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The Digital Manufacturing & Cybersecurity Institute

Heidi Davidz, Matthew Taylor, Mark Schriner

Enhancing Industry 4.0 Transformation Success with a Solution Debt Playbook

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Key Points

Industry 4.0 success is a systems challenge

Solution debt is more holistic than technical debt

Managing solution debt can enhance Industry 4.0 transformation success

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Industry 4.0 Definitions

- Synonymous with smart manufacturing; realization of the digital transformation of the field, delivering real-time decision making, enhanced productivity, flexibility and agility to revolutionize the way companies manufacture, improve and distribute their products.

Source: IBM, 2024

- The integration of intelligent digital technologies into manufacturing and industrial processes.

Source: SAP, 2024

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Industry 4.0 Challenges

Need to modernize

"The organic industrial base was designed and really implemented in World War II, and so what we have is really a 20th century capability to support a 21st century Army and joint force."

General Edward Daly, United States Army Materiel Command

Source: Judson, 2022

US Defense Industrial Base (DIB) is losing small suppliers

"Over the past decade, small businesses in the DIB shrunk by over 40%…if the DIB continues along the same trend, DoD could lose an additional 15,000 suppliers over the next 10 years."

Source: US DoD, 2022

Manufacturing Industrial Base is Shrinking

2020 DATA **239,607 U.S. MANUFACTURING FIRMS**

178,210 Small Manufacturers
< 20 Employees

57,373 Medium Manufacturers
20 < Employees < 500

4,024 Large Manufacturers
>500 Employees

Source: US Census Bureau, 2020

2010 DATA **258,662 U.S. MANUFACTURING FIRMS**

197,701 Small Manufacturers
< 20 Employees

57,512 Medium Manufacturers
20 < Employees < 500

3,449 Large Manufacturers
>500 Employees

Source: US Census, 2010

Many Manufacturing Firms Not Resourced for Digital Transformation

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THE THREAT FOR MANUFACTURING IS INCREASING

#1 In 2021, manufacturing was the top attacked industry, with ransomware accounting for 23% of the attacks

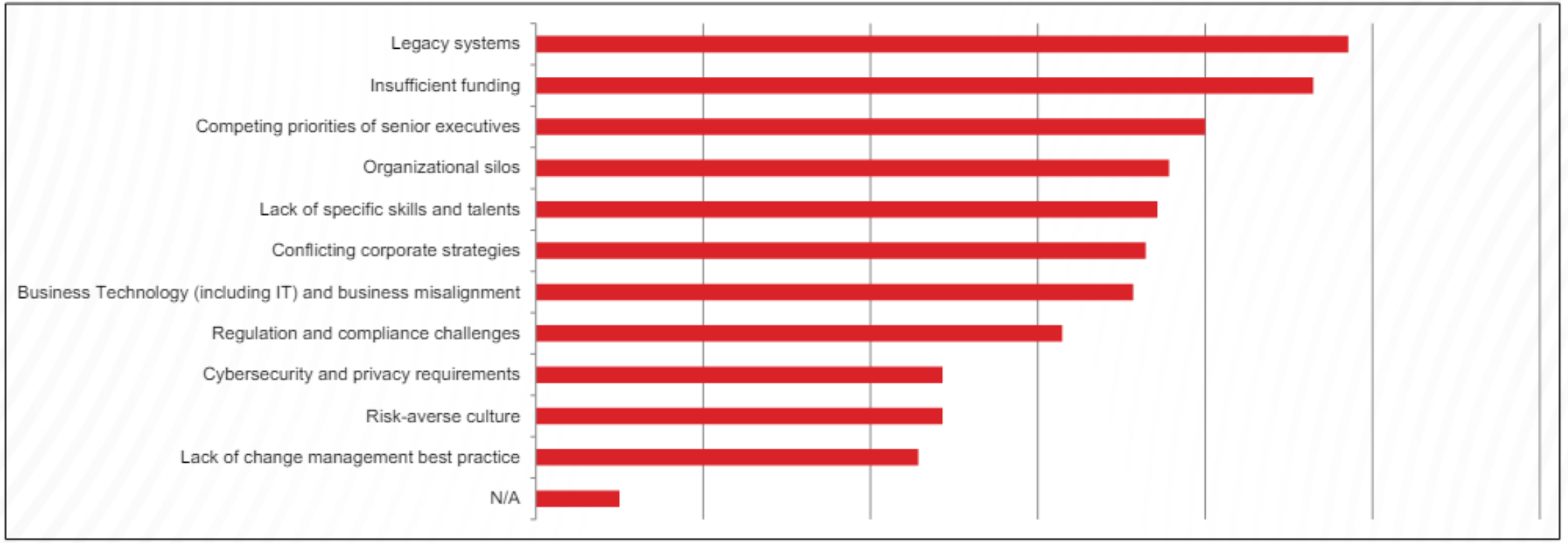
61% of incidents at organizations with network connected operations technology (OT) were in the manufacturing industry

2,204% increase in reconnaissance against industrial controlled operations technology and software accessible by the internet

Source: IBM, 2022

Cybersecurity is Part of the System

Obstacles to Digital Transformation



"There was a consistent thread across most respondents when it came to legacy systems, insufficient funding, and competing priorities of senior executives as challenges to better digital transformation successes. One could see the correlation between the three despite the order they were presented in. It was felt that in the business systems the ERP systems were expensive to implement and to upgrade without significant cost and disruption. Most respondents commented that the have several legacy systems and anticipate the maintenance of these and future systems to cause legacy issues on an ongoing basis."

Source: Reed, et al 2021 (FDA-funded study conducted by MxD and IAAE)

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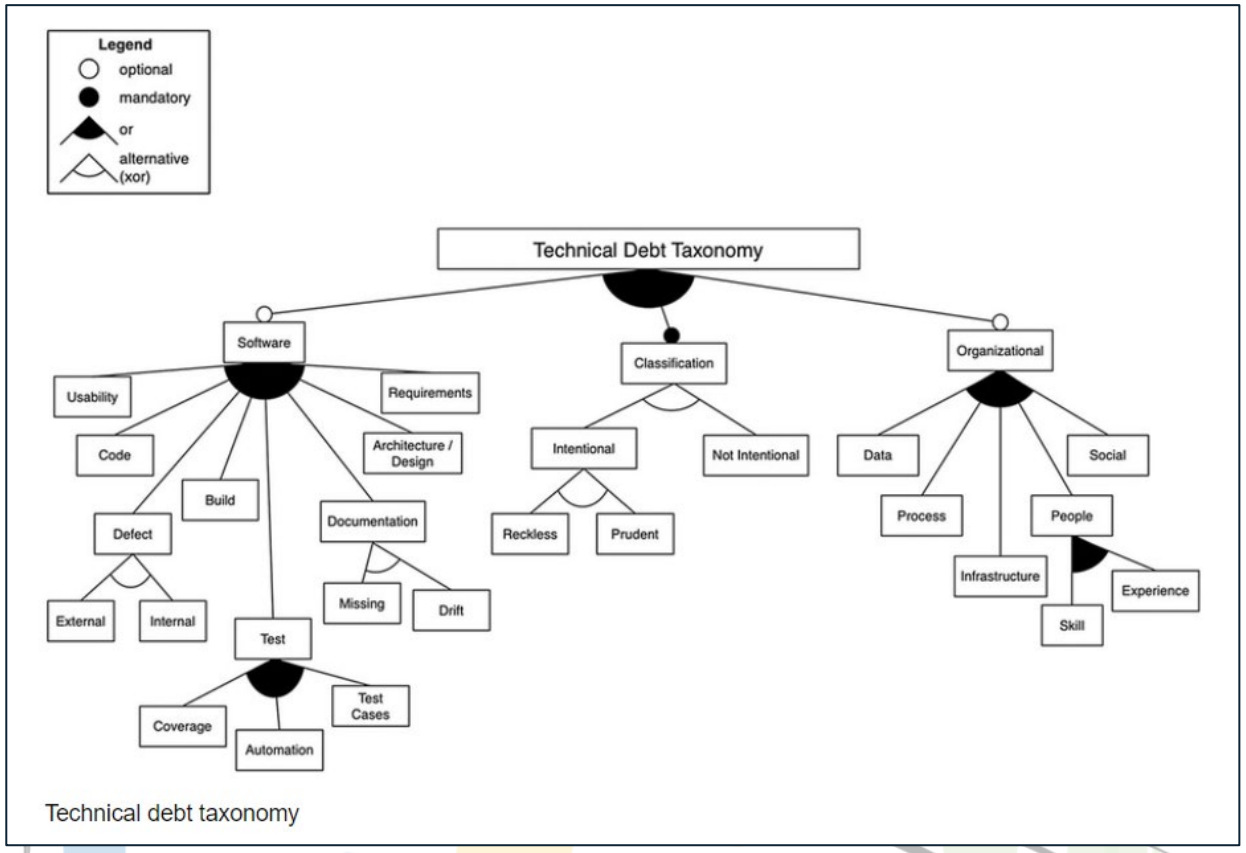
Technical Debt



Technical debt taxonomy

- Debt – deferred payment due in the future
- Technical Debt – implied cost of additional rework caused by choosing a limited solution now instead of using a better approach that would take longer
- Technical debt literature is almost exclusively focused on software
- However, the debt metaphor is not just for software and is not limited to development phase

Sources: Codabux et al, 2017; Rouse, 2017; Mitton, 2023; Gartner Research, 2020

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Common Causes

Sources: DoD, 2017; DoD, 2022; DoD 2024; Section 809 Panel, 2019; DAU, 2024; DIU, 2024; Engler, 2020; Frankiewicz and Tomas Chamorro-Premuzic, 2020; INCOSE 2021

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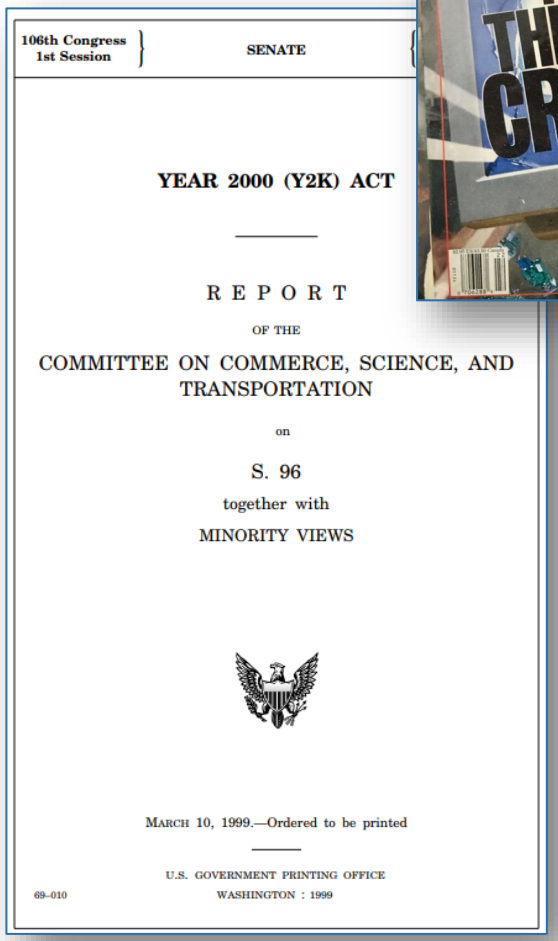
Example: Y2K

- Estimates of up to $1 Trillion spent in just the United States
- Estimates of $8.5B spent by the federal government
- $250M by Chase Manhattan Bank alone
- …all because storage and processing used to be so precious most software stored only two digits of the year – even after that wasn't strictly necessary.
- This was brought up as a debt to be paid as far back as 1971



106th Congress
1st Session
SENATE

YEAR 2000 (Y2K) ACT

REPORT
OF THE
COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION
on
S. 96
together with
MINORITY VIEWS

MARCH 10, 1999.—Ordered to be printed

U.S. GOVERNMENT PRINTING OFFICE
69-010 WASHINGTON : 1999

Sources: Smith, 2016; Loeb, 2019; Newsweek, 1999; McCain, et al, 1999

Solution Debt

- Systems engineers worry about debt incurred at the solution level, spanning the lifecycle
- Broader term is Solution Debt
- Solution Debt – implied cost of additional rework across disciplines and lifecycle caused by choosing a limited solution now instead of using a better approach that would take longer
- Debt incurred during engineering may need payment during manufacturing

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Solution Debt Taxonomy

		Debt	Common Symptoms
Business Debt	**Organization Debt**	Management Debt	Inconsistent views of roles/responsibilities, Unchecked resistance to change
		Supply Chain Debt	Reliance on single sources, Lack of visibility into supply sub-tiers
		Service Debt	Ill-defined service level agreement, high service switching cost
		People Debt	Poor workforce morale, Missing skills or experience
		Social Debt	Strained interactions with stakeholders, Soiled reputation internally or externally
	Approach Debt	Innovation Debt	Lack of differentiating capability, Unbalanced R&D portfolio, Misapplied skills
		Process Debt	Inefficient process, Undocumented process, Rigid process
		Infrastructure Debt	Insufficient facilities or equipment, Lack of internal/external collaboration capability
Lifecycle Debt	**Development Debt**	Requirement Debt	Unverifiable requirements, Incomplete traceability, Requirement Quality Issues
		Architecture Debt	Unintended system behavior, Lack of variation management, Incomplete architecture, Lack of or incomplete traceability, lack of interoperability
		Design Debt	Design for export not considered, Lack of design guidance, Multiple sources of truth
		Technical Data Package Debt	Incomplete specification, Inconsistent model methods and style
		Security Debt	Limited cyber recovery planning, Conflicting classification guides
		User Interface Debt	Unnecessary cognitive load on user, Lack of reliable interpretation
		Build & Validation Debt	Lack of automated validation suite, Ill-defined dependencies
		Code Debt	Duplicate code, Poor code metrics, Unmaintainable code, Inefficient code
	Sustainment Debt	Production Operation	Uncharacterized value streams, Inability to meet contracted volumes, Unvalidated requirements
		Defect Debt	Unmanaged backlog, Uncorrected major defects
		Test Debt	Lack of control and observability points, Unrepeatable test results
		Technology Debt	Ad-hoc technology adoption, Solution no longer effective in intended environment
		Obsolescence Debt	Surprise lifetime buys, Obsolete inventory
		Data Debt	Ad-hoc data controls, No data disposal plan, Dark data
		End of Life Debt	Lack of plan for removal from service

Adapted from Source: Alves, et al, 2014.

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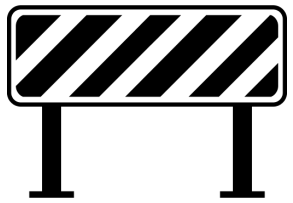
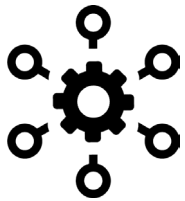
Evaluating Debt



Impact



Fix Cost

Contagion

Who pays?
(Directly, Indirectly)

Access Denied?
(No ability to impact)

Sources: Cognopia, 2024; Clark, 2018

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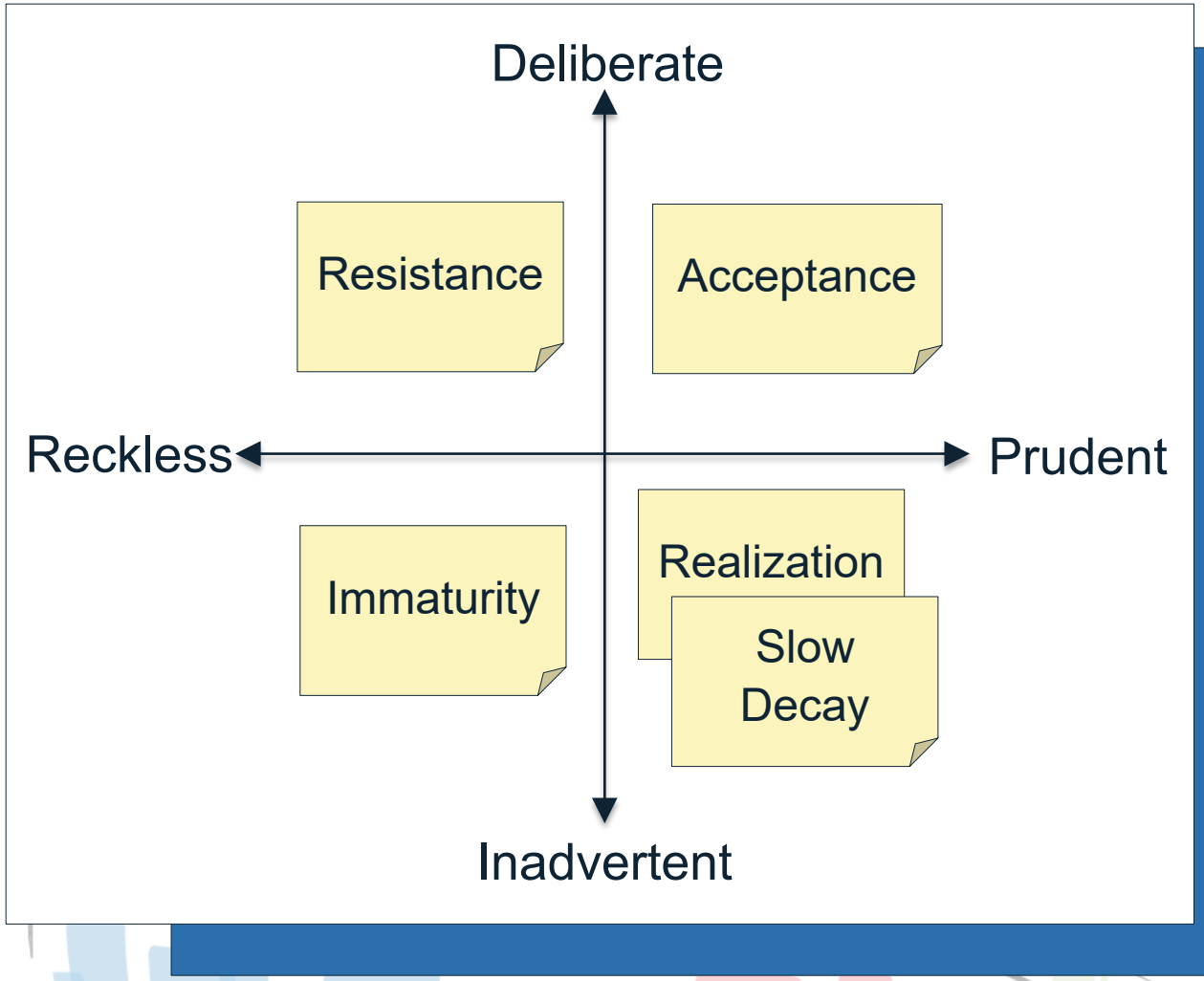
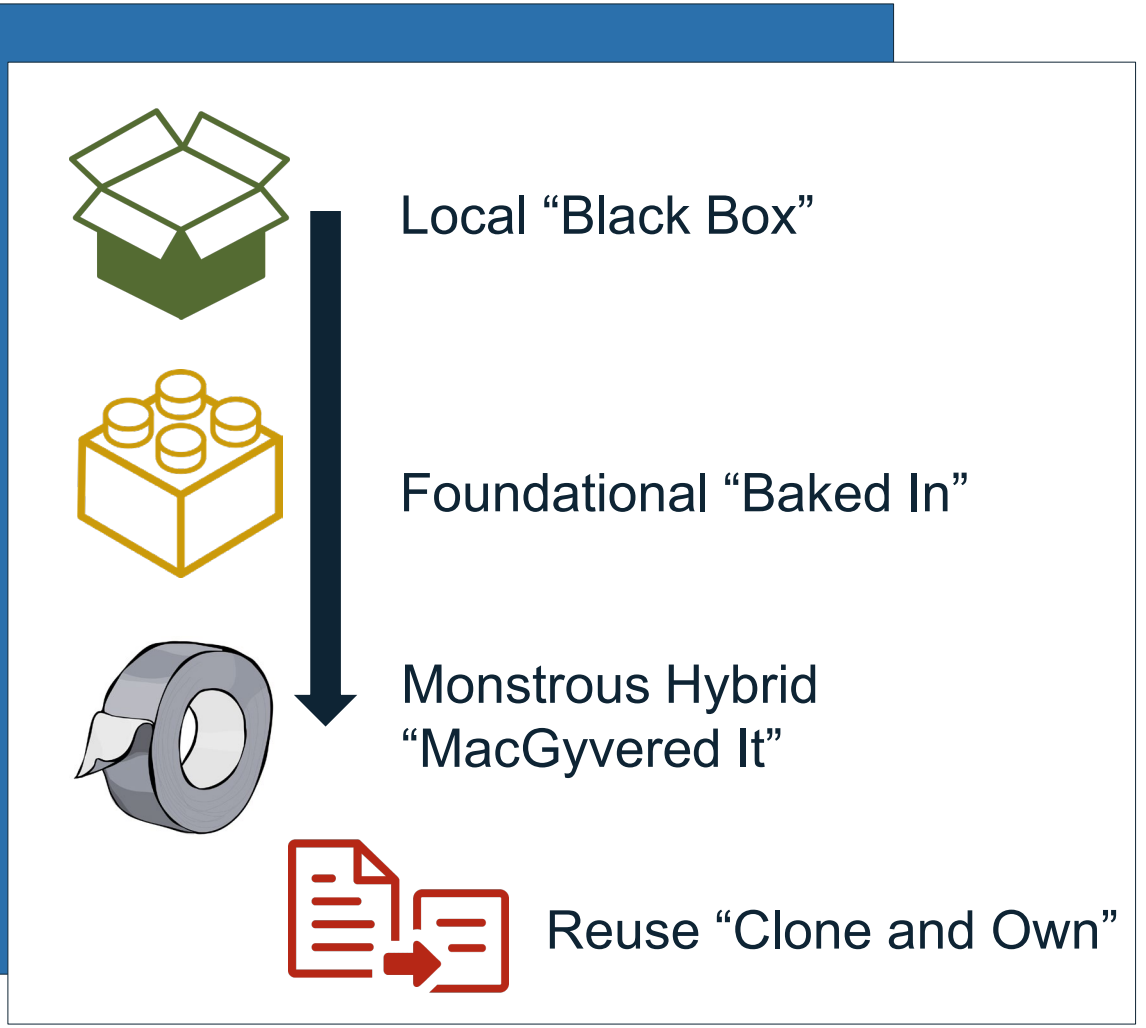
Common Types of Debt





Sources: Clark, 2018; Cognopia, 2024; Ladley, 2020

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Example: Legacy Equipment

Legacy factory equipment can still be highly productive

However, it poses unique challenges to a digital enterprise that desires real-time production data to justify capital expenditures or inform process improvements

Keep it?
Replace it?
Retrofit it?

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New Equipment Solves Some Problems, but Understand Debt

Keep It

Type	Observation
Management Debt	
Supply Chain Debt	
Innovation Debt	
Infrastructure Debt	**Limited remaining useful life**
People Debt	**Have artisan; artisan required**
Process Debt	**Process understood**
Service Debt	
Social Debt	
Production Operation	**Well-understood performance**
Architecture Debt	
Technical Data Package Debt	
Security Debt	**Not connected**
Obsolescence Debt	**Limited access to repair parts**
Design Debt	
User Interface Debt	
Requirement Debt	
Code Debt	
Defect Debt	
Test Debt	
Technology Debt	
Build & Validation Debt	
Data Debt	**Lack of real-time data**
End of Life Debt	**Decommision plan**

Replace It

Type	Observation
Management Debt	
Supply Chain Debt	
Innovation Debt	
Infrastructure Debt	**Extensive remaining useful life**
People Debt	**Training required; lower bar**
Process Debt	**New processes and/or roles**
Service Debt	
Social Debt	
Production Operation	**Must characterize performance**
Architecture Debt	
Technical Data Package Debt	
Security Debt	**Increased attack surface**
Obsolescence Debt	**Warrantied and supported**
Design Debt	
User Interface Debt	
Requirement Debt	
Code Debt	
Defect Debt	
Test Debt	
Technology Debt	
Build & Validation Debt	
Data Debt	**Have data, but now what?**
End of Life Debt	**Must create a plan**

Mitigates debt

Incurs debt

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Key Points

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Solution debt is more holistic than technical debt

Managing solution debt can enhance Industry 4.0 transformation success

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Solution Debt Playbook

Table of Contents

Overview of solution debt
- Traditional definitions
- Common causes
- Solution debt taxonomy with definitions
- Program risk management vs. solution debt

Step 1: Identify current debt
- Identify current program debt
- Characterize debt type

Step 2: Evaluate debt
- Assess impact
- Assess fix cost
- Assess contagion factor
- Assess source and recipient of debt
- Assess who pays / who benefits
- Assess ability to impact
- Determine quadrant for improvement
- Determine structural context

Step 3: Link to program assets
- Link evaluated debt to program and enterprise risks
- Link evaluated debt to guardrails

Step 4: Develop debt reduction plan
- Develop debt reduction activities
- Assess timeline and resourcing
- Document debt reduction plan

Step 5: Execute the debt reduction plan
- Program and enterprise metrics
- P-D-C-A Cycle

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Using Solution Debt Playbook for "Replace It"

Step 1: Identify current debt
- Identify current program debt
- Characterize debt type

Step 2: Evaluate debt
- Assess impact
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Step 5: Execute the debt reduction plan
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Replace It

Type	Observation
Infrastructure Debt	Extensive remaining useful life
People Debt	Training required; lower bar
Process Debt	New processes and/or roles
Production Operation	Must characterize performance
Security Debt	Increased attack surface
Obsolescence Debt	Warrantied and supported
Data Debt	Have data, but now what?
End of Life Debt	Must create a plan

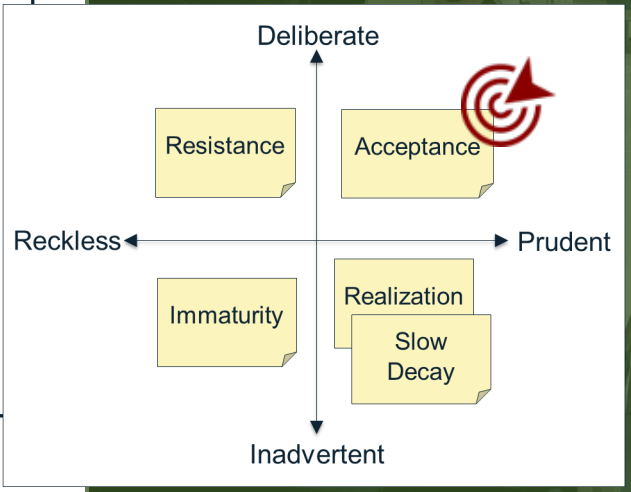
Who pays?
(Directly, Indirectly)
Company

Access Denied?
(No ability to impact
No

Impact 4/5

Fix Cost 3/5

Contagion 3/5



Solution Debt Management – Matrix

Solution Debt Matrix

Source	Debt Type	Observation	Impact	Fix Cost ($K)	Contagion Factor	Who Pays	Access	Quadrant	Risk Link	Guardrail Link	Reduction Plan
Machine XYZ Replacement	Process Debt	New process and roles	3	$250	3	Company	Yes	1			
Machine XYZ Replacement	Security Debt	Increased attack surface	2	$500	4	Company	Yes	1			
Machine XYZ Replacement	End of Life Debt	Must create a plan	3	$50	1	Company	Yes	4			
Machine XYZ Replacement	People Debt	Training required	4	$100	2	Company	Yes	1			
Machine XYZ Replacement	Data Debt	Determine handling of new data	5	$250	5	Company	Yes	1			
PLC 123 Upgrade	Process Debt	New process and roles	3	$20	3	Company	Yes	2			
PLC 123 Upgrade	People Debt	Training required	4	$120	2	Company	Yes	1			
PLC 123 Upgrade	Security Debt	Increased attack surface	2	$400	4	Company	Yes	3			

Solution Debt Matrix Tracks Playbook Information

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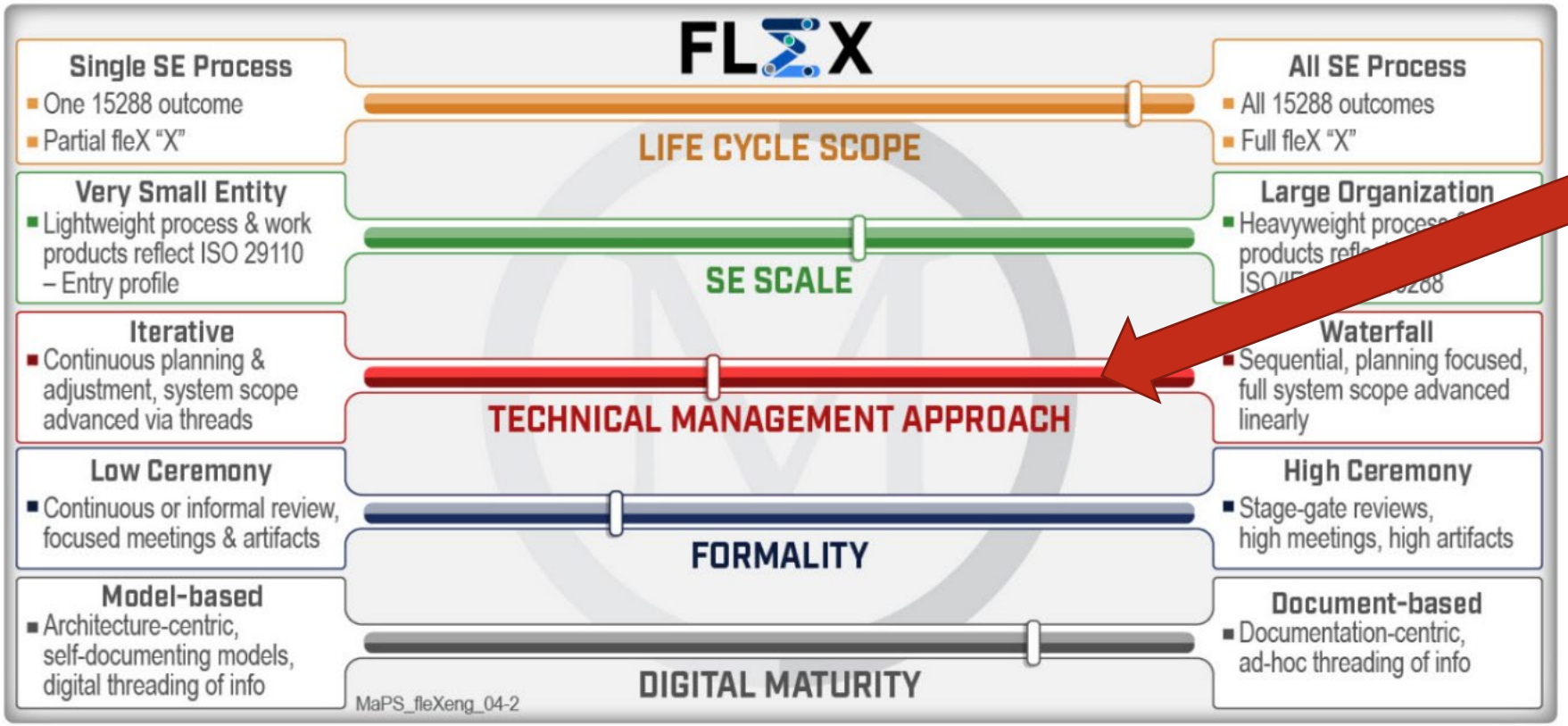
Solution Debt Management Implementation Example for flex-engineering®



Solution debt integrated in technical management approach

Example Embedding Solution Debt in Process Definition

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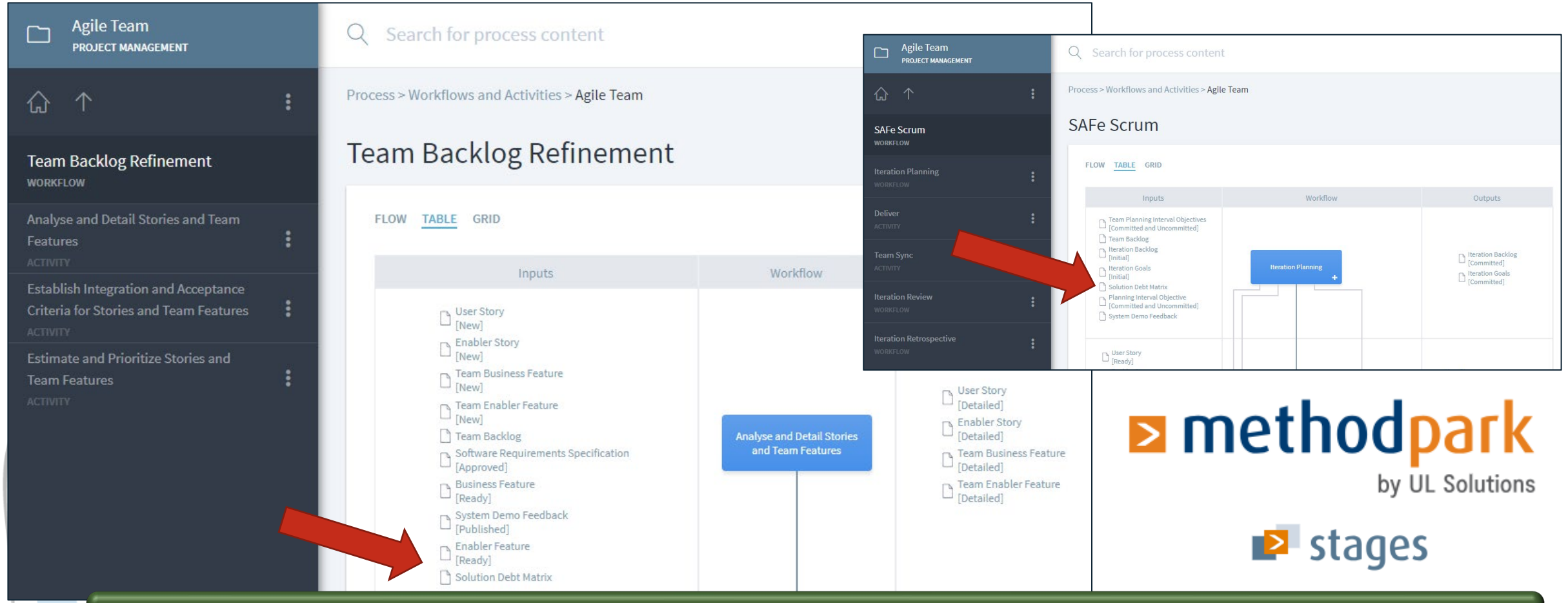
Solution Debt Management Implementation Example for Scaled Agile Framework (SAFe)



For SAFe, Utilize Solution Debt Matrix in Backlog Refinement

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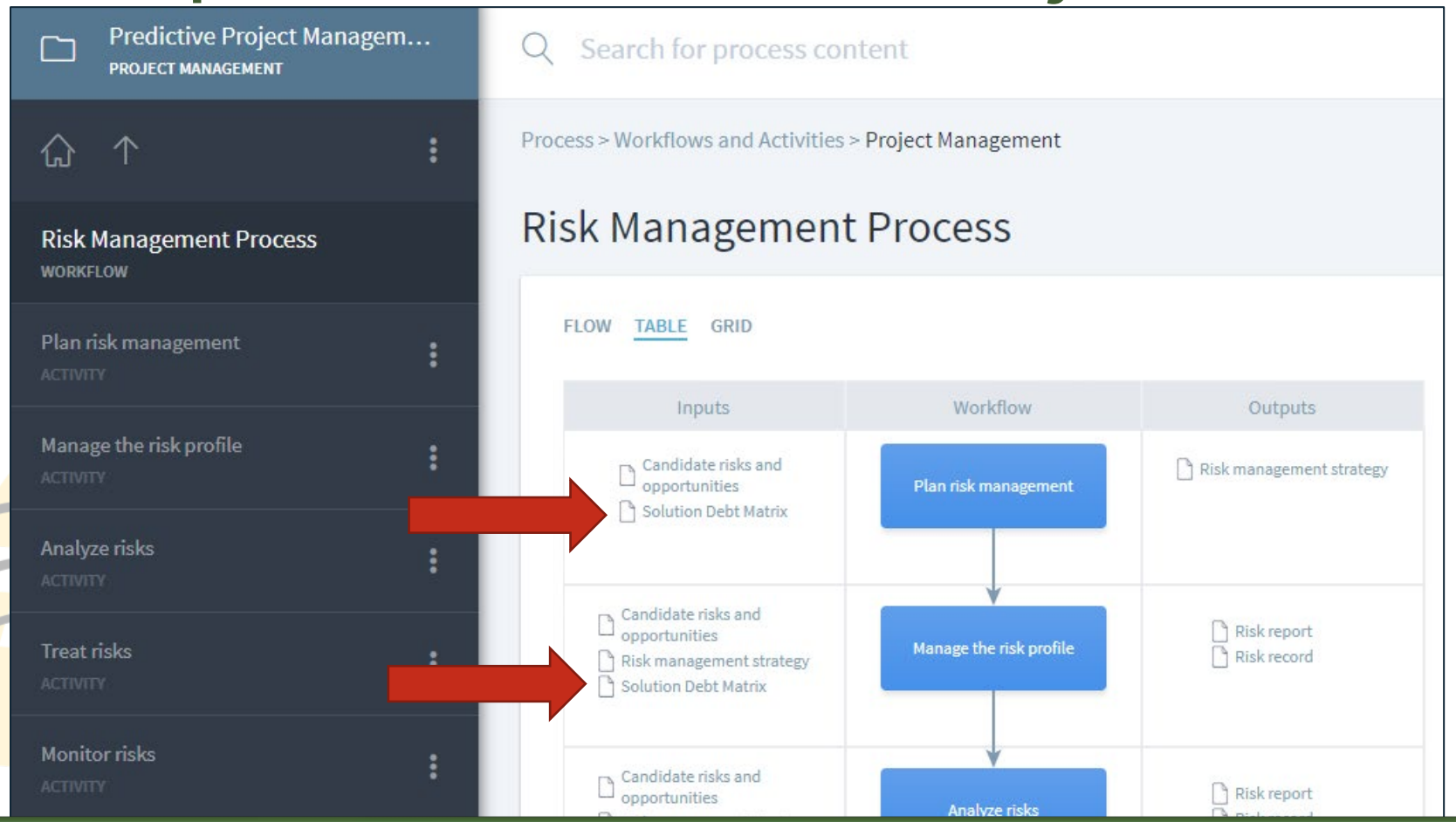
Solution Debt Management Implementation, Example for Predictive Project Management



methodpark by UL Solutions

stages

For Predictive PM, Utilize Solution Debt Matrix in Risk Management

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Solution Debt Management Aids Industry 4.0

- Holistic characterization of debt
- Structure to systematically address solution debt
- Solution debt resolution embedded in execution

Active Management of Solution Debt Can Aid Industry 4.0 Transformation

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Call to Action: Consider Managing Solution Debt in System Development

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Thank you!

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