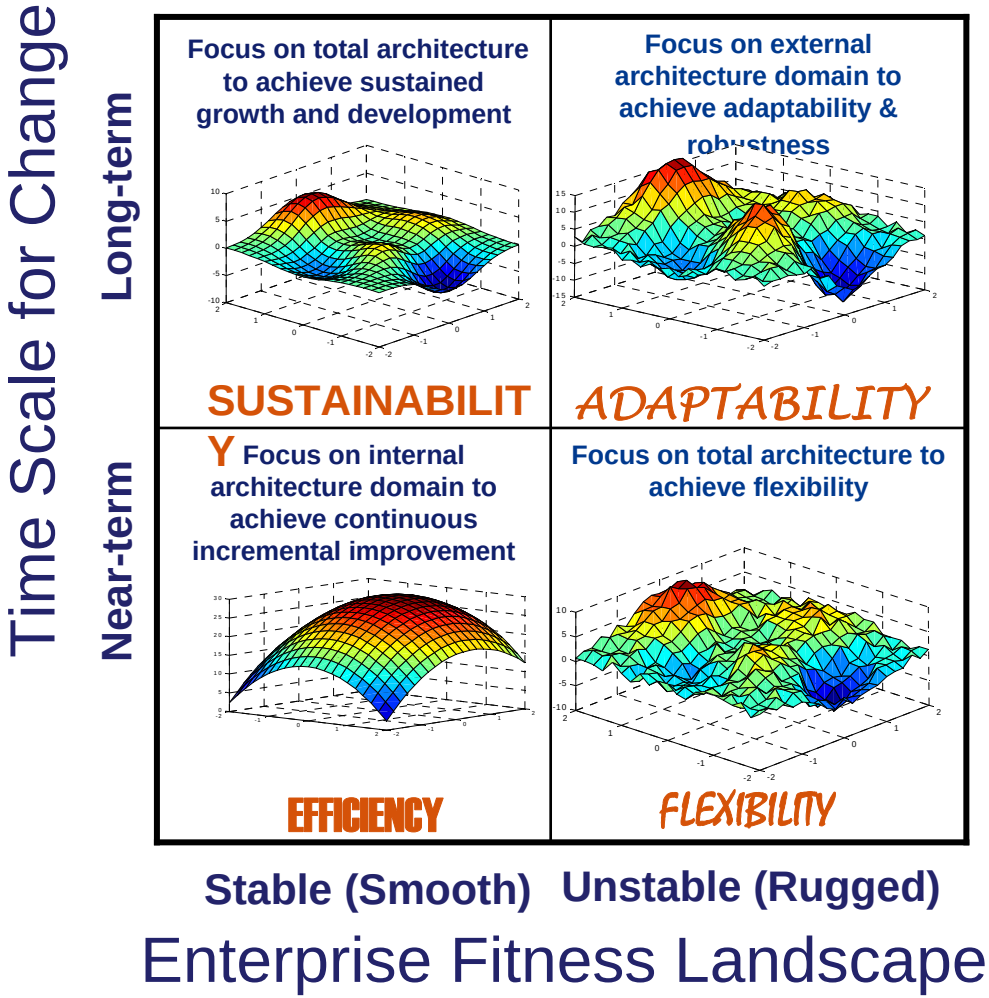
What is the enterprise architecture domain requiring the greatest design focus?

What are the (typical) salient set of decision issues requiring greatest attention to achieve the target design goal?

What are the appropriate modeling approaches for addressing the identified class of decision issues?

No such thing as an all-purpose enterprise model -- need to define specific context and purpose for best modeling application

A Close-up View: Navigating the Enterprise Terrain -- Smooth and Rugged Regions



- **EFFICIENCY: Relatively greater emphasis on managing internal interactions (near-term)**
  - Cost of service
  - Productivity
- **SUSTAINABILITY; Emphasis on managing both external and internal interactions (long-term)**
  - Retaining market share
  - Providing reliable services
- **ADAPTABILITY: Relatively greater emphasis on managing external interactions (long-term)**
  - Ability to adjust to "hits" to the program
  - Learning & coping in new environment
- **FLEXIBILITY: Emphasis on managing both internal and external interactions (near-term)**
  - Ability to quickly reconfigure operations (scale/mix of services, production)
  - Meeting new missions rapidly at little additional cost

Linking Modeling to Salient Context-Dependent Enterprise Decision Issues

Time Scale for Change

Long-term

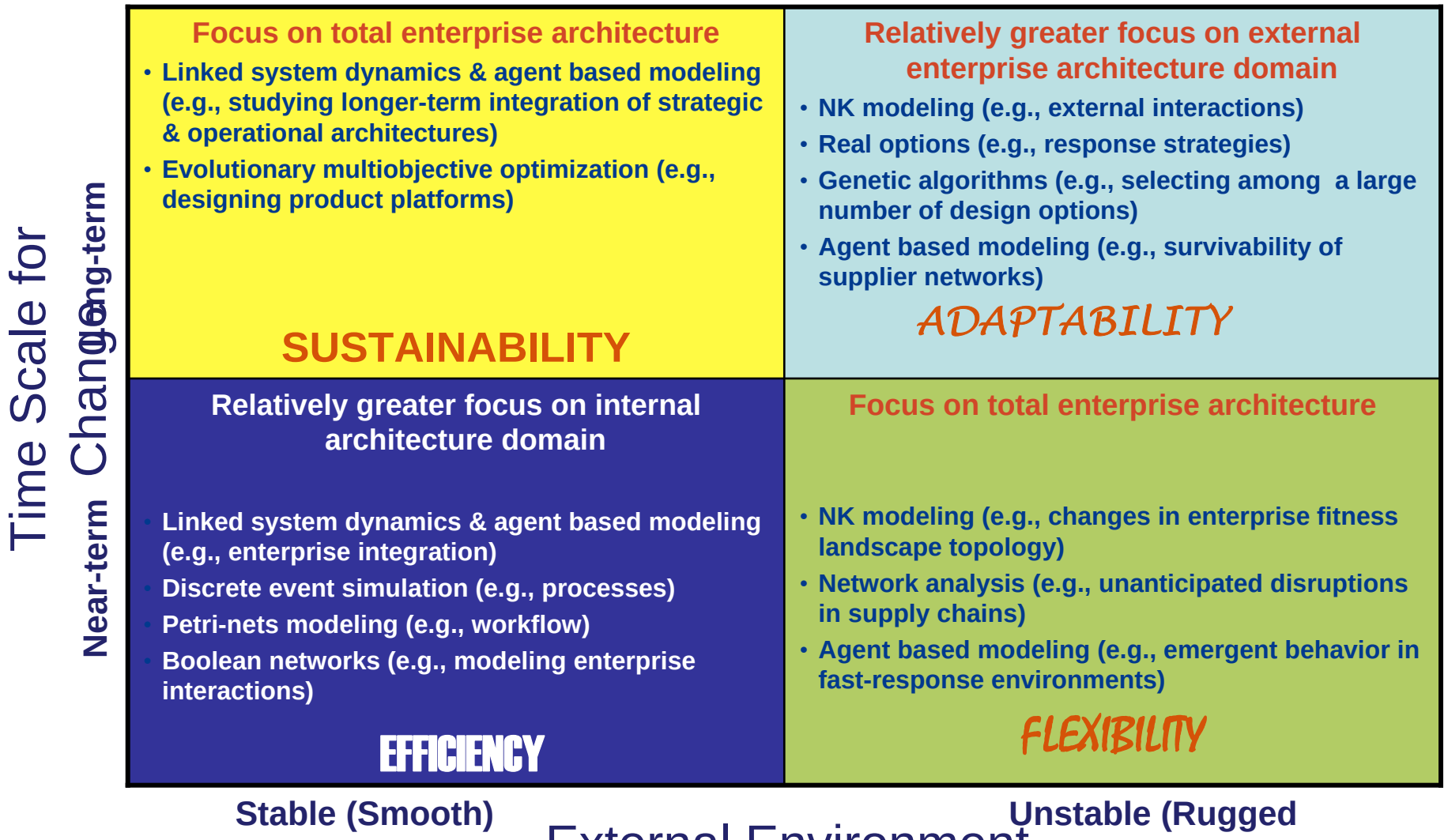
Near-term

SUSTAINABILITY • Pursue value stream integration --Emphasize both internal & external interactions • Maximize efficiency & effectiveness via greater enterprise congruence & coherence • Pursue product subsystem commonality, modular & architectural innovation • Consolidate process improvement gains	**ADAPTABILITY** • Manage uncertainty and risk -- Place much greater emphasis on external interactions • Pursue emergent "real-options" strategy (investment, technology, markets, alliances) • Create learning networked organization • Establish collaborative relationships
EFFICIENCY • Focus on streamlining business processes, placing relatively greater emphasis on internal interactions • Stress continuous process improvement (e.g., lean thinking, sigma, re-engineering) • Improve coordination, standardization, and IT-enabled enterprise integration • Maximize complementarities	**FLEXIBILITY** • Develop "sense-and-respond" capabilities, placing much heavier emphasis on internal and external interactions • Evolve built-in flexibility & resilience; adopt "trauma-center-like" fast-coordination methods • Achieve IT-enabled integration (value stream) • Design new business models; establish virtual enterprises; pursue agile manufacturing

Smooth **Rugged**

Enterprise Fitness Landscape Topology

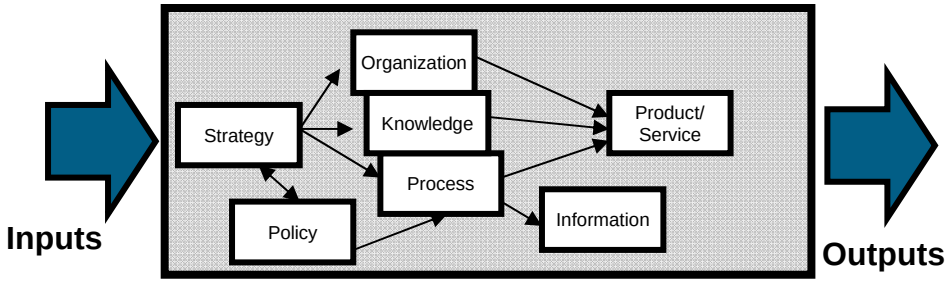
More Specific Guidance on Modeling Choices



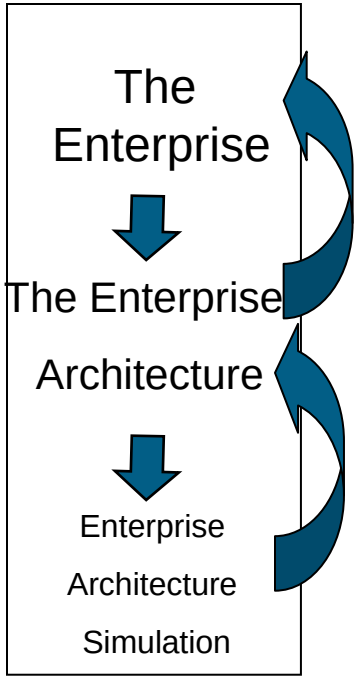
Research Project Overview

Synopsis:

This research develops a methodology and supporting theory for simulating complex enterprise behaviors with multi-scale, hybrid, executable models and simulations, using enterprise architecture frameworks to guide model development.



An executable architecture model



Why:

Such simulations can be used to find key levers across the enterprise to affect change and to evaluate future changes to the enterprise architecture

Hypothesis:

Hybrid modeling of an enterprise's *architecture* can allow a deeper understanding of enterprise dynamics arising from its structure and can identify key control levers and critical areas for alignment.

Method:

•Simulate enterprise behavior arising from the enterprise architecture using hybrid (multi-agent, system dynamics, event-based) modeling techniques.
•Match modeling methodologies with views of the enterprise architecture based on the context of the view and the methodology.
•After developing proof of concept models of enterprise dynamics, apply approach in a case study of an engineering enterprise.

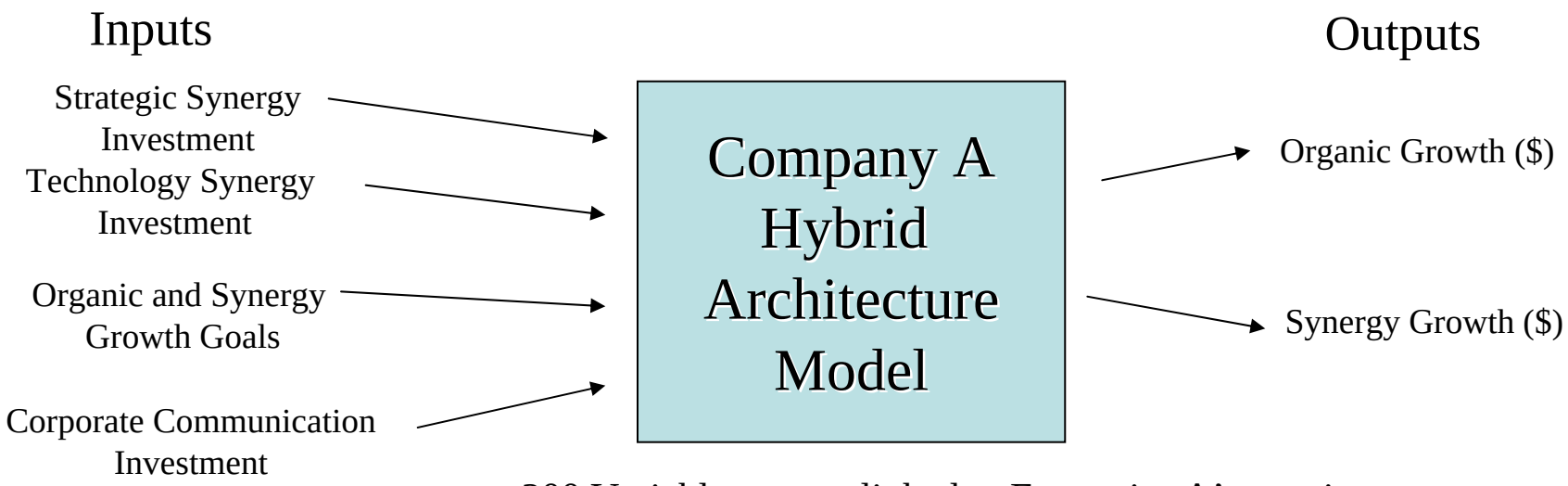
Open Research Question

How do we create simulations of enterprise architecture that:

- Are dynamic;
- Support enterprise leaders and their decision making and hypothesis testing;
- Capture behavioral and structural complexity across domains and scales in the appropriate context;
- Are capable of adaptation, and
- Can be “validated” and “verified?”

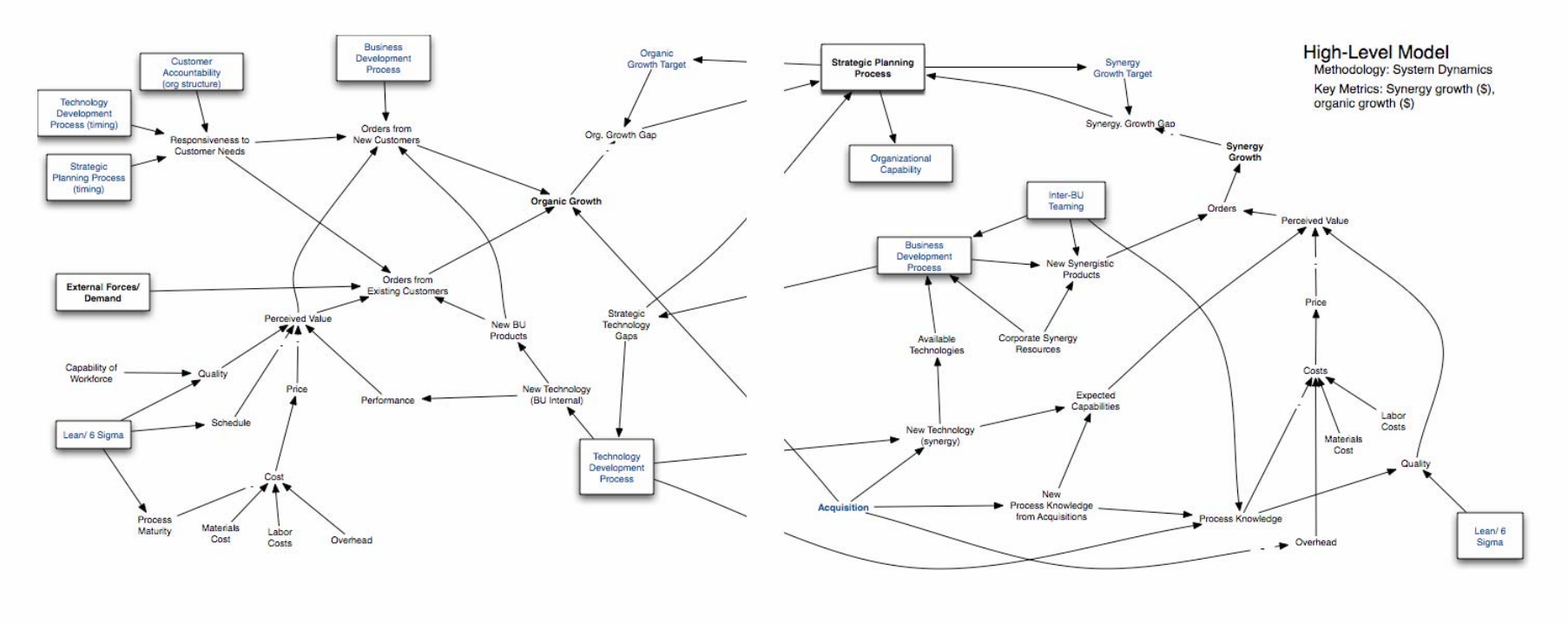
Synergy Architecture Model Overview

Questions: *Can Enterprise A achieve its growth goals given its current architecture with feasible inputs? How much growth from synergy is possible? What are viable combinations of inputs to achieve goals?*



- ~200 Variables, many linked to Enterprise A's metrics
- Interacting sub-models of :
  - Strategy (planning and execution)
  - processes (technology development, business development)
  - organization (incentives, business unit structure, teaming)
  - external environment

High Level Notional Diagram



- **Status:**
  - **Alpha Model functional, with estimated parameters**
  - **Currently working to refine model, obtain more data, and begin model testing.**

Conclusions (1)

- **Proposed conceptual framework provides unifying approach to modeling choices in support of enterprise performance improvement, modernization and transformation decisions**
  - Maps out alternative generic *enterprise change regimes*
  - *Each change regime* suggests a different relative emphasis in terms of what actions to pursue
  - Defines “bull’s eye”enterprise design targets e.g., (efficiency, sustainability, adaptability, flexibility) guiding actions
  - Defines when and what enterprise architecture domains to emphasize
  - Guides choice of *enterprise modeling and simulation strategies*
- **Modeling must be tightly integrated with the enterprise architecture design [enterprise architecting] process to obtain the greatest benefits**
  - Simultaneous consideration of enterprise architecture design decisions (for performance improvement, modernization, transformation), implementation actions, and modeling choices
  - Moving from “local search” (a given “quadrant” in the landscape) to “global search” (another quadrant) suggests important balancing & tradeoff decisions on desirable future-state enterprise attributes (e.g., efficiency vs. flexibility, etc.)
  - Modeling choices must take into account such possible tradeoff issues

Conclusions (2)

- **Propose two basic approaches to the challenge of enterprise architecture design (for performance improvement, modernization, transformation), what architecture domain to emphasize, and modeling choice**
  - *Planned change*
    - Well-suited for the relatively stable environment case
    - Performed over regular time periods (e.g., reset near-term every year; reset longer-term every 3-5 yrs.)
    - Lean enterprise thinking (and six sigma, etc.) represent good fit here
  - *Emergent (guided) change*
    - Well-suited for the relatively unstable environment case
    - Performed on an on-going basis (more in tune with "the organizational becoming" idea)
    - Near-term & longer-term linked on a rolling basis
    - Need to consider alternative change strategies with "generative properties" (opening up new future improvement possibilities), stressing greater agility, flexibility, responsiveness, reconfigurability of capabilities as well as longer-term adaptability properties
- **Specific illustrative application provides "proof-of-concept" demonstration of the feasibility and usefulness of computational enterprise modeling and simulation**
  - Strategic alignment of enterprise capabilities to support rapid growth
  - Useful management tool -- "what-if" analysis; guiding strategic decisions

REFERENCE CHARTS

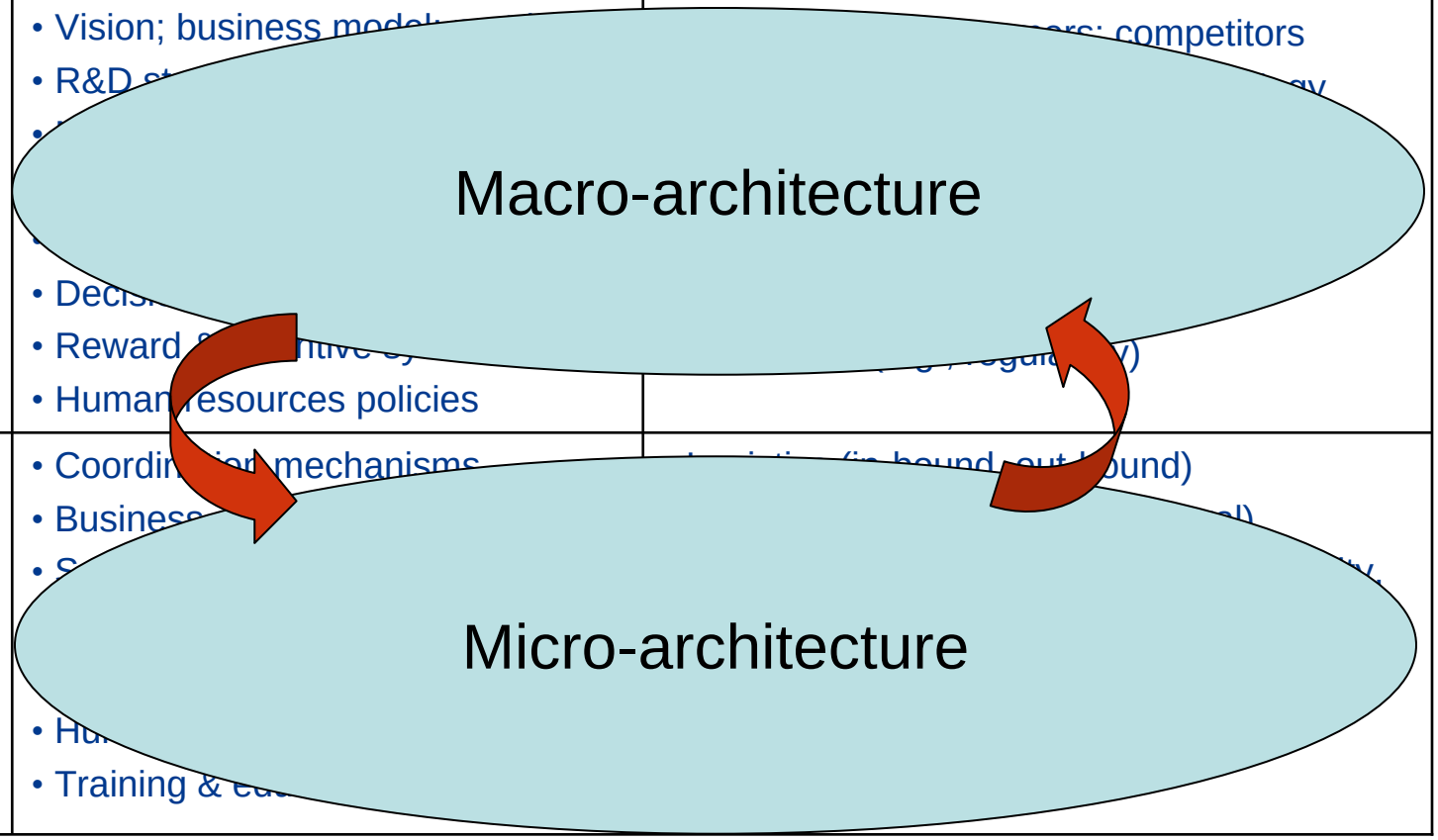
Thinking about Interactions among Decisions*

Description		Primary Locus of Decisions	
		Internal-Looking	**External-looking**
Types of Decisions	**Strategic**	• Vision; business model; metrics • R&D strategy; core capabilities • New product development • Investment (plant & equipment) • Organizational form & structure • Decision rights (authority) • Reward & incentive systems • Human resources policies	• Stakeholders; customers; competitors • Joint ventures; acquisitions; technology licensing • Access to capital markets (funding) • Strategic alliances; supplier partnerships; forming virtual enterprises • Institutions (e.g., regulatory)
	Tactical & Operational	• Coordination mechanisms • Business processes (engineering & product development, manufacturing, etc.) • Supporting infrastructure systems • Knowledge management • Human resources practices • Training & education	• Logistics (in-bound, out-bound) • External communications (general) • Supplier relationships (certification, quality, process improvement, electronic linkages) • Public relations • Environmental scanning • Technology scouting

*Illustrative; intended only to highlight major decision elements expected to have important interactions

Thinking about Interactions*-- Enterprise Architecture Partitioning - 1

Description		Locus of interactions	
		Internal	External
Type of interactions	Strategic	• Vision; business model • R&D st • Decis • Reward & • Human resources policies	ers: competitors gy y)
	Tactical	• Coordin ion mechanisms • Business • S • Hu • Training & ed	ound) l) y



*Illustrative; intended only to highlight major decision elements expected to have important interactions with other enterprise domains (e.g., engineering, manufacturing), functions, processes, activities

Thinking about Interactions*-- Enterprise Architecture Partitioning - 2

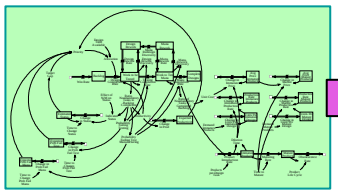
Description		Locus of interactions	
		Internal	**External**
Type of interactions	**Strategic**	• Vision; bu… l; metrics • R&D … ities • Ne… • I… • …	• Stakeholders: … petitors • J… ventu… …logy lic… …n • Acces… • Strat… …; form… • Inst…
	Tactical	• … (… • Kn… • Hum… • Training	• Log… • Exte… • Supp… …y, proc… …es) • Pub… • En… onme… • Technology s…

Internal architecture

External architecture

*Illustrative; intended only to highlight major decision elements expected to have important interactions with other enterprise domains (e.g., engineering, manufacturing), functions, processes, activities

Enterprise Architecture Design Provides the Roadmap for Enterprise Transformation -- A Tightly-Coupled Process

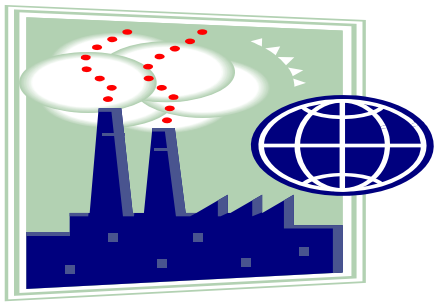


Current Enterprise Architecture

Enterprise Architecture Design

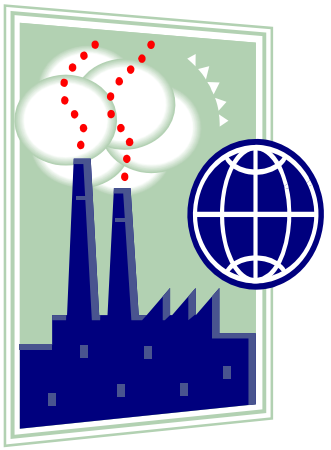
Transition Moves

Computational Enterprise Simulation Modeling

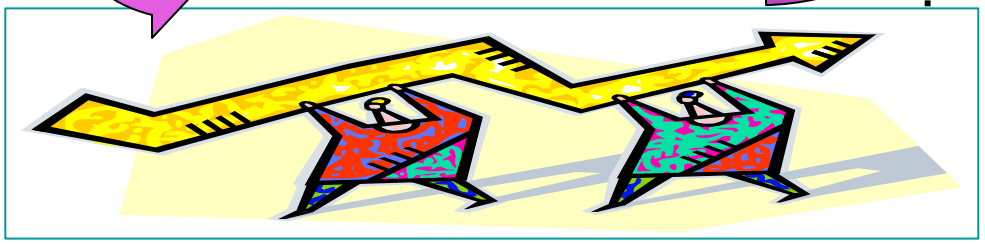


"Real-life" Enterprise (Current State)

New Enterprise Architecture



"Real-life" Enterprise (Future State)



Enterprise Transformation -- Planning & Implementation

Enterprise Modeling & Simulation - Links to Enterprise Architecture Design and Enterprise Transformation

➔ Information/knowledge ➔ Action

Enterprise Dynamics

Theory, Practices & Methods

- Unifying principles, conceptual frameworks, causal relationships, tools & methods -- through knowledge integration from multiple domains
- Emerging enterprise architectures (case studies)
- Enterprise architecture reference frameworks
- System-of-systems; system architectures
- Value-based systems architecting
- Enterprise metrics systems
- Best practices (benchmarking)

Enterprise Architecture Design

(Enterprise Architecting)

- Develop conceptual framework, principles, metrics, design rules & heuristics
  - Define enterprise "views" & interdependencies (interactions)
  - Define design elements, contingency factors, underlying structural & behavioral relationships
  - Develop causal maps (interactions or causal links among design decisions, contingency factors, and underlying structural & behavioral relationships)
  - Define design rules & propositions
- Define & assess current-state enterprise architecture
- Design future-state enterprise architecture options; design for X (e.g., efficiency, flexibility, adaptability)

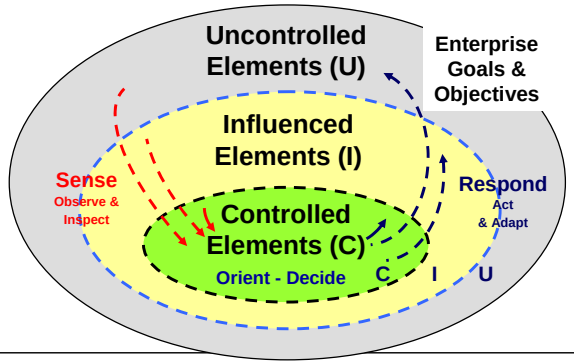
Enterprise Modeling and Simulation

- Develop modeling & simulation capability to help define, test and analyze alternative enterprise architecture solution options
- Conduct sensitivity & impact analysis; tradeoff analysis
- Conduct "what-if" analyses to test impacts of design choices on selected outcome variables (e.g., efficiency, flexibility, etc.)
- Test hypotheses -- explore how enterprises learn, respond, adapt, evolve

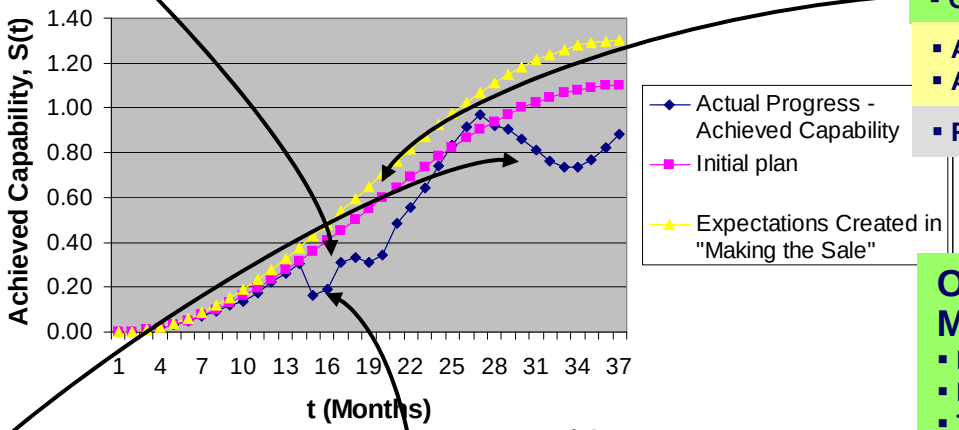
Enterprise Transformation

- Assess organizational readiness for change
- Develop planning framework, principles, approaches and methods for achieving enterprise change and transformation (e.g., gradual incremental change vs.radical change; transition trajectory; diagnostics;change initiatives)
- Execute enterprise change implementation & transformation process

Progress: Stakeholder Perspective for Planning & Acquisition Facility



Program Evolution



Agency Management CIO, CTO, CFO

- Agency policies
- Funding allocation
- Objectives
- Acquisition Strategy
- Architecture
- Standards
- Technology maturity
- Contract type & Incentives

- Contractor selection
- Business Outcomes

- Random Events, e.g.
- Contractor performance
- Legislation

The Public & Commerce ("Customers")

- Acceptance
- Funding
- Random Events in RoW

Congressional, OMB

- Funding
- Goals
- Governance Policies

- Acquisition Strategy
- Architecture

- Random Events in RoW

Program Management

- Tactical management
- Personnel Mgmt and Staffing
- Resource allocation

- Incentives
- Contractor performance
- Business Outcomes

- Random Events, e.g.
- Loss of key personnel

Program

- Complexity

- Outcomes

- Random Events
- Technical glitches

Operations Management, COO

- Implementation
- Process change
- Training
- Operational performance

- Implementation Outcomes

- Random Events, e.g.
- Legislation

Interactions in an Enterprise Architecture Framework