Ilities Tradespace and Affordability Analysis

Barry Boehm, USC

GSW/INCOSE-LA/SPIN talk
Feb 26, 2014
• Context: DoD-Stevens-USC SERC Ilities Tradespace and Affordability Analysis Program (iTAP)

• Ilities Tradespace and Affordability Analysis

• Affordability and Cost Analysis

• Cost-Schedule Tradespace Analysis
Context: SERC iTAP Initiative Elements

- Tradespace and affordability analysis foundations
  - More precise ility definitions and relationships
  - Stakeholder value-based, means-ends relationships
  - Ility strategy effects, synergies, conflicts
  - U. Virginia, MIT, USC

- Next-generation system cost-schedule estimation models
  - Initially for full-coverage space systems (COSATMO)
  - Extendable to other domains
  - USC, AFIT, GaTech, NPS

- Applied iTAP methods, processes, and tools (MPTs)
  - For concurrent cyber-physical-human systems
  - Experimental MPT piloting, evolution, improvement
  - Wayne State, AFIT, GaTech, NPS, Penn State, USC
GaTech – FACT Tradespace Tool
Being used by Marine Corps

- Configure vehicles from the “bottom up”
- Quickly assess impacts on performance
MIT: ilities in Tradespace Exploration
Based on SEArí research

Enabling Construct: Tradespace Networks

Changeability

Survivability

Value Robustness
Pareto Set Tracing across 7 Epochs

Set of Metrics

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WSU: Versatility Factors and Physical Organization
Components that Can be in Different Positions or Orientations
Isolated or Separated Compartments

Mass & Structure Properties
- Mass
- Angular moments
- Imbalances*
- Load bearing wall strength
- Deck surface area
- Interior volumes**
- Interior surface areas**

*Angular moments of the CG about axes of rotation
** By crew station and compartment
Outline

• Context: DoD-Stevens-USC SERC Ilities Tradespace and Affordability Analysis Program (iTAP)

Ilities Tradespace and Affordability Analysis

• Affordability and Cost Analysis

• Cost-Schedule Tradespace Analysis
• Critical nature of the ilities
  – Major source of project overruns, failures
  – Significant source of stakeholder value conflicts
  – Poorly defined, understood
  – Underemphasized in project management
• Challenges for cyber-physical-human systems
• SERC Foundations efforts
  – Stakeholder value-based, means-ends hierarchy
  – Formal analysis of ility definitions and relations
  – Architecture strategy synergies and conflicts
Importance of ility Tradeoffs

Major source of DoD system overruns

- System ilities have systemwide impact
  - System elements generally just have local impact
- ilities often exhibit asymptotic behavior
  - Watch out for the knee of the curve
- Best architecture is a discontinuous function of ility level
  - “Build it quickly, tune or fix it later” highly risky
  - Large system example below

![Diagram showing cost and response time tradeoffs between different architectures.](Image)
Role-Based Ilities Value Diversity

Bank of America Master Net

Users
- Many features
- Changeable requirements
- Applications compatibility
- High levels of service
- Voice in acquisition
- Flexible contract
- Early availability

Maintainers
- Ease of transition
- Ease of maintenance
- Applications compatibility
- Voice in acquisition

Acquirers
- Mission cost/effectiveness
- Limited development budget, schedule
- Government standards compliance
- Political correctness
- Development visibility and control
- Rigorous contact

Developers
- Flexible contract
- Ease of meeting budget and schedule
- Stable requirements
- Freedom of choice: process
- Freedom of choice: team
- Freedom of choice: COTS/reuse

PC: Process
PD: Product
PP: Property
S: Success
Example of Current Practice

• “The system shall have a Mean Time Between Failures of 10,000 hours”
• What is a “failure?”
  – 10,000 hours on liveness
  – But several dropped or garbled messages per hour?
• What is the operational context?
  – Base operations? Field operations? Conflict operations?
• Most management practices focused on functions
  – Requirements, design reviews; traceability matrices; work breakdown structures; data item descriptions; earned value management
• What are the effects on other –ilities?
  – Cost, schedule, performance, maintainability?
USC: COCOMO II-Based Tradeoff Analysis
Better, Cheaper, Faster: Pick Any Two?

- For 100-KSLOC set of features
- Can “pick all three” with 77-KSLOC set of features
• Critical nature of the ilities
  – Major source of project overruns, failures
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  Challenges for cyber-physical-human systems

• SERC Foundations efforts
  – Stakeholder value-based, means-ends hierarchy
  – Formal analysis of ility definitions and relations
  – Architecture strategy synergies and conflicts
Importance of Cyber-Physical Systems

Major gap in tradespace analysis capabilities

- Current ERS, DARPA tradespace research focused on physical system tradeoffs
  - Range, payload, size, weight, lethality, power and fuel consumption, communications bandwidth, etc.
  - Some focus on physical modularity, composability

- Current cyber tradespace research focused on software, computing, human factors tradeoffs
  - Security, safety, interoperability, usability, flexibility, adaptability, dependability, response time, throughput, etc.

- Gaps in capabilities for co-design of hardware, software, and human factors; integration of tradespace analyses
Prioritized JCIDSilities
User View by Combatant Commands: Top priority first

• Intelligence, Surveillance, and Reconnaissance
  – Comprehensive Persistent Survivable Integrated Timely Credible
    Adaptable Innovative

• Command and Control (note emphasis on Usability aspects)
  – Interoperability Understanding Timeliness Accessibility Simplicity
    Completeness Agility Accuracy Relevance Robustness Operational Trust

• Logistics: Supply
  – Responsiveness Sustainability Flexibility Survivability Attainability
    Economy Simplicity

• Logistics: Maintenance
  – Sustainability Responsiveness Attainability Flexibility Economy
    Survivability Simplicity

• Net-Centric: Information Transport
  – Accessible Capacity Accurate Timely Throughput Expeditionary Latency
• Critical nature of the ilities
  – Major source of project overruns, failures
  – Significant source of stakeholder value conflicts
  – Poorly defined, understood
  – Underemphasized in project management

• Challenges for cyber-physical-human systems
  ➔ SERC Foundations efforts
  – Stakeholder value-based, means-ends hierarchy
  – Formal analysis of ility definitions and relations
  – Architecture strategy synergies and conflicts
SERC Value-Based ilities Hierarchy
Based on ISO/IEC 9126, 25030; JCIDS; previous SERC research

• Individual ilities
  – Resource Utilization: Cost, Duration, Personnel, Scarce Quantities (capacity, weight, energy, ...); Manufacturability, Sustainability
  – Protection: Security, Safety
  – Robustness: Reliability, Availability, Maintainability, Survivability
  – Flexibility: Modifiability, Tailorability, Adaptability
  – Composability: Interoperability, Openness, Service-Orientation

• Composite ilities
  – Comprehensiveness/Suitability: all of the above
  – Dependability: Mission Effectiveness, Protection, Robustness
  – Resilience: Protection, Robustness, Flexibility
  – Affordability: Mission Effectiveness, Resource Utilization
Means-Ends Framework: Affordability

Affordability Improvements and Tradeoffs

- **Get the Best from People**
  - Staffing, Incentivizing, Teambuilding
  - Facilities, Support Services
  - Kaizen (continuous improvement)

- **Make Tasks More Efficient**
  - Tools and Automation
  - Work and Oversight Streamlining
  - Collaboration Technology

- **Eliminate Tasks**
  - Lean and Agile Methods
  - Task Automation
  - Model-Based Product Generation

- **Eliminate Scrap, Rework**
  - Early Risk and Defect Elimination
  - Evidence-Based Decision Gates
  - Modularity Around Sources of Change
  - Incremental, Evolutionary Development
  - Value-Based, Agile Process Maturity

- **Simplify Products (KISS)**
  - Risk-Based Prototyping
  - Value-Based Capability Prioritization
  - Satisficing vs. Optimizing Performance

- **Reuse Components**
  - Domain Engineering and Architecture
  - Composable Components, Services, COTS
  - Legacy System Repurposing

- **Reduce Operations, Support Costs**
  - Automate Operations Elements
  - Design for Maintainability, Evolvability
  - Streamline Supply Chain
  - Anticipate, Prepare for Change

- **Value- and Architecture-Based Tradeoffs and Balancing**
### Architecture Strategy Synergy-Conflict Matrix

<table>
<thead>
<tr>
<th>Reliability</th>
<th>Modifiability</th>
<th>Interoperability</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reliability</strong></td>
<td>Nanosensor-based smart monitoring improves reliability, makes mods more effective</td>
<td>Domain architecting improves reliability, interoperability within the domain</td>
<td>Automated input, output validation reduces human costs</td>
</tr>
<tr>
<td></td>
<td>Domain architecting (using domain knowledge in defining interfaces) improves reliability and modifiability</td>
<td>High-cohesion, low-coupling modules improve interoperability and reliability</td>
<td>Increased reliability reduces life cycle ownership costs</td>
</tr>
<tr>
<td></td>
<td>Modularity (high module cohesion, low module coupling) improves modifiability and reliability</td>
<td>Common, multi-layered services and architecture improve interoperability and reliability</td>
<td>Product line architectures reduce cost, increase reliability</td>
</tr>
<tr>
<td><strong>Modifiability</strong></td>
<td>Reliability-optimized designs may complicate fault diagnosis, system disassembly</td>
<td>Modularization around sources of change improves modifiability and interoperability</td>
<td>Modularization around sources of change reduces life cycle costs</td>
</tr>
<tr>
<td></td>
<td>Domain architecting assumptions complicate multi-domain system modifiability</td>
<td>High-cohesion, low-coupling modules improve modifiability and interoperability</td>
<td>High-cohesion, low-coupling modules reduce life cycle costs</td>
</tr>
<tr>
<td></td>
<td>Data redundancy improves reliability, but updates may complicate distributed real-time systems interoperability</td>
<td>Open standards, service-oriented architectures improve both modifiability and interoperability</td>
<td>Domain architecting enables domain product lines, reducing costs</td>
</tr>
<tr>
<td></td>
<td>Optimizing on reliability as liveness may degrade message delivery, accuracy</td>
<td></td>
<td>Providing excess capacity improves modifiability and decreases lifecycle cost</td>
</tr>
<tr>
<td><strong>Interoperability</strong></td>
<td>Domain architecting assumptions complicate multi-domain system interoperability</td>
<td></td>
<td>Common, multi-layered services and architecture reduce life cycle costs</td>
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<td>Data redundancy improves reliability, but updates may complicate distributed real-time systems interoperability</td>
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<td>Product line architecture improves interoperability, reduces cost of later systems</td>
</tr>
<tr>
<td></td>
<td>Optimizing on reliability as liveness may degrade message delivery, accuracy</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>Increased reliability increases acquisition costs</td>
<td>Fixed-requirements, fixed-cost contracts generally produce brittle, hard-to-modify systems</td>
<td>Neglecting or deferring interfaces to co-dependent systems will reduce initial costs, but degrade interoperability</td>
</tr>
<tr>
<td></td>
<td>Hardware redundancy adds cost</td>
<td>Domain architecting increases multi-domain system costs</td>
<td>Product line architecture increases cost of initial system</td>
</tr>
<tr>
<td></td>
<td>Making easiest-first initial commitments reduces early costs but degrades later reliability, adds later costs</td>
<td>Providing excess capacity improves modifiability but increases acquisition cost</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Formal verification adds cost</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Software Development Cost vs. Quality

Relative Cost to Develop

COCOMO II RELY Rating

MTBF (hours) 1 10 300 10,000 300,000

Very Low 0.82 0.92 1.0 1.10 1.26

Low 1.0

Nominal 1.1

High 1.2

Very High 1.3

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Software Ownership Cost vs. Quality

Relative Cost to Develop, Maintain, Own and Operate

COCOMO II RELY Rating

MTBF (hours) 1 10 300 10,000 300,000

VL = 2.55,
L = 1.52

Operational-defect cost at Nominal dependability = Software life cycle cost

Operational-defect cost = 0

70% Maint.

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Affordability and Tradespace Framework

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- Value- and Architecture-Based Tradeoffs and Balancing
Costing Insights: COCOMO II Productivity Ranges

Scale Factor Ranges: 10, 100, 1000 KSLOC

Product Complexity (CPLX)
Analyst Capability (ACAP)
Programmer Capability (PCAP)
Time Constraint (TIME)
Personnel Continuity (PCON)
Required Software Reliability (RELY)
Documentation Match to Life Cycle Needs (DOCU)
Multi-Site Development (SITE)
Applications Experience (AEXP)
Platform Volatility (PVOL)
Use of Software Tools (TOOL)
Platform Experience (PEXP)
Data Base Size (DATA)
Required Development Schedule (SCED)
Language and Tools Experience (LTEX)
Process Maturity (PMAT)
Storage Constraint (STOR)
Development Flexibility (FLEX)
Team Cohesion (TEAM)
Develop for Reuse (RUSE)
Precedentedness (PREC)
Architecture and Risk Resolution (RESL)

Staffing
Teambuilding
Continuous Improvement

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COSYSMO Sys Engr Cost Drivers

**Teambuilding**
- Multisite coordination
- Process capability

**Continuous Improvement**
- Personnel experience/continuity
- Stakeholder team cohesion
- Personnel/team capability
- Architecture Understanding

**Staffing**
- Technology Risk
- Level of Service Requirements
- Requirements Understanding

**Effort Multiplier Ratio (EMR)**

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Legacy System Repurposing

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Value- and Architecture-Based Tradeoffs and Balancing

Get the Best from People

Affordability Improvements and Tradeoffs

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Value-Based Testing: Empirical Data and ROI

LiGuo Huang, ISESE 2005

(a) Bullock data – Pareto distribution

Automated test generation (ATG) tool - all tests have equal value

(b) Return On Investment (ROI)

% Tests Run

- Value-Neutral ATG Testing
- Value-Based Pareto Testing
Value-Neutral Defect Fixing Is Even Worse

Automated test generation tool
- all tests have equal value

Value-neutral defect fixing:
Quickly reduce # of defects

Pareto 80-20 Business Value

% of Value for Correct Customer Billing

Customer Type
Outline

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Cost-Schedule Tradespace Analysis
Cost-Schedule Tradespace Analysis

• Generally, reducing schedule adds cost
  – Pair programming: 60% schedule * 2 people = 120% cost

• Increasing schedule may or may not add cost
  – Pre-planned smaller team: less communications overhead
  – Mid-course stretchout: pay longer for tech, admin overhead

• Can often decrease both cost and schedule
  – Lean, agile, value-based methods; product-line reuse

• Can optimize on schedule via concurrent vs. sequential processes
  – Sequential; cost-optimized: Schedule = 3 * cube root (effort)
    • 27 person-months: Schedule = 3*3=9 months; 3 personnel
  – Concurrent, schedule-optimized: Schedule = square root (effort)
    • 27 person-months: Schedule = 5.5 months; 5.4 personnel

• Can also accelerate agile square root schedule
  – SERC Expediting SysE study: product, process, people, project, risk
SERC Expediting SysE study: Product, process, people, project; risk factors

Final Database
Over 30 Interviews with Gov’t/Industry Rapid Development Organizations
Over 23,500 words from interview notes

Product, Process, People … all in a Project Context
## CORADMO-SE Rating Scales, Schedule Multipliers

<table>
<thead>
<tr>
<th>Accelerators/Ratings</th>
<th>Very Low</th>
<th>Low</th>
<th>Nominal</th>
<th>High</th>
<th>Very High</th>
<th>Extra High</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Product Factors</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simplicity</td>
<td>Extremely complex</td>
<td>Highly complex</td>
<td>Mod. complex</td>
<td>Moderately simple</td>
<td>Highly simple</td>
<td>Extremely simple</td>
</tr>
<tr>
<td>Element Reuse</td>
<td>None (0%)</td>
<td>Minimal (15%)</td>
<td>Some (30%)</td>
<td>Moderate (50%)</td>
<td>Considerate (70%)</td>
<td>Extensive (90%)</td>
</tr>
<tr>
<td>Low-Priority Deferrals</td>
<td>Never</td>
<td>Rarely</td>
<td>Sometimes</td>
<td>Often</td>
<td>Usually</td>
<td>Anytime</td>
</tr>
<tr>
<td>Models vs Documents</td>
<td>None (0%)</td>
<td>Minimal (15%)</td>
<td>Some (30%)</td>
<td>Moderate (50%)</td>
<td>Considerate (70%)</td>
<td>Extensive (90%)</td>
</tr>
<tr>
<td>Key Technology Maturity</td>
<td>&gt;0 TRL 1,2 or &gt;1 TRL 3</td>
<td>1 TRL 3 or &gt;1 TRL 4</td>
<td>1 TRL 4 or &gt;2 TRL 5</td>
<td>1-2 TRL 5 or &gt;2 TRL 6</td>
<td>1-2 TRL 6</td>
<td>All &gt; TRL 7</td>
</tr>
<tr>
<td><strong>Process Factors</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concurrent Operational Concept, Requirements, Architecture, V&amp;V</td>
<td>Highly sequential</td>
<td>Mostly sequential</td>
<td>2 artifacts mostly concurrent</td>
<td>3 artifacts mostly concurrent</td>
<td>All artifacts mostly concurrent</td>
<td>Fully concurrent</td>
</tr>
<tr>
<td>Process Streamlining</td>
<td>Heavily bureaucratic</td>
<td>Largely bureaucratic</td>
<td>Conservative bureaucratic</td>
<td>Moderate streamline</td>
<td>Mostly streamlined</td>
<td>Fully streamlined</td>
</tr>
<tr>
<td>General SE tool support CIM (Coverage, Integration, Maturity)</td>
<td>Simple tools, weak integration</td>
<td>Minimal CIM</td>
<td>Some CIM</td>
<td>Moderate CIM</td>
<td>Considerable CIM</td>
<td>Extensive CIM</td>
</tr>
<tr>
<td><strong>Project Factors</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Project size (peak # of personnel)</td>
<td>Over 300</td>
<td>Over 100</td>
<td>Over 30</td>
<td>Over 10</td>
<td>Over 3</td>
<td>≤ 3</td>
</tr>
<tr>
<td>Collaboration support</td>
<td>Globally distributed, weak comm., data sharing</td>
<td>Nationally distributed, some sharing</td>
<td>Regionally distributed, moderate sharing</td>
<td>Metro-area distributed, good sharing</td>
<td>Simple campus, strong sharing</td>
<td>Largely collocated, very strong sharing</td>
</tr>
<tr>
<td>Single-domain MMPTs (Models, Methods, Processes, Tools)</td>
<td>Simple MMPTs, weak integration</td>
<td>Minimal CIM</td>
<td>Some CIM</td>
<td>Moderate CIM</td>
<td>Considerable CIM</td>
<td>Extensive CIM</td>
</tr>
<tr>
<td>Multi-domain MMPTs</td>
<td>Simple; weak integration</td>
<td>Minimal CIM</td>
<td>Some CIM or not needed</td>
<td>Moderate CIM</td>
<td>Considerable CIM</td>
<td>Extensive CIM</td>
</tr>
<tr>
<td><strong>People Factors</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>General SE KSAs (Knowledge, Skills, Agility)</td>
<td>Weak KSAs</td>
<td>Some KSAs</td>
<td>Moderate KSAs</td>
<td>Good KSAs</td>
<td>Strong KSAs</td>
<td>Very strong KSAs</td>
</tr>
<tr>
<td>Single-Domain KSAs</td>
<td>Weak</td>
<td>Some</td>
<td>Moderate</td>
<td>Good</td>
<td>Strong</td>
<td>Very strong</td>
</tr>
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<td>Multi-Domain KSAs</td>
<td>Weak</td>
<td>Some</td>
<td>Moderate or not needed</td>
<td>Good</td>
<td>Strong</td>
<td>Very strong</td>
</tr>
<tr>
<td>Team Compatibility</td>
<td>Very difficult interactions</td>
<td>Some difficult interactions</td>
<td>Basically cooperative interactions</td>
<td>Largely cooperative</td>
<td>Highly cooperative</td>
<td>Seamless interactions</td>
</tr>
<tr>
<td><strong>Risk Acceptance Factor</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Highly risk-averse</td>
<td>Partly risk-averse</td>
<td>Balanced risk aversion, acceptance</td>
<td>Moderately risk-accepting</td>
<td>Considerably risk-accepting</td>
<td>Strongly risk-accepting</td>
<td></td>
</tr>
<tr>
<td>Application Type</td>
<td>Technologies</td>
<td>Person Months</td>
<td>Duration (Months)</td>
<td>Duration / √PM</td>
<td>Product</td>
<td>Process</td>
</tr>
<tr>
<td>---------------------------</td>
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</tr>
<tr>
<td>Insurance agency system</td>
<td>HTML/VB</td>
<td>34.94</td>
<td>3.82</td>
<td>0.65</td>
<td>VH</td>
<td>VH</td>
</tr>
<tr>
<td>Scientific/engineering</td>
<td>C++</td>
<td>18.66</td>
<td>3.72</td>
<td>0.86</td>
<td>L</td>
<td>VH</td>
</tr>
<tr>
<td>Compliance - expert</td>
<td>HTML/VB</td>
<td>17.89</td>
<td>3.36</td>
<td>0.79</td>
<td>VH</td>
<td>VH</td>
</tr>
<tr>
<td>Barter exchange</td>
<td>SQL/VB/ HTML</td>
<td>112.58</td>
<td>9.54</td>
<td>0.90</td>
<td>VH</td>
<td>H</td>
</tr>
<tr>
<td>Options exchange site</td>
<td>HTML/SQ</td>
<td>13.94</td>
<td>2.67</td>
<td>0.72</td>
<td>VH</td>
<td>VH</td>
</tr>
<tr>
<td>Commercial HMI</td>
<td>C++</td>
<td>205.27</td>
<td>13.81</td>
<td>0.96</td>
<td>L</td>
<td>N</td>
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<tr>
<td>Options exchange site</td>
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Schedule Acceleration Case Study: From Plan-Driven to Agile

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Case Study: From Plan-Driven to Agile
Initial Project: Focus on Concurrent SE

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Expected schedule reduction of 1.09/0.96 = 0.88 (green arrow)
Actual schedule delay of 15% due to side effects (red arrows)
Model prediction: 0.88*1.09*1.04*1.06*1.06 = 1.13
# Case Study: From Plan-Driven to Agile

## Next Project: Fix Side Effects; Reduce Bureaucracy

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Model estimate: 0.88*(0.92/0.96)*(0.96/1.05) = 0.77 speedup
Project results: 0.8 speedup
Model tracks project status; identifies further speedup potential