SYSTEMS ENGINEERING RESEARCH CENTER

Digital Engineering Measurement Framework

WRT-1001 Digital Engineering Measures

Tom McDermott, Alejandro Salado, Eileen Van Aken, Kaitlin Henderson

Sponsor: Phil Zimmerman OUSD/RE

STEVENS INSTITUTE OF TECHNOLOGY 1870

VIRGINIA TECH

ANNUAL RESEARCH REVIEW 2022

Digital Engineering Measurement Framework - Project Overview and Timeline

2020

AIA EMC Project Plan

- Refined list of DE metrics serving as Key Performance Indicators for program execution, and model health
- Detailed descriptions of each metric, traceable to SE metrics, quality, & requirements volatility

Established collaborative WG (9/14/20)

(PSM, NDIA, INCOSE, AIA, SERC, Aerospace, OUSD R&E, …)

Objectives

- Define industry consensus measurement framework for DE, MBSE
- Align measures with business information needs for project execution and organizational performance improvement.

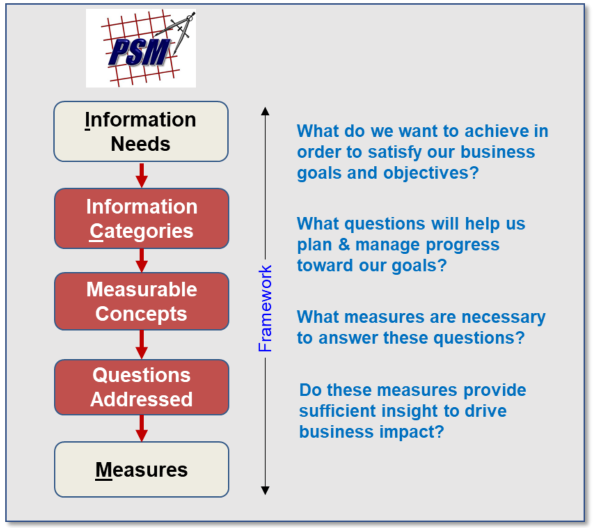
Leverage partner resources and assets

- Practical Software and Systems Measurement (PSM) Continuous Iterative Development Measurement Framework
- SERC / INCOSE / NDIA MBSE Maturity Survey
- SERC DE metrics research (SERC-2020-SR-003, SERC-2020-TR-002)
- Systems Engineering Leading Indicators Guide
- DoD Digital Engineering Strategy

2021

Follow PSM process to define DE measurement framework

- Aligned with ISO/IEC/IEEE 15939 measurement process standard



Team product development

- Front matter (concepts, terms, …)
- Information Needs (ICM Table)
- Measurement specifications

2022

Initial framework draft for review (Jan 2022)
V1.0 Publication release (May 2022)

Practical Software and Systems Measurement (PSM) Digital Engineering Measurement Framework

Version 1.0c
June 21, 2022

Developed and Published by Members of:

Practical Software & Systems Measurement · Systems Engineering Research Center · Aerospace Industries Association · National Defense Industrial Association · International Council on Systems Engineering · Department of Defense Research & Engineering · The Aerospace Corporation

Initial Measurement Specifications

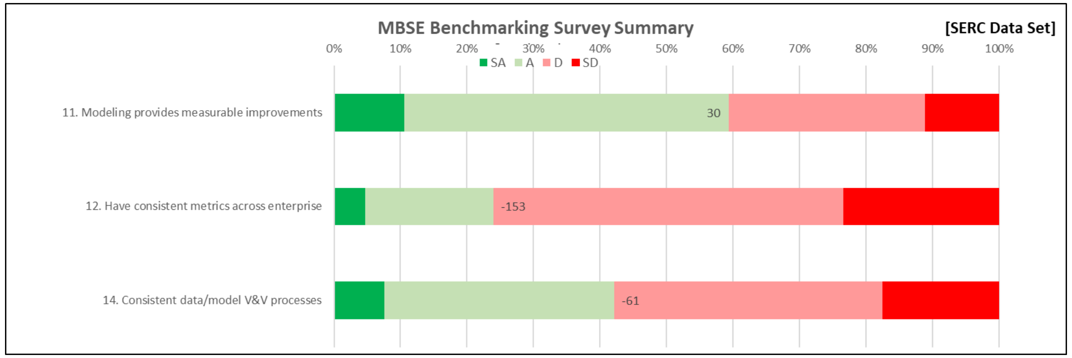
- Architecture Completeness and Volatility
- Model Traceability
- Product Size
- DE Anomalies
- Adaptability and Rework
- Product Automation
- Deployment Lead Time
- Runtime Performance

http://www.psmsc.com/DEMeasurement.asp

Lack of effective DE/MBSE measures has been an inhibitor to digital transformation

Substantiated by DoD SERC research

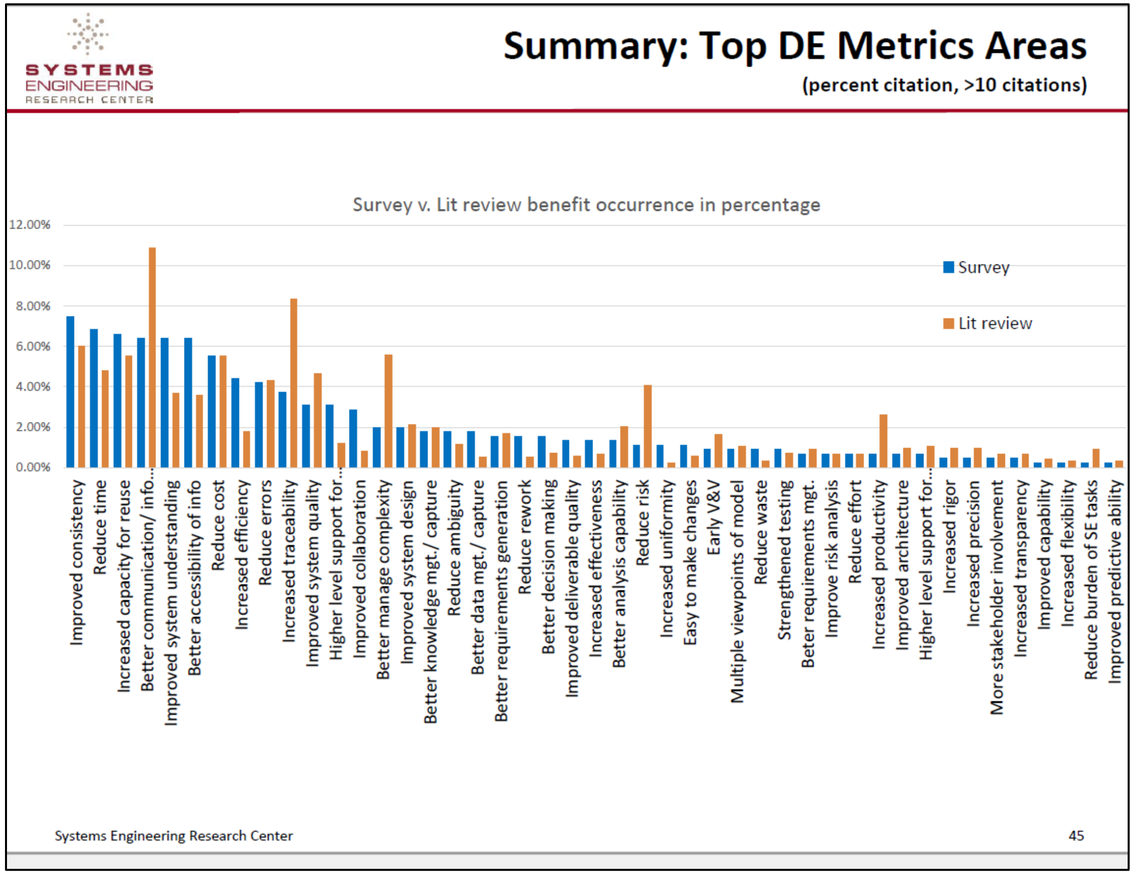
Benchmarking the Benefits and Current Maturity of Model-Based Systems Engineering across the Enterprise (SERC-2020-SR-001)



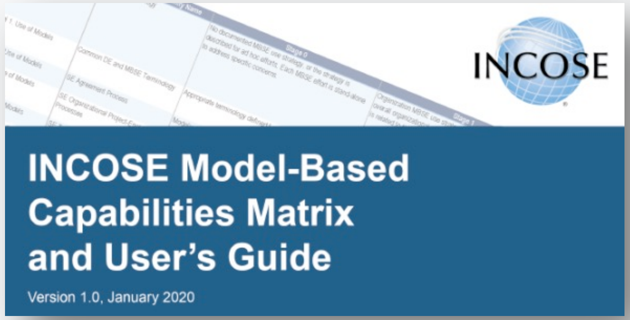
Category	Question title	SERC MBSE Questionnaire	Survey Score	SA	A	D	SD	Chart	Calculated Score
Model Metrics	11. Modeling provides measurable improvements	Modeling activities in our organization provide measurable improvements within and across projects.	30	18	83	50	19		30
	12. Have consistent metrics across enterprise	We have consistent metrics across our program(s)/enterprise that include our modeling activities.	-153	8	33	90	40		-153

https://sercuarc.org/results-of-the-serc-incose-ndia-mbse-maturity-survey-are-in/

Summary Report Task Order WRT-1001: Digital Engineering Metrics Supporting Technical Report (SERC-2020-SR-003)
Task Order WRT-1001: Digital Engineering Metrics Technical Report (SERC-2020-TR-002)



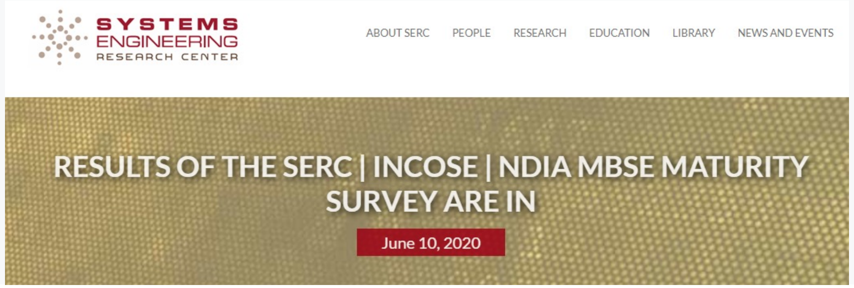
INCOSE Model-Based Capabilities Matrix



- Released January 2020 by INCOSE
- Framework for assessing organizational maturity

Model-Based Capability Stages	Stage 0	Stage I	Stage 2	Stage 3	Stage 4
Tools & IT Infrastructure					
Collaboration	E-mail, telecom.	System Model File Exchange.	Various organizations working on different parts of model. Full model integrated by a single organizations.	Partial On-line, real-time collaboration amongst distributed teams	On-line, real-time collaboration amongst distributed teams
Disparate Database/Tool interoperability	None	Tool-to-Tool, ad hoc interoperability	Partial Federated Database Management System (FDBMS)	Main tools interoperable. Supporting tools interact through file transfer.	Fully Federated w/ standard "plug-and-play" interfaces. Data is interchanged among tools
Inter-Database/Tool Data Item Associations	Databases/tools are independent	Inter-Database/Tool Data Item associations defined	Inter-Database/Tool Data Item associations defined, captured, managed	Inter-Database/Tool Data Item associations among all data items defined, captured, managed, and traceable	Inter-Database/Tool Data Item associations among all data items defined, captured, managed, and traceable where changes in one data source alerts owners of other data sources of intended updates
User IF, Viewpoint/Views	N/A	Doc Gen	UI draws from Model app	UI draws from multiple models/DBs	UI supports Interrogation; multiple configs

Download the Results



https://sercuarc.org/results-of-the-serc-incose-ndia-mbse-maturity-survey-are-in/

June 8, 2020 – Summary Report Task Order WRT-1001: Digital Engineering Metrics Supporting Technical Report SERC-2020-SR-003

View the DE Metrics Summary Report (June 8, 2020)

March 19, 2020 — Benchmarking the Benefits and Current Maturity of Model-Based Systems Engineering across the Enterprise Results of the MBSE Maturity Survey / Part 1: Executive Summary

View the SERC-2020-SR-001 report on the results of the MBSE Maturity Survey

June 8, 2020 – Task Order WRT-1001: Digital Engineering Metrics Technical Report SERC-2020-TR-002

View the Digital Engineering Metrics Full Technical Report

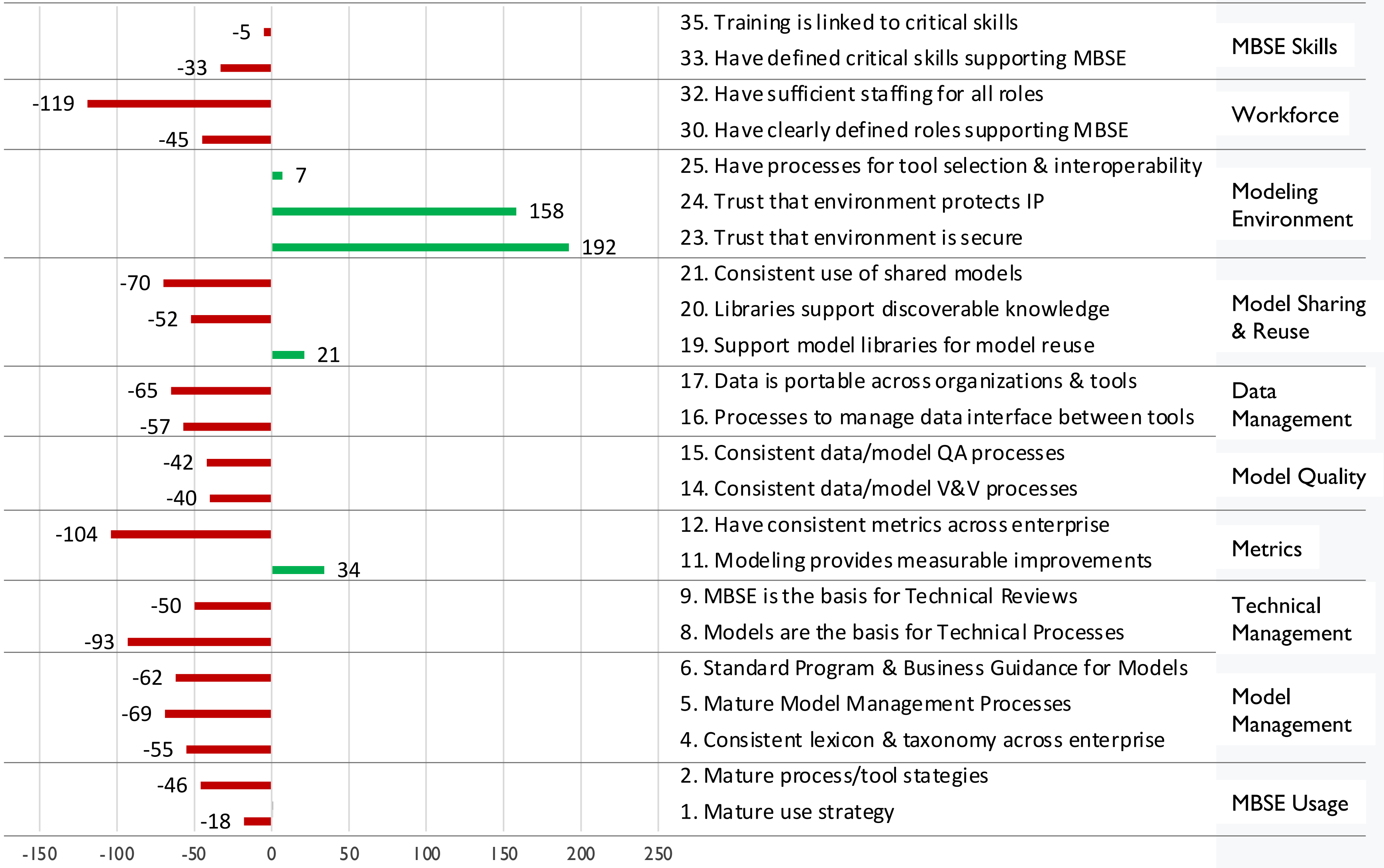
MBSE Survey Overview

Topics	Summary of Survey Questions
1. MBSE Usage	1. MBSE strategy documented at enterprise level 2. MBSE processes & tools integrated, inform enterprise staff *3. Q: Primary value of cross-functional MBSE integration?*
2. Model Manage-ment	4. Taxonomy for modeling across organization 5. Well-defined processes/tools for model management. 6. Standard org guidance for model management/tools *7. Q: Business value from consistent model management?*
3. Technical Manage-ment	8. Modeling basis for enterprise org processes 9. MBSE process support for technical reviews *10. Q: Value of MBSE (or digital engrg) in technical reviews?*
4. Metrics	11. Modeling provides measurable improvement across projects 12. Consistent metrics across programs/enterprise? *13. Q: Most useful metrics?*
5. Model Quality	14. Defined processes/tools for V&V of models 15. Defined processes/tools for data/model quality assurance
6. Data Manage-ment	16. Org approach for data interface between tools 17. Data managed independent of tools for portability *18. Q: Data management roles/processes?*

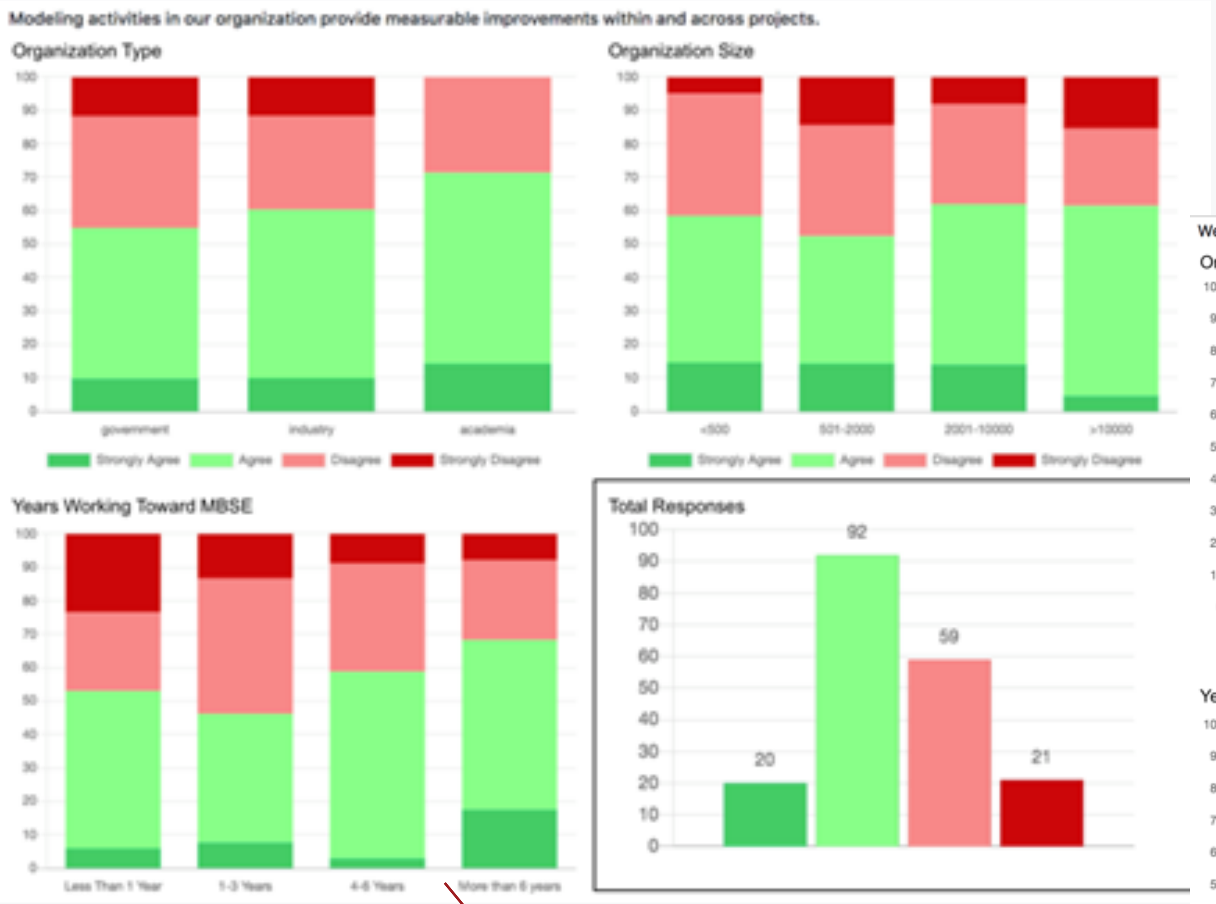
Topics	Summary of Survey Questions
7. Model Sharing and Reuse	19. Teams establish, share, reuse org model libraries 20. Org interface around models for stakeholder use 21. Shared models used to consistently manage programs across lifecycle *22. Q: org implementation for data/model discovery, reuse?*
8. Modeling Environments	23. Modeling environment security 24. Modeling environment protects IP 25. Cross-discipline processes for tools, data interoperability *26. Q: value from collaborating on models across disciplines*
9. Organizationa l Implementati on	*27. Q: most challenging org obstacles for MBSE?* *28. Q: Best organizational enablers for MBSE?* *29. Q: Biggest changes our org needs forMBSE?*
10. Workforce	30. Organization defined critical roles to support MBSE *31. Q: Top MBSE roles in your organization?* 32. Org staffing adequate to fill MBSE-related roles?
11. MBSE Skills	33. Defined critical skills for MBSE *34. Q: The most critical skills for MBSE?*
12. Demographics	Organizational size, domain, MBSE experience

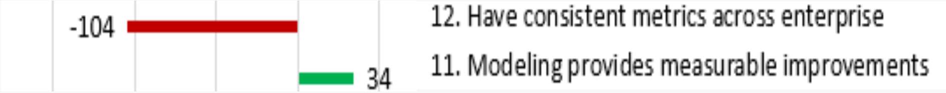
Survey content is derived from the draft INCOSE Digital Engineering Capabilities Definition

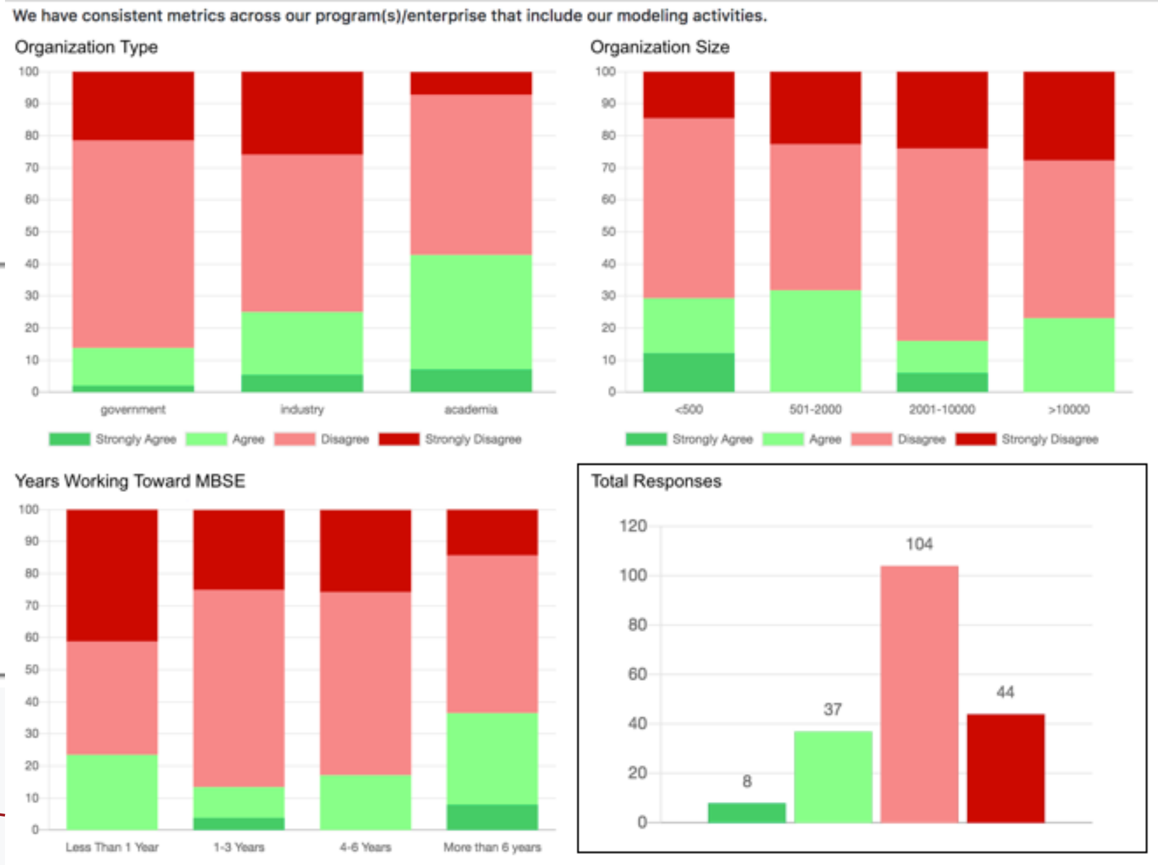
Overall Survey Scores



DE Metrics Survey Result





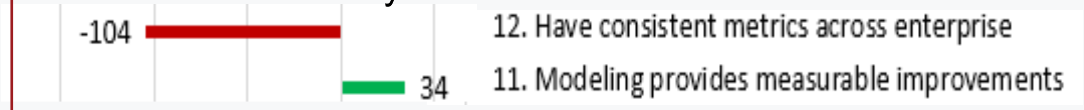


Consistent across all experience levels

Literature Review Results

- Searched papers that mention a benefit of MBSE and what the source of that benefit was: measured gains, observed gains, perceived gains (no source for benefit), reference.
  - ➢ Total Papers that mention MBSE: 847
  - ▪ Papers that mention benefits: 360
    - ○ Measured gains: **2**
    - ○ Observed gains: 27
    - ○ Perceived gains: **236**
    - ○ Reference: 114
    - ○ Misc.: 2

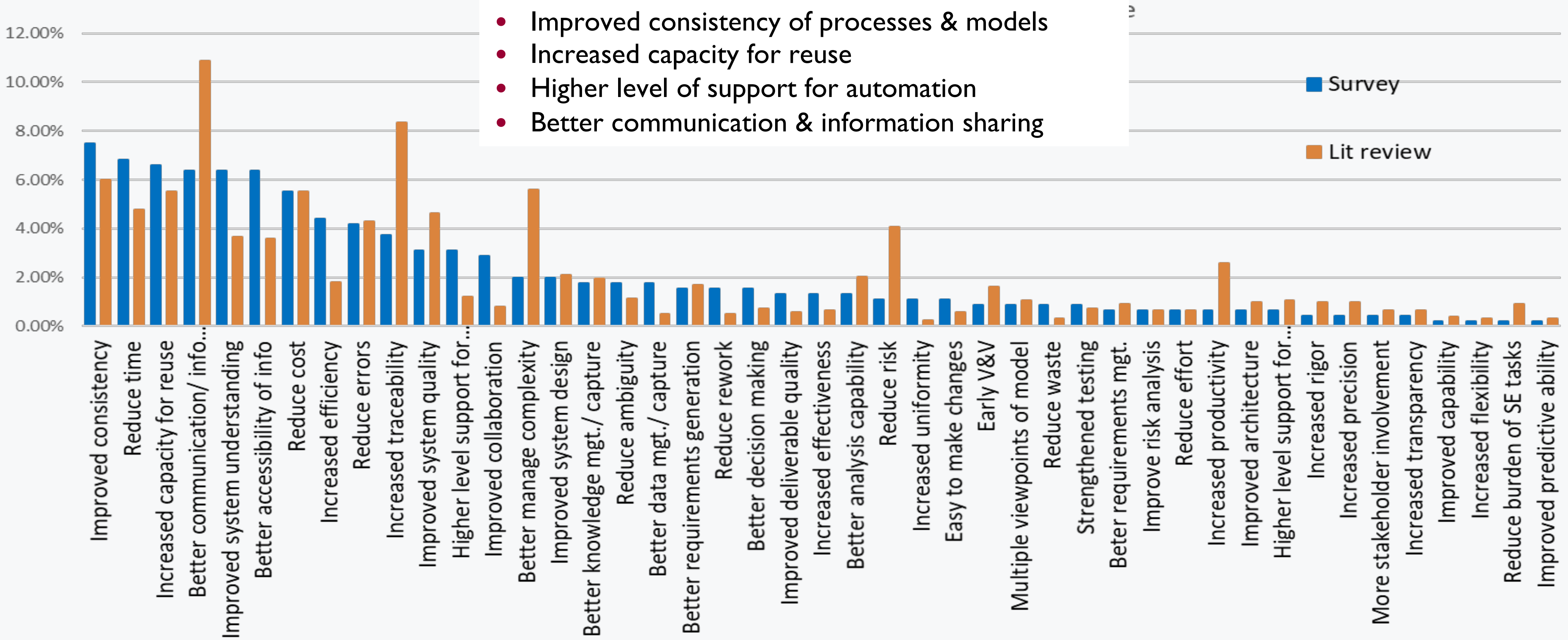
Survey Preview: Metrics



*Kaitlin Henderson (VT) PhD studies

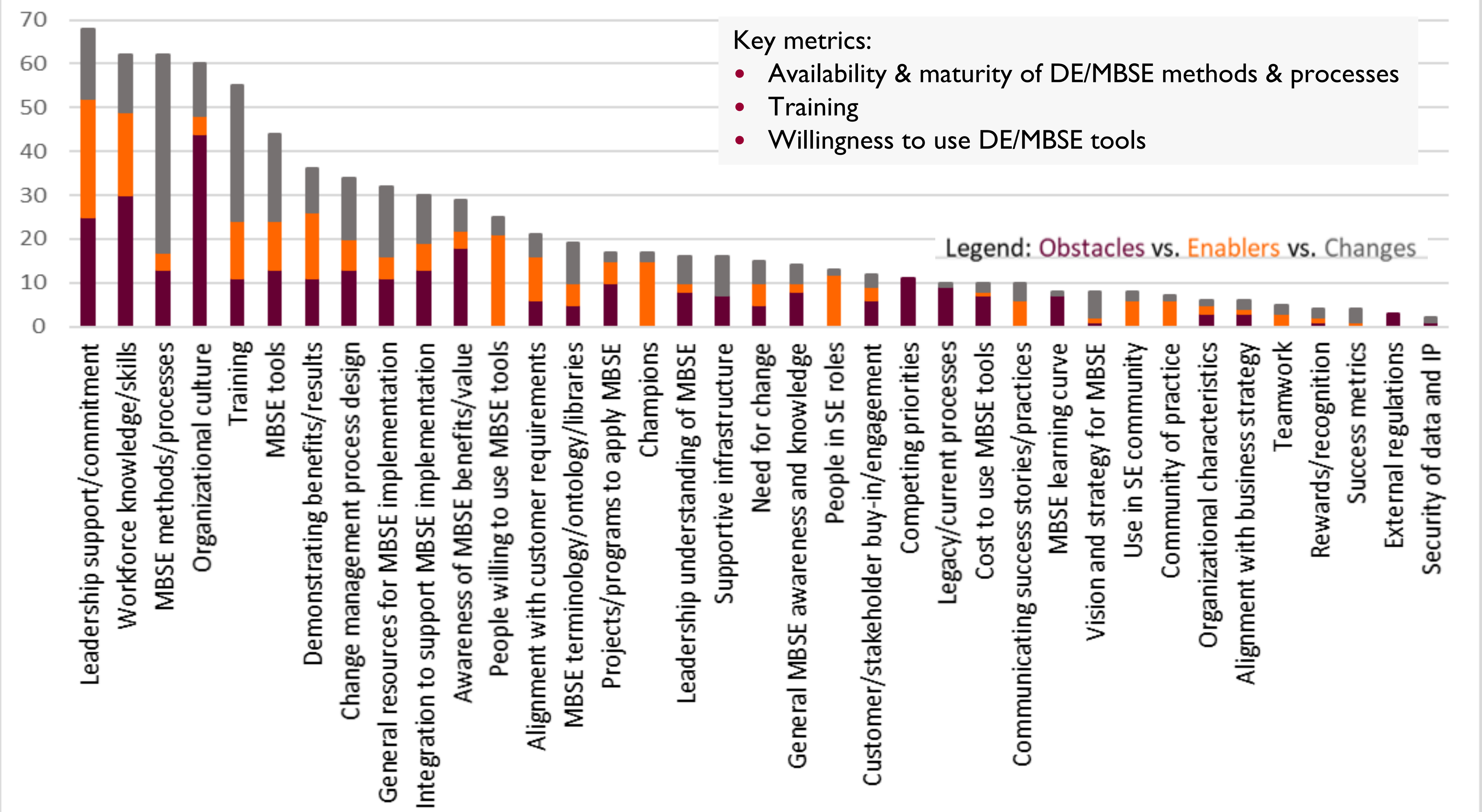
Top Cited DE Benefits Areas from Literature and Survey Results

Key metrics:
- Increased traceability
- Reduced defects/errors
- Reduced time
- Improved consistency of processes & models
- Increased capacity for reuse
- Higher level of support for automation
- Better communication & information sharing



Top-cited Adoption Metrics

Obstacles vs. Enablers vs. Changes



Summary: Top DE Metrics Areas

(>10 citations)

Category	Most Cited Benefits	Survey	Lit Review
Quality	Reduce Cost	5.5%	5.5%
	Reduce Defects/Errors/Rework	4.2%	1.3%
	Increased Traceability	3.7%	8.4%
	Higher Level of Support for Integration	3.1%	1.2%
	Improved System Quality	3.1%	4.6%
Velocity/Agility	Improved Consistency	7.5%	6.0%
	Reduce Time	6.8%	4.8%
	Improved Capacity for Reuse	6.6%	5.5%
	Increased Efficiency	4.4%	1.8%
	Improved Collaboration	2.9%	0.8%
User Experience	Improved System Understanding	6.4%	3.7%
	Better Manage Complexity	2.0%	5.6%
Knowledge Transfer	Better Accessibility of Information	6.4%	3.6%
	Better Communication/ Information Sharing	6.4%	10.9%
Adoption	Methods/Processes	8.0%	*
	Roles/Skills, People Willing to Use	6.8%	*
	Leadership support/Commitment	5.5%	*
	Training/Tools, People Willing to Use	4.4%	*
	Change Management Process Design	3.1%	*

*not assessed in lit review

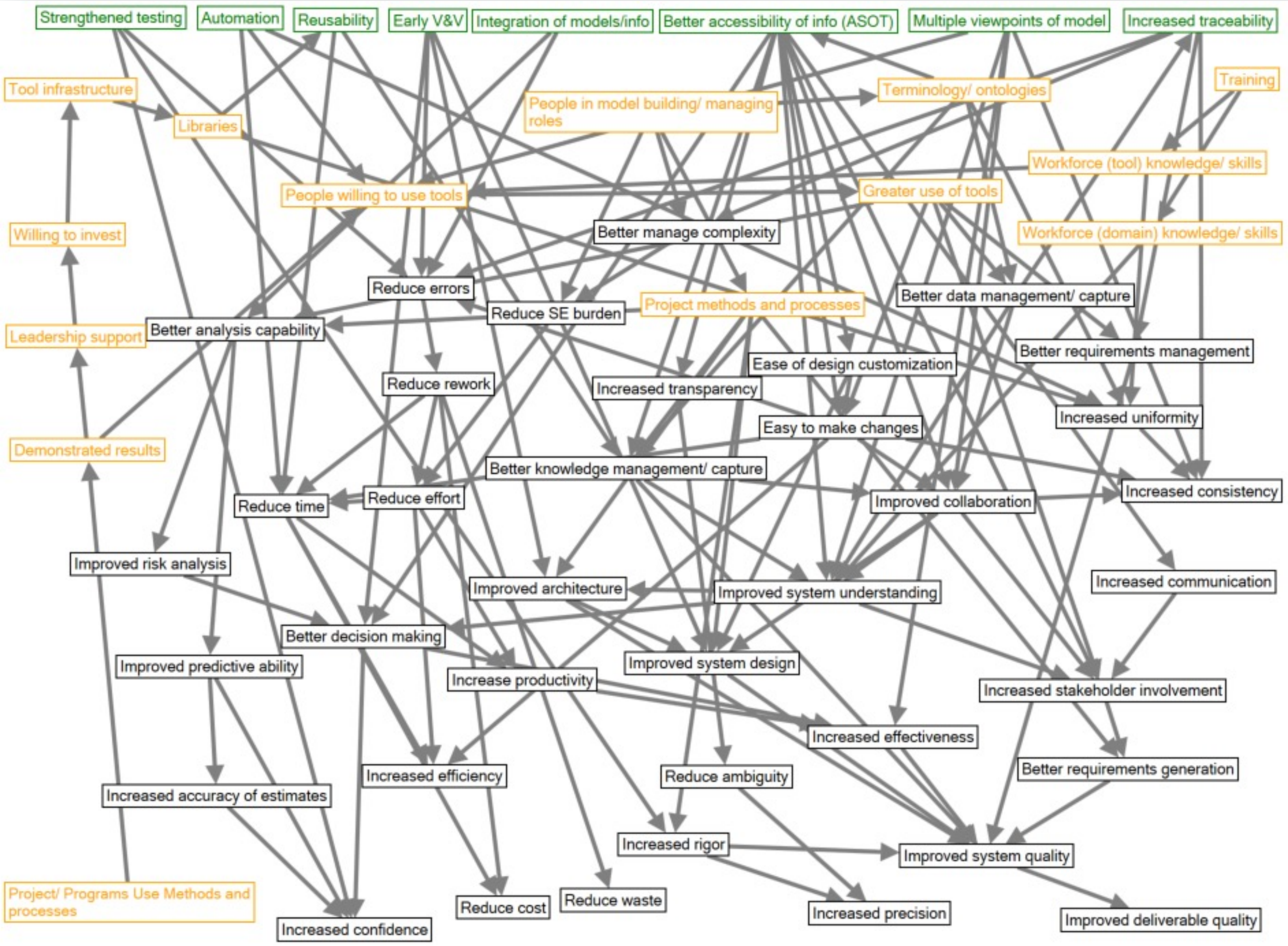
Causal Analysis for Measurement Model

Primary Benefits

Secondary Benefit Metrics

Secondary Adoption Metrics

- Causal Analysis of benefits and adoption data
- Link primary benefits to measures
- Used to scope detailed measurement specifications

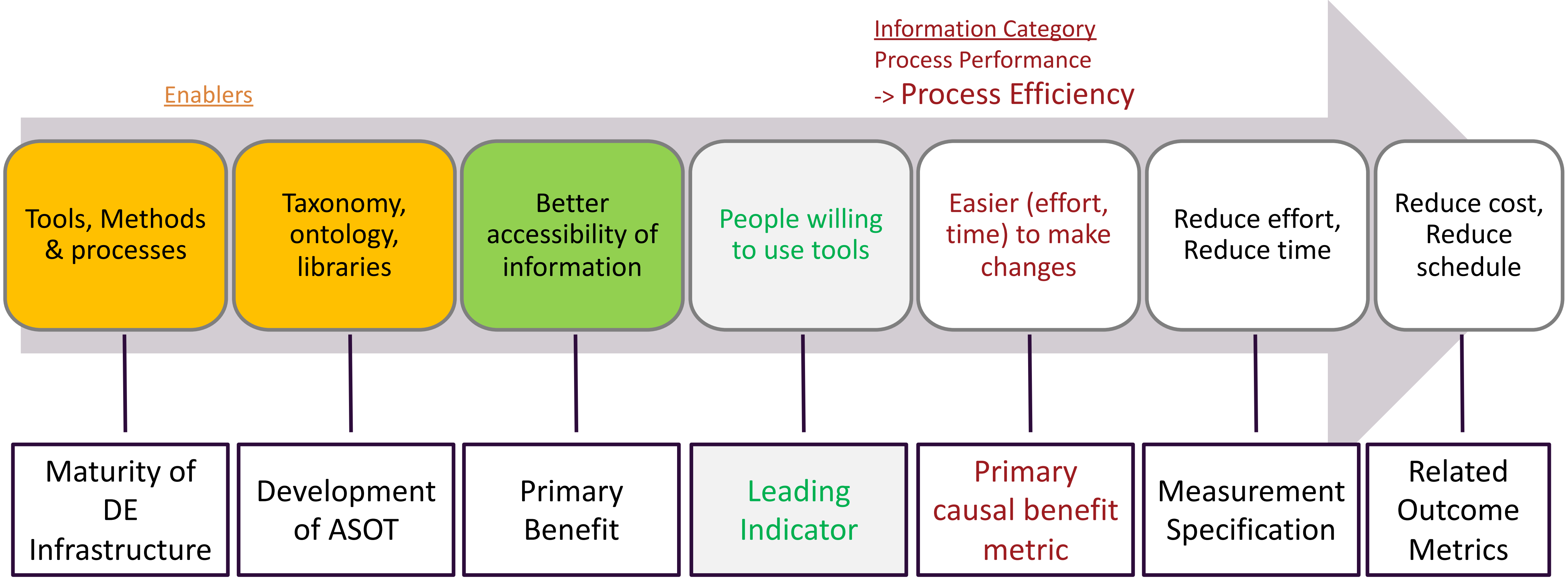


Develop Causal Links

- Starting nodes for causal map: benefits that can be directly influenced by improving MBSE capabilities/ features

Direct Benefits	Definition
Higher level support for automation	Use of tools and methods that automate previously manual tasks and decisions
Early V&V	Moving tasks into earlier development phases that would have required effort in later phases
Reusability	Reusing existing data, models, and knowledge in new development
Increased traceability	Formally linking requirements, design, test, etc. through models
Strengthened testing	Using data and models to increase test coverage in any phase
Better accessibility of information (ASOT)	Increasing access to digital data and models to more people involved in program decisions
Higher level support for integration	Using data and models to support both the integration of information and system integration tasks
Multiple viewpoints of model	Presentation of data and models in the language and context of those that need access

Example Causal Pathway



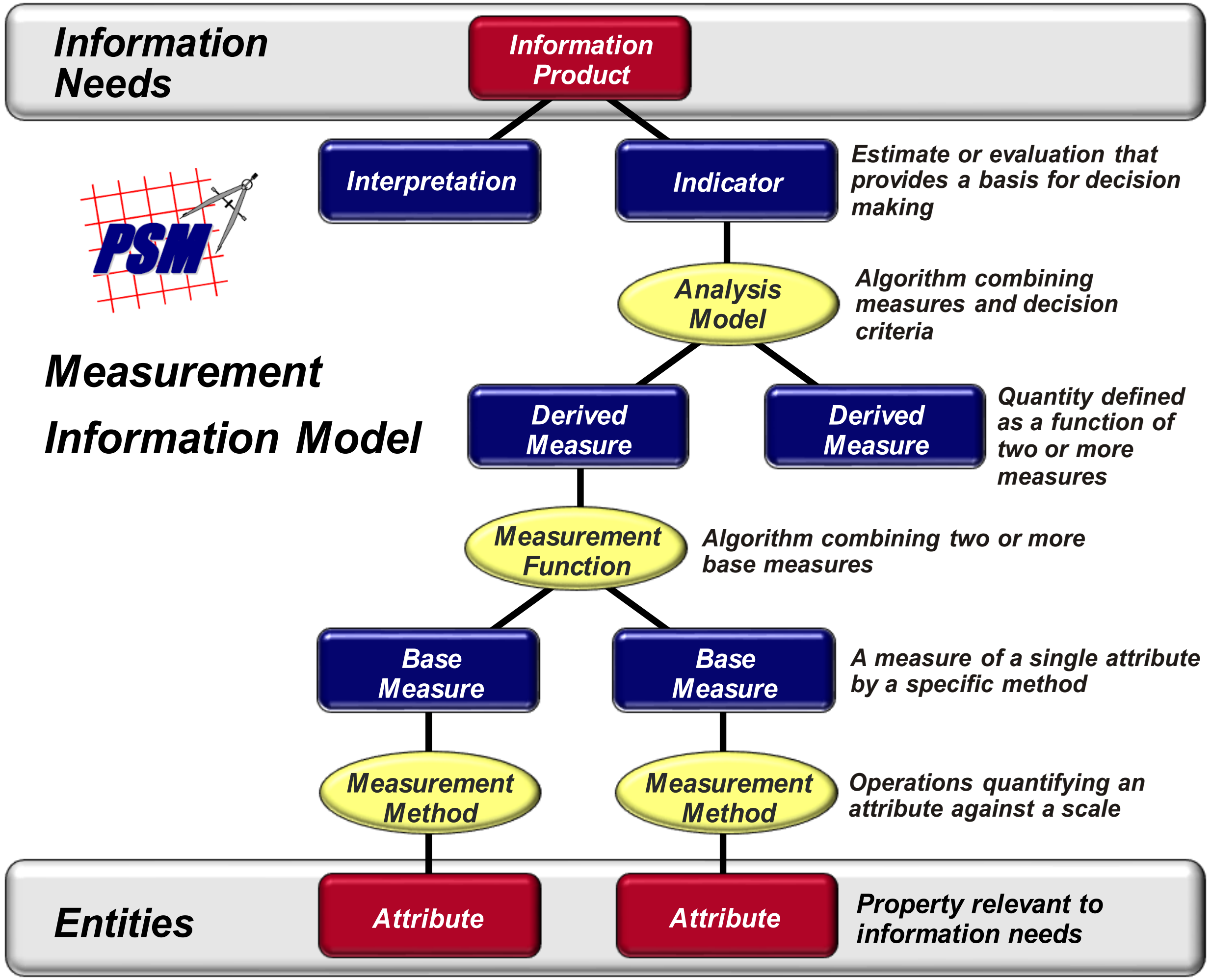
Specifications:
Defect Resolution
Rework

PSM measures are derived from business information needs

Based on objectives and issues from the project or enterprise levels

- *Objective* - a project goal or requirement
- *Issue* - an area of concern that could impact the achievement of an objective, including risks, problems, and lack of information

Measures should provide insight into project or enterprise information needs to support decision-making

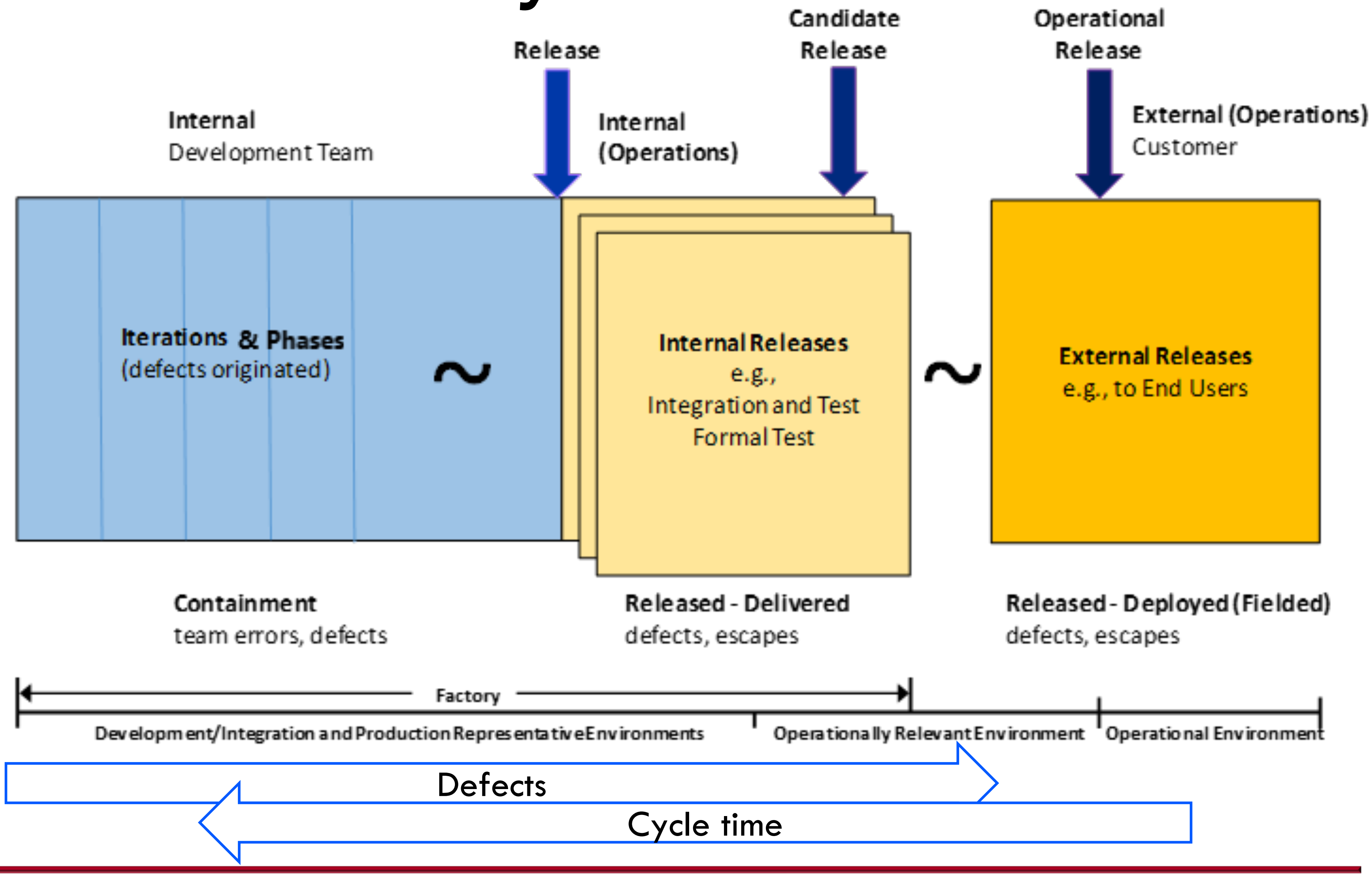


PSM Practical Software and Systems Measurement, www.psmsc.com

See Framework for more information

Defects and Cycle Time

It is the goal of agile full systems engineering to continuously iterate and contain defects into earlier and earlier developmental phases



Example Measurement Information Model – Anomalies

Digital engineering measures and indicators are specified in a structured template aligned with the PSM Measurement Information Model

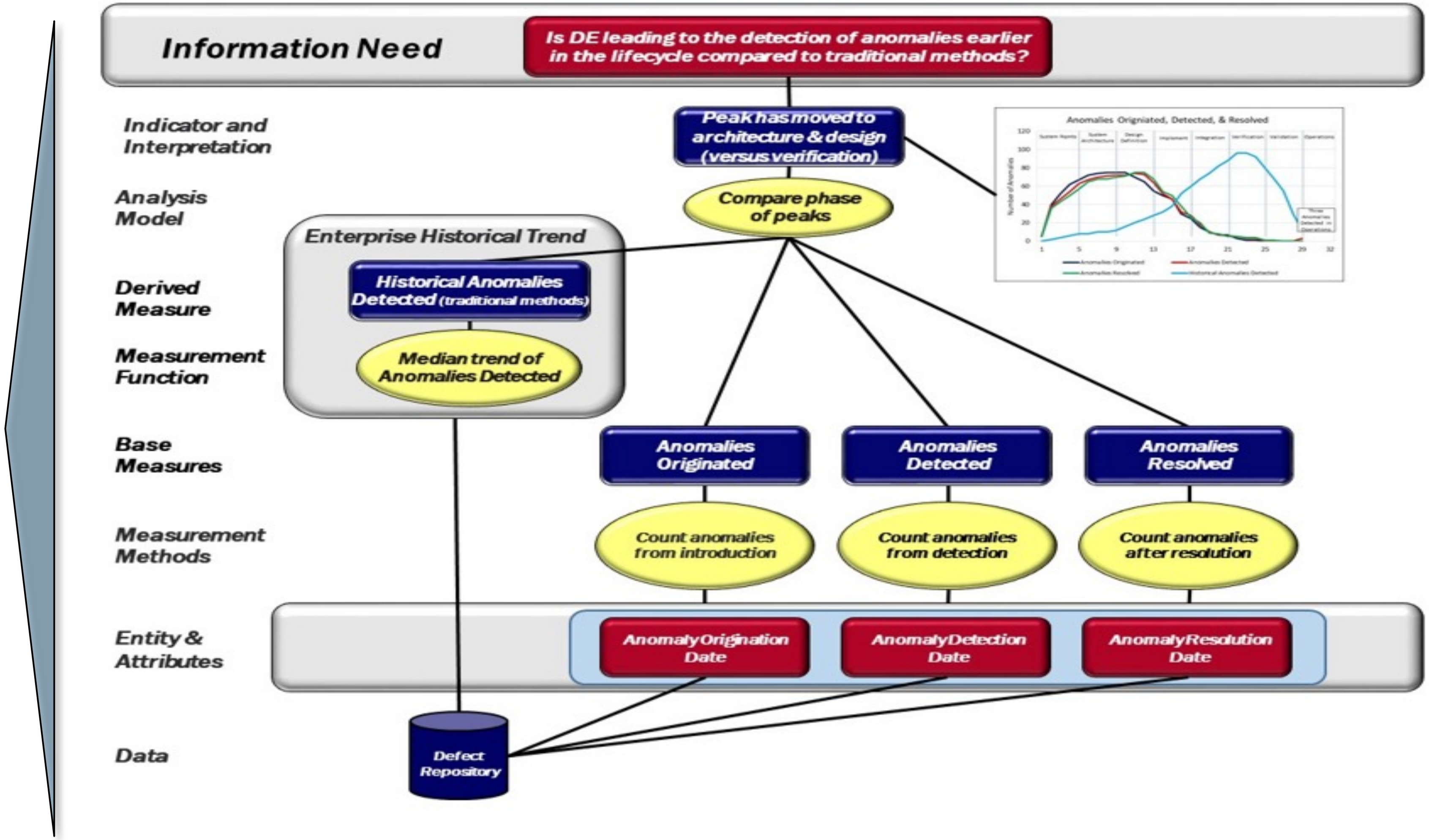


Figure 3.2-4: Mapping Data to Measures

Example Measurement Specification (Excerpts)

8.2 MODEL TRACEABILITY

Description

Measure Introduction	
Description	The usefulness and quality of a digital model depends on the completeness and integrity of the relationships among model elements. Traceability between elements, such as requirements allocation and flow down to architectural, design, and implementation components, assures that the system solution is complete and consistent. Gaps in bi-directional traceability between the artifacts of two models or might indicate where further analysis or refinement are needed. This might further apply to traceability gaps within a single model. when there is no implicit traceability between artifacts of different design stages. The prerequisites of any traceability measurement are agreed-upon, a priori guidelines and definitions, e.g., what model elements and relationships shall be traced, that apply to the specific DE model of the system. *Note:* While traceability might be applied to any model elements of interest that shall be defined a priori, functional architecture completeness always explicitly focuses on functions, requirements, and the associated hierarchy. Traceability reports and analyses might be facilitated by digital modeling tools. The traceability concepts and indicators in this specification are representative examples of more general traceability mappings and reports across the development life cycle, such as: • Traceability between stakeholder needs, system requirements, and allocated or derived requirements at each level of the system hierarchy • Traceability and flow down of requirements to the logical or physical solution domain (e.g., design, implementation, integration, verification, validation) • Allocation and traceability of performance measures or parameters, such as Measures of Effectiveness (MOEs) or Key Performance Parameters (KPPs) • Traceability of system interfaces

Definitions

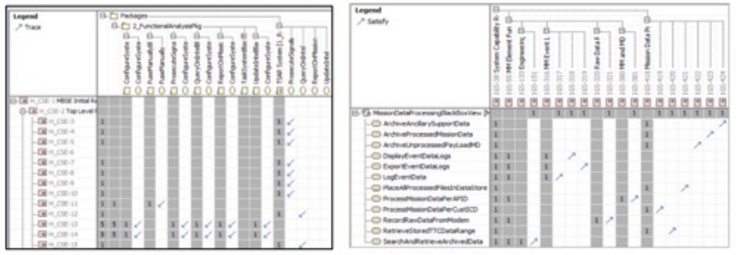
Relevant Terminology	Model Element	Modeling constructs used to capture the structure, behavior, and relationships among system model components (See 2.2.2 Model Element)
	Source Element	The *a priori* base model elements defined per DE model from which other model elements shall be derived from or allocated to, e.g., a stakeholder needs.
	Destination Element	The model elements defined per DE model that shall be derived from or allocated to the Source Elements.
	Traceability Gap	One or more model elements defined per DE model that shall be traced, but that have not yet been derived or allocated to Source Elements.
		Note: For enhanced traceability concepts refer to the advanced topic discussion.

Measures (Base, Derived)

Information Need and Measure Description	
Information Need	What is the extent of achieved traceability coverage from Source Elements, e.g., requirements, down to the logical or physical solution domain? What is our progress in completing the digital model? What traceability gaps exist?
Base Measure 1	Model Elements Traced [integer] "Number of model elements in a 1...n source/destination element relationship(s) as defined in an agreed upon, *a priori* guideline.
Base Measure 2	Model Elements Not Traced [integer] Number of model elements not in any 1...n source/destination *element relationship as* defined in an agreed upon, *a priori* guideline.
Derived Measure 1	Total Model Elements = Model Elements Traced + Model Elements Not Traced [integer] Total number of model elements *Note:* As defined in an agreed upon, a priori guideline (See Base Measure 1 and Base Measure 2).

Indicator(s) and Interpretation

Indicator Specification	
Indicator Description and Sample	Model Traceability can be depicted using visual or tabular summaries of the relationships among model elements. The specific indicators may depend on the model elements for which traceability is being measured, and the built-in reports and analyses provided by the digital modeling tool. For example, traceability among model elements might be implemented by showing requirements derivation and model traceability coverage of stakeholder needs into system and component requirements. Representative example indicators used to assess traceability dependencies among selectable model elements (e.g., requirements, use cases, activities, logical architecture and design, physical design, interfaces, parameters, measures of performance) are depicted in Figure 8.2-1. Here, mostly 2-dimensional matrices containing model specific model elements of interest are utilized. Alternatively, the relationship between model elements might be depicted as flow down. With respect to Figure 8.2-1 (bottom left), a specific use case is linked to related actions via an activity diagram.



Traceability Between Model Elements (Dependency Matrix) Relationships to Problem or Solution Domain («satisfy» or «refine» Matrix)

Analysis Guidance

Analysis Model	Projects and organizations shall define the objectives, constraints, and criteria for establishing traceability among applicable model elements. This is typically guided by a model schema, metamodel, or blueprint that constrains traceability to meet the model's purpose. Review and analyze traceability dependencies among model elements to assess the completeness, adequacy, quality, and integrity of the digital model. The analysis may vary according to the types of specific model elements selected, but general guidelines may include: • Each source (parent) model element (Model Element 1) should be traceable to one or more allocated or derived destination (child) model elements (Model Element 2). • Each destination (child) model element (Model Element 2) should be derived from, or refine, a parent requirement or model element (Model Element 1). • Determine if the set of linked dependencies are, in aggregate, sufficient to adequately implement the parent requirement or model element.
Decision Criteria	In case a desired model traceability coverage (Derived Measure 2), e.g., 70%, of model elements of interest has not been met, the team shall specifically address these gaps. To validate whether the system meets stakeholder needs, at minimum, the system requirements should be traceable to these stakeholder needs. Model elements that do not satisfy requirements, might be obsolete and shall be evaluated. Again, the prerequisites of any decision making are agreed-upon, a priori guidelines and definitions, e.g., what model elements and relationships shall be traced, that apply to the specific DE model of the system

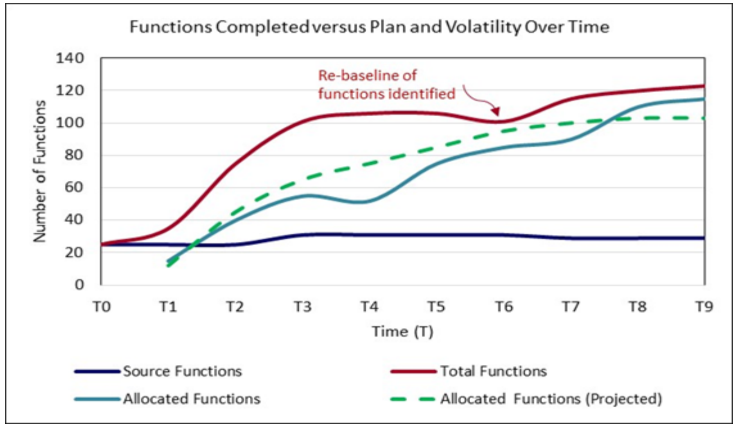
Additional Information and Guidance

Additional Analysis Guidance
Implementation Considerations

Information Category
Measurable Concept
Relevant Entities
Attributes
Data Collection Procedure
Data Analysis Procedure

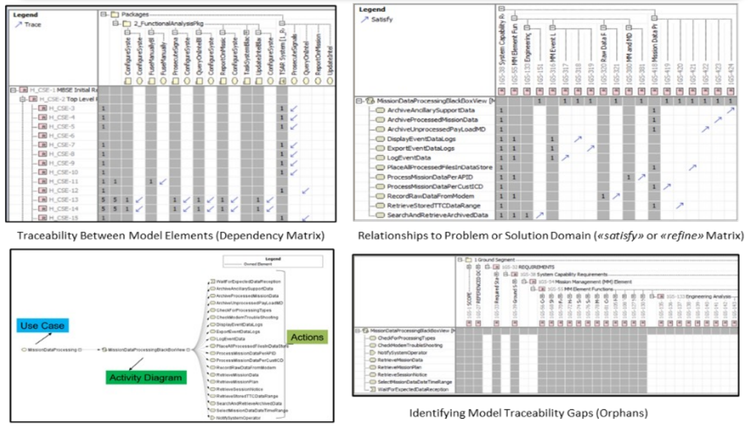
Digital Engineering Measurement Framework – Example Indicators

Architecture Completeness and Volatility



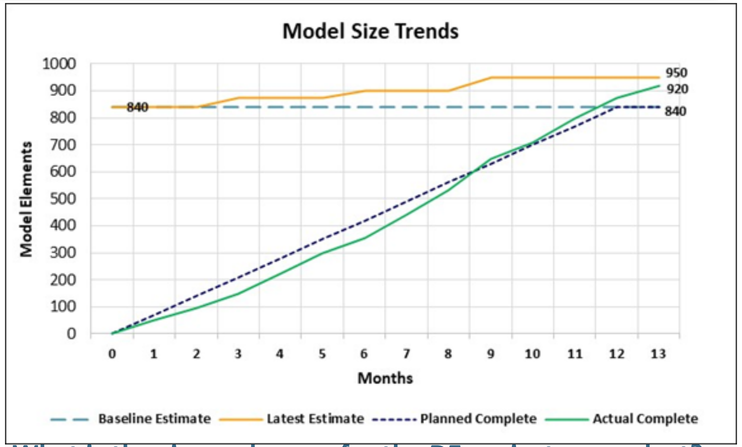
Is the architecture complete to proceed with design?

Model Traceability



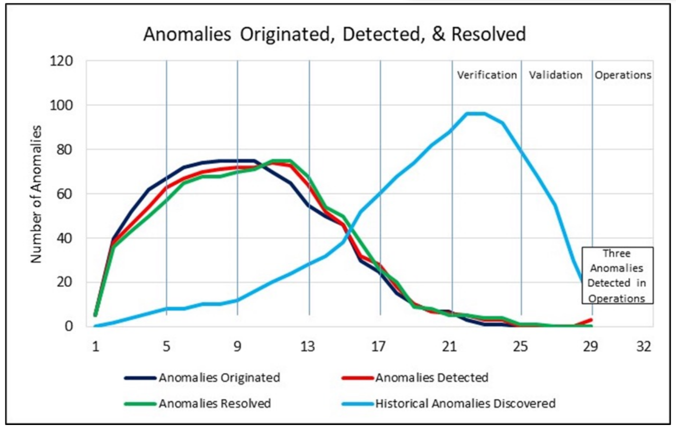
What is the traceability and coverage of model elements?

Product Size (Model Elements)

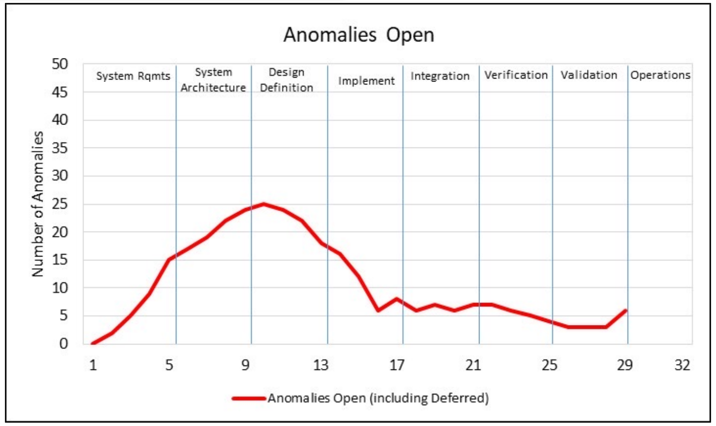


What is the size and scope for the DE project or product?

DE Anomalies

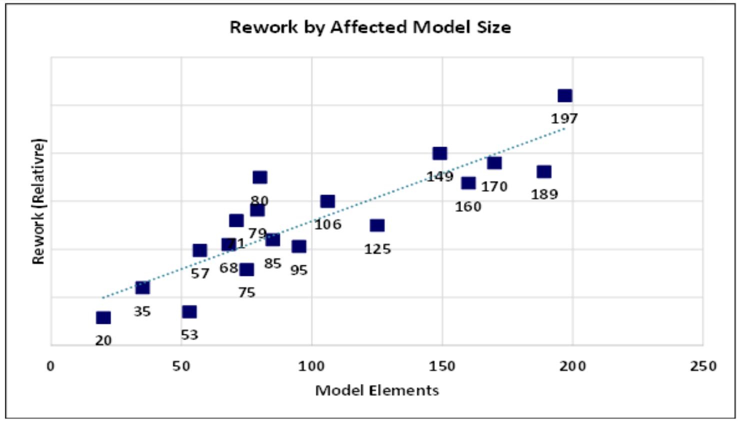


Are we finding and removing anomalies earlier using DE?



Is product quality adequate to be used in subsequent phases?

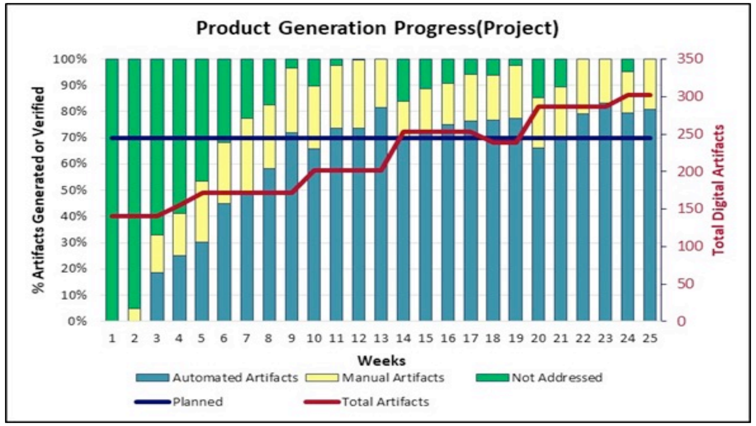
Adaptability and Rework



How much rework is for planned and unplanned changes?

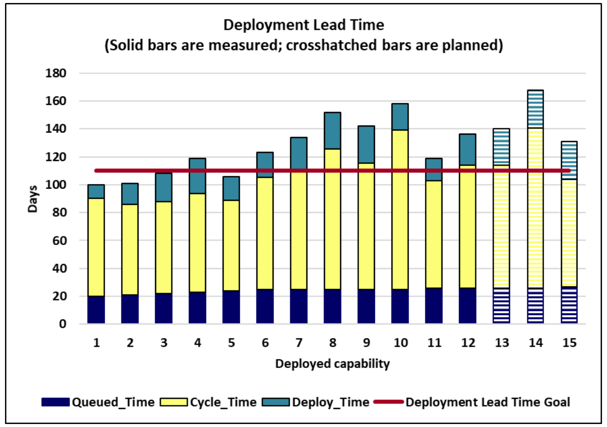
Digital Engineering Measurement Framework – Example Indicators

Product Automation



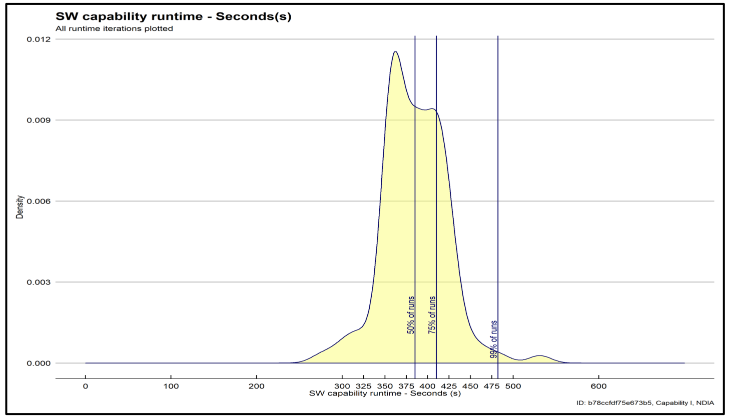
What percentage of artifacts are automatically model-generated?

Deployment Lead Time



How long does it take to deploy an identified capability?

Runtime Performance



What is the likelihood performance will meet operational needs?

Excerpts only from DE measurement specifications. Some specs have multiple sample indicators. See framework Section 8 - Measurement Specifications for details.

Editors	Organization
Joseph M. Bradley	Main Sail, LLC
Cheryl Jones	US Army DEVCOM AC Practical Software and Systems Measurement (PSM)
Geoff Draper	L3Harris Technologies AIA Engineering Management Committee NDIA Systems Engineering Division
Tom McDermott	Systems Engineering Research Center (SERC) Stevens Institute of Technology
Paul Janusz	US Army DEVCOM AC Practical Software and Systems Measurement (PSM)

Authors	Organization
Lennis Bearden	L3Harris Technologies
Giacomo Gentile	Collins Aerospace
Richard Halliger	Volkswagen Group
Ray Madachy	Naval Postgraduate School
Drew Miller	The Boeing Company
Young Park	Collins Aerospace
Bob Scheurer	The Boeing Company NDIA Systems Engineering Division AIA Engineering Management Committee

Core Team	Organization
Kaitlin Henderson	Virginia Tech
Al Hoheb	Aerospace Corporation
Bill Luk	BAE Systems AIA Engineering Management Committee
Lisa Murphy	Siemens Digital Industries Software
Jeff Nartatez	Office of the Undersecretary of Defense for Research and Engineering (OUSD R&E) [SAIC]
Garry Roedler	INCOSE NDIA Systems Engineering Division
Alejandro Salado	The University of Arizona
Frank Salvatore	Office of the Undersecretary of Defense for Research and Engineering (OUSD R&E) [SAIC]
Paul Segura	The Boeing Company AIA Engineering Management Committee
Natasha Shevchenko	Software Engineering Institute, Carnegie Mellon University
Marilee Wheaton	Aerospace Corporation INCOSE

Additional Contributors	Organization
David Allsop	The Boeing Company
Sanjay Angadi	Ansys AIA Engineering Management Committee
David Cooper	BAE Systems
Mimi Davidson	Office of the Undersecretary of Defense for Research and Engineering (OUSD R&E) [SAIC]
John Dilger	BAE Systems
Paul Embry	L3Harris Technologies AIA Engineering Management Committee
Ann Hodge	Sandia National Laboratories
Mike McLendon	Retired
Robert Minnichelli	Aerospace Corporation
Gery Mras	Aerospace Industries Association (AIA)
Rosco Newsome	Ernst & Young (EY)
Bill Nichols	Software Engineering Institute, Carnegie Mellon University
Ryan Noguchi	Aerospace Corporation
Macaulay Osaisai	L3Harris Technologies
Steven Quinn	BAE Systems
Donna Rhodes	Massachusetts Institute of Technology (MIT)
Chris Schreiber	Lockheed Martin Corporation NDIA Systems Engineering Division
Paul Solomon	Retired
Brian Tenney	Lockheed Martin Corporation
Sundar Thyagarajan	L3Harris Technologies
Steven Turek	United States Air Force
Timothy Walden	Lockheed Martin Corporation
John Wood	Naval Information Warfare Command

Much appreciation to the many individuals and organizations that supported development of the V1.0 Digital Engineering Measurement Framework!

Support to Systems Engineering

- The Systems Engineering Leading Indicators Guide, published by INCOSE, identified a set of measures to assess the effectiveness of the systems engineering process. Despite the maturity of these indicators, few complete examples of actual measurement exist, primarily due to the lack of tools that can quantitatively track these measures.
- Important quantitative measures supporting selected leading indicators include:
  - Requirements Trends: Model Traceability, Functional Architecture Completeness & Volatility
  - System Definition Change Backlog Trends: Rework, Effort, Efficiency
  - Interface Trends: Model Traceability, Functional Architecture Completeness & Volatility
  - Requirements Verification & Validation Trends: Deployment Lead Time, Efficiency
  - Work Product Approval Trends: Number of Model Views/Artifacts, Deployment Lead Time
  - Review Action Closure Trends: Model Review Item Discrepancies
  - Defect & Error Trends: Defect Detection, Defect Resolution, Rework
  - Technical Measurement Trends: ASOT Frequency of Access
  - Architecture Trends: Functional Architecture Completeness and Volatility, Functional Correctness, Product Size
  - Cost & Schedule Pressure: Efficiency, Rework, Deployment Lead Time

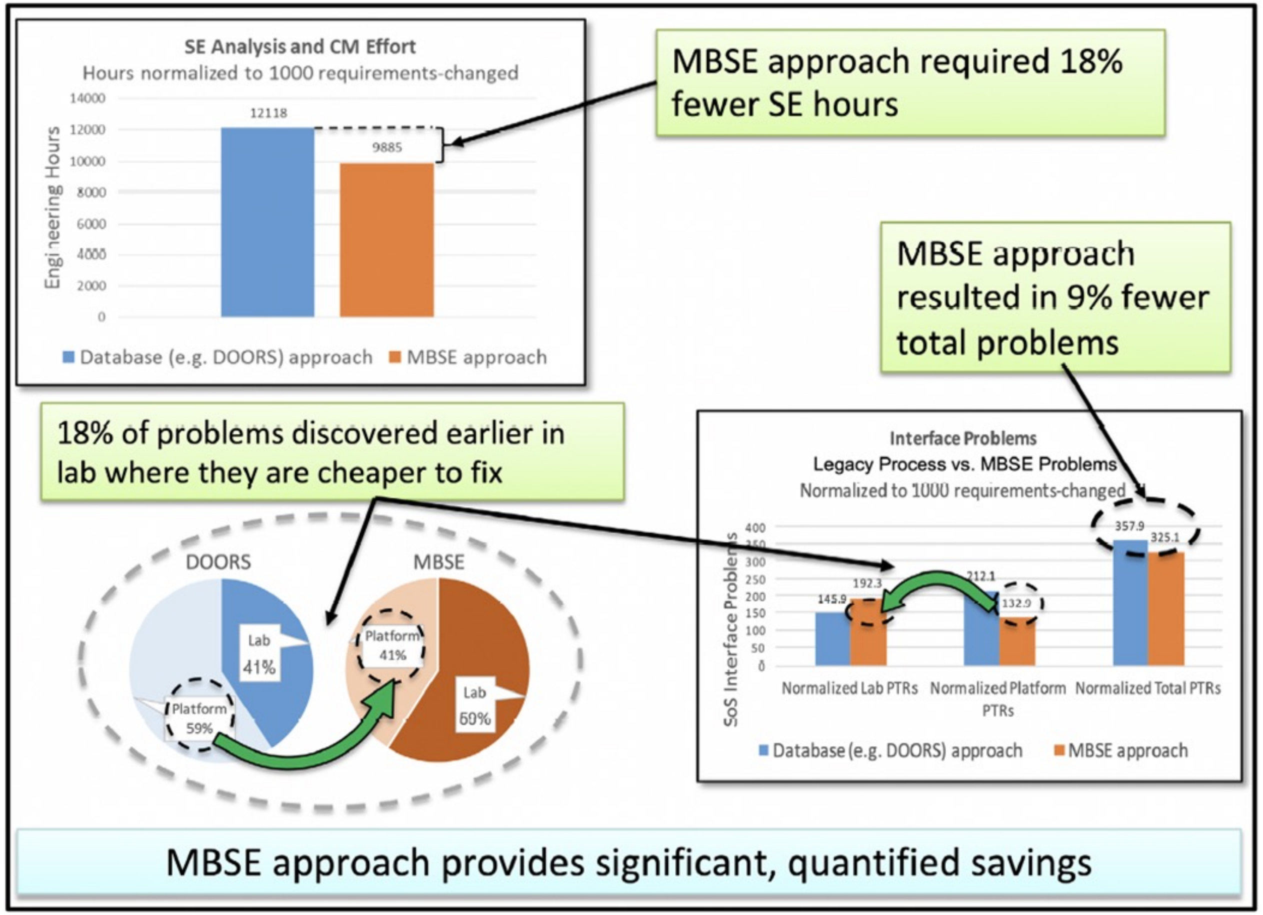
Massachusetts Institute of Technology, INCOSE, and PSM, Systems Engineering Leading Indicators Guide, v. 2.0, International Council on Systems Engineering, 2010.

Validating DE Measures

- very few developmental and sustainment programs that are implementing a formal measurement program, and fewer are publishing results

- U.S. Navy Submarine Warfare Federated Tactical Systems (SWFTS) program used for initial metrics framework validation

- SWFTS quantified these primary benefits: Increased Traceability, Early V&V and Strengthened Testing, Support for Integration, and Automation.



Rogers, E. and Mitchell, S., "Submarine Warfare Federated Tactical Systems (SWFTS) program," *Systems Engineering*, 2021: 1-24

Where do we go from here?

- *DE measures for the enterprise*
- *Measure breadth of usability and user experience with digital tools*
- *Measure return on investment*
- *Measure additional productivity indicators related to velocity and agility*
- *Measure additional indicators that isolate new value to the enterprise through DE, in areas such as quality and knowledge transfer*
- *Measure enterprise and personnel process adoption*
- *Measure usability and user experience with digital tools*
- *Supportability and maintainability measures (impact assessment agility)*
- *Measures for security*
- *Identify typical digital artifacts*
- *Specify leading indicators*

Plan to start Framework 2.0 development activity this November

SYSTEMS ENGINEERING RESEARCH CENTER

THANK YOU

Stay connected with us online.