34th Annual INCOSE international symposium

hybrid event

Dublin, Ireland
July 2 - 6, 2024

Takaharu Igarashi & Dr. Karen Marais
Purdue University

Lifecycle of Accident Pathogens: Common Systemic Factors in Construction System Accidents

Constructed systems everywhere

Quality defect

Structural failure

can fail in many ways

Malfunctioning

Uncontrolled release of energy

Construction system

A sociotechnical system that produces constructed systems

National Transportation Safety Board (2008) Collapse of I-35W Highway Bridge, Minneapolis, Minnesota, August 1, 2007. *Highway Accident Report*.

Built-in defects in construction system accidents

Accident

An unplanned and undesired event resulting in an unacceptable loss

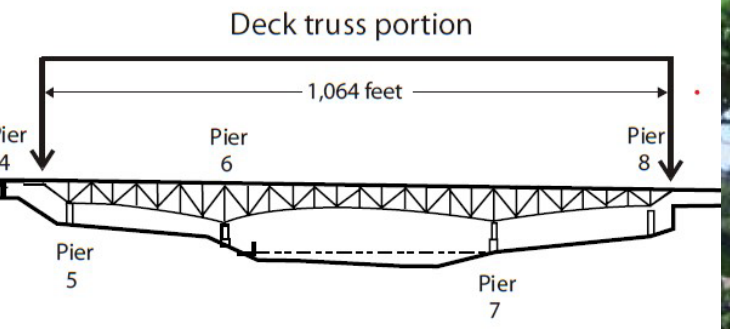
National Transportation Safety Board (2007) Ceiling Collapse in the Interstate 90 Connector Tunnel, Boston, Massachusetts, July 10, 2006. *Highway Accident Report*.

National Transportation Safety Board (2008) Collapse of I-35W Highway Bridge, Minneapolis, Minnesota, August 1, 2007. *Highway Accident Report*.

Latent failures = “Resident pathogens”
Built-in defects = “Embedded pathogens”

Reason, J. (1990). The contribution of latent human failures to the breakdown of complex systems. *Philosophical Transactions of the Royal Society of London. Series B*, *327*(1241), 475–484.

National Transportation Safety Board (2007) Ceiling Collapse in the Interstate 90 Connector Tunnel, Boston, Massachusetts, July 10, 2006. *Highway Accident Report*.



NTSB (2008)

NTSB (2008)

NTSB (2008)

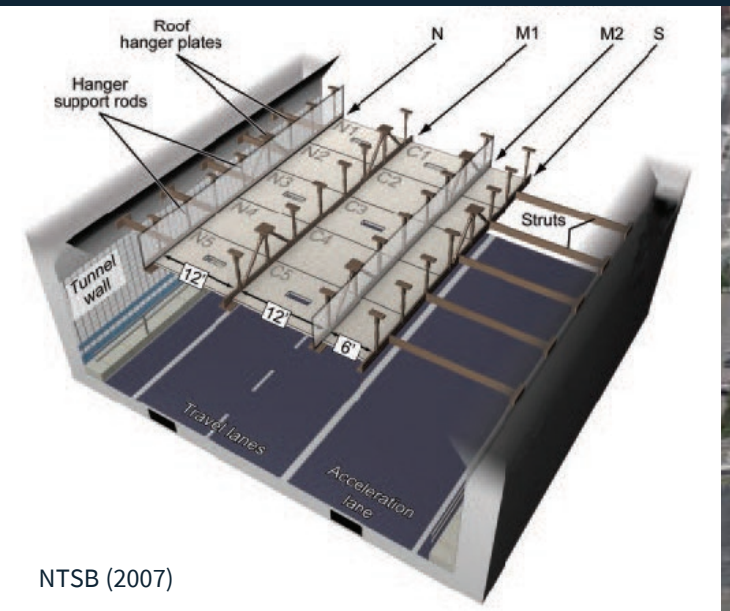
1967 ····· 2007

Build

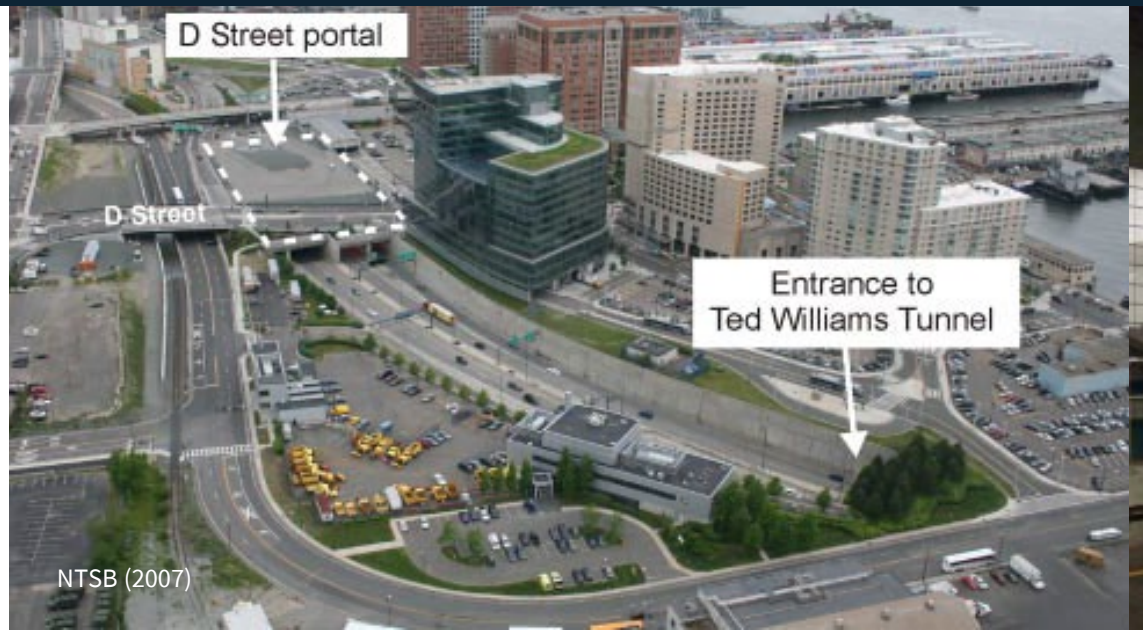
Operate

Accident

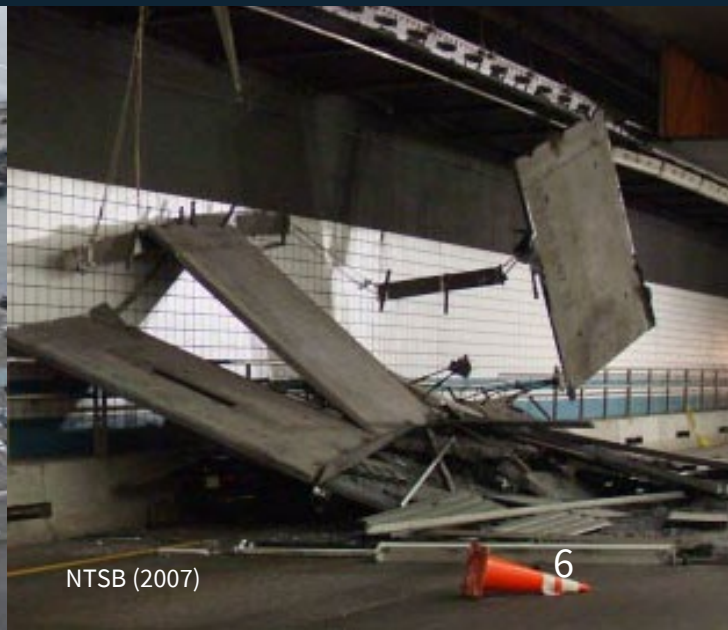
2000 ····· 2006



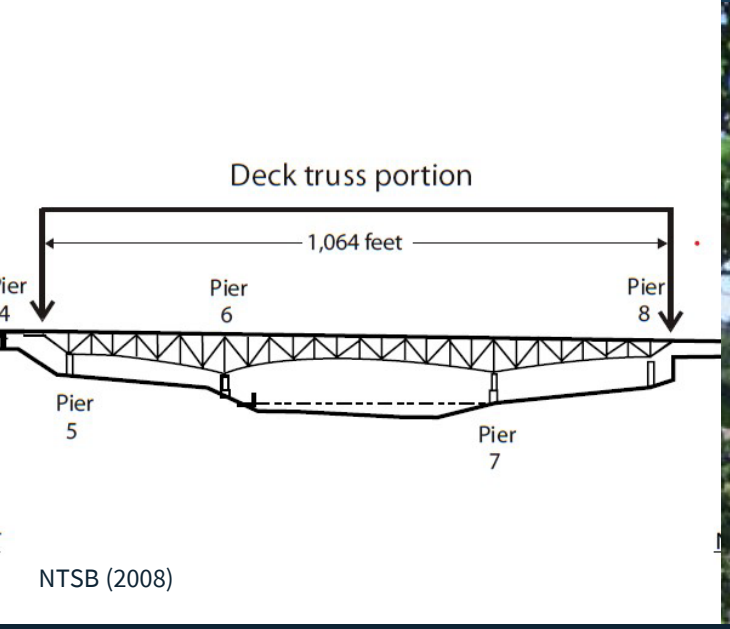
NTSB (2007)



NTSB (2007)



NTSB (2007)



NTSB (2008)

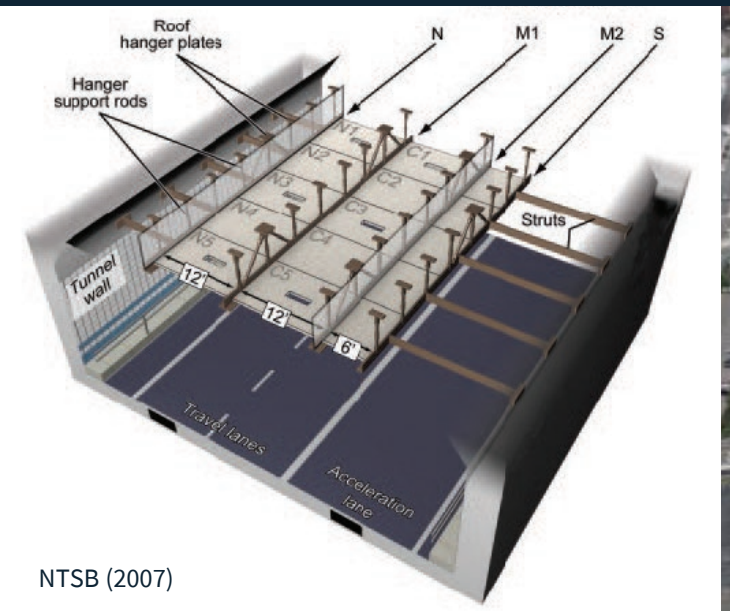
NTSB (2008)

NTSB (2008)

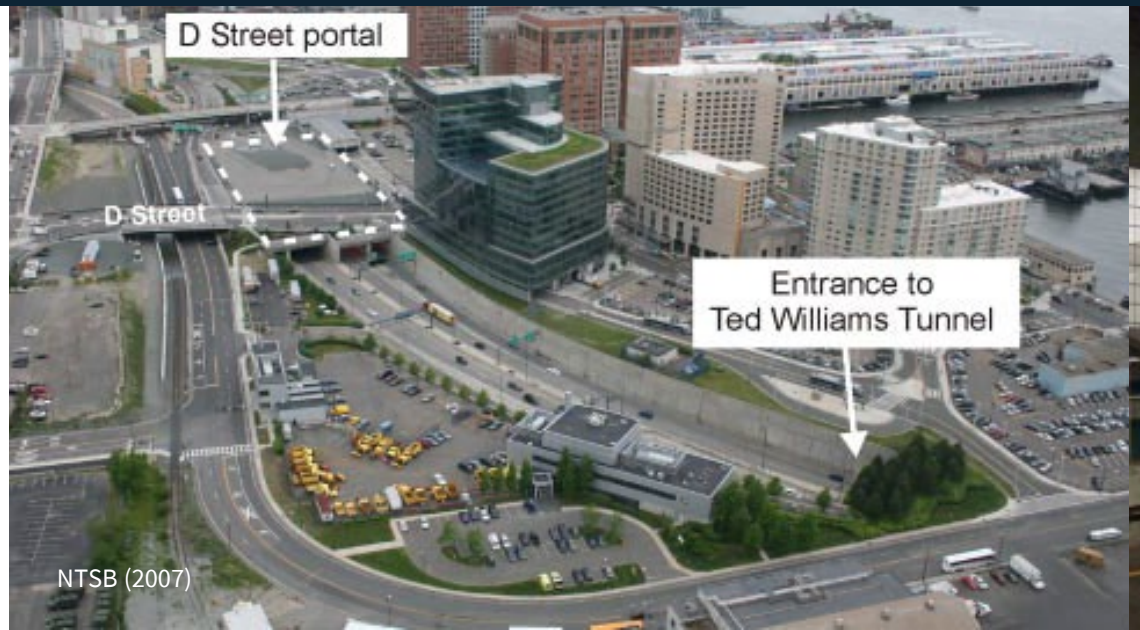
1967 ····· 2007

Embedded pathogens persisting through variable time spans

2000 ····· 2006



NTSB (2007)



NTSB (2007)

NTSB (2007)

Difficulty of applying systems engineering

INCOSE Infrastructure Working Group (2012) Guide for the Application of Systems Engineering in Large Infrastructure Projects.

Complexity, dynamism, and ephemerality of construction project organizations

Difficulty of applying safety management concepts

Harvey, E. J., Waterson, P., & Dainty, A. R. J. (2019). Applying HRO and resilience engineering to construction: Barriers and opportunities. *Safety Science*, 117, 523–533.

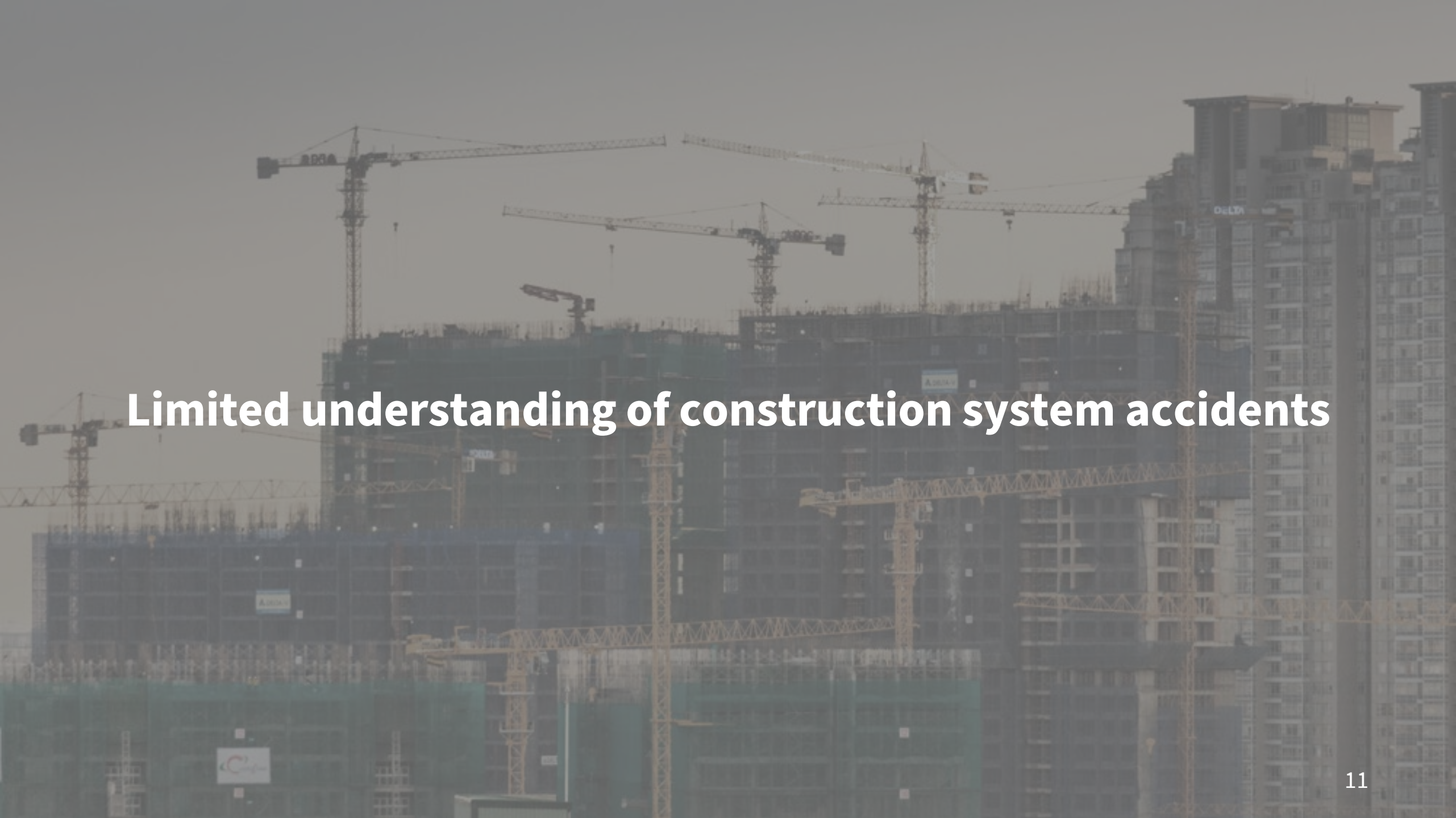
Limited applications of systems perspective in the construction safety literature

Woolley, M. J., Goode, N., Read, G. J. M., & Salmon, P. M. (2019). Have we reached the organisational ceiling? a review of applied accident causation models, methods and contributing factors in construction. *Theoretical Issues in Ergonomics Science*, *20*(5), 533–555.

Perspectives and frameworks
in the system safety literature
(aviation, nuclear, etc.)
unfit for construction systems

Accident causation models

- Abstractions of how accidents occur
- Underlie views on accidents in reports, investigations, and analyses



Limited understanding of construction system accidents

Research objective

Use an accident model tailored to construction systems

Identify common patterns in the lifecycles of “accident pathogens”

Devise a systems-based framework to understand the underlying mechanisms of construction system accidents

Outline

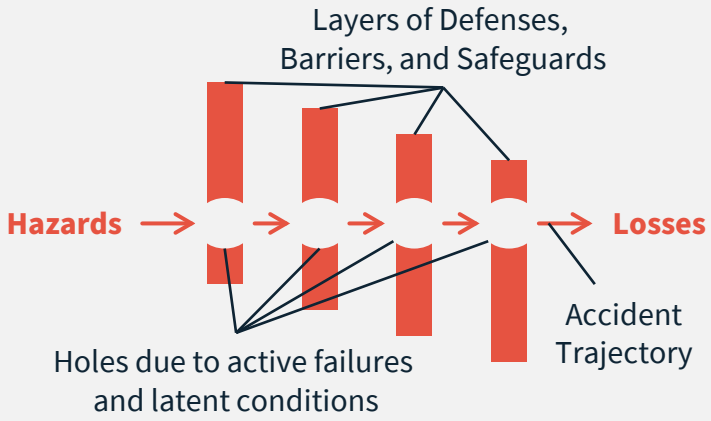
- The accident causation model
- Sample accident cases
- Model application results
- Discussion & conclusion

Outline

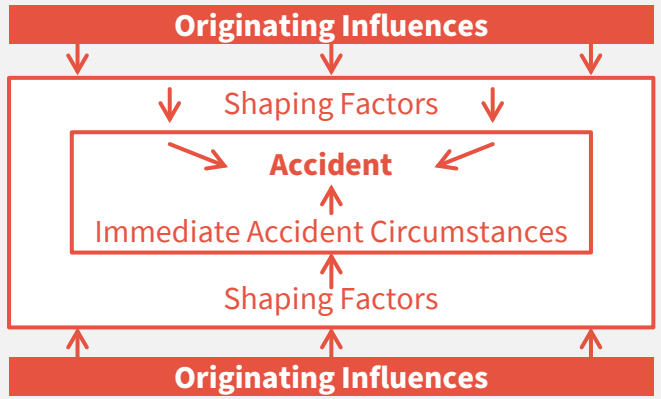
- **The accident causation model**
- Sample accident cases
- Model application results
- Discussion & conclusion

Existing accident causation models

Single direction



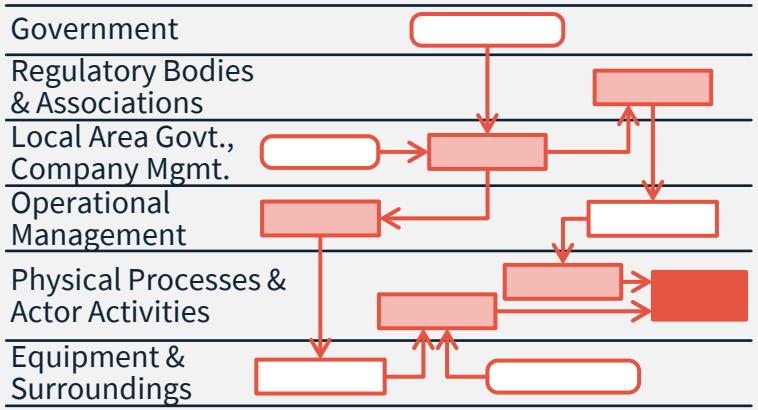
Swiss Cheese Model



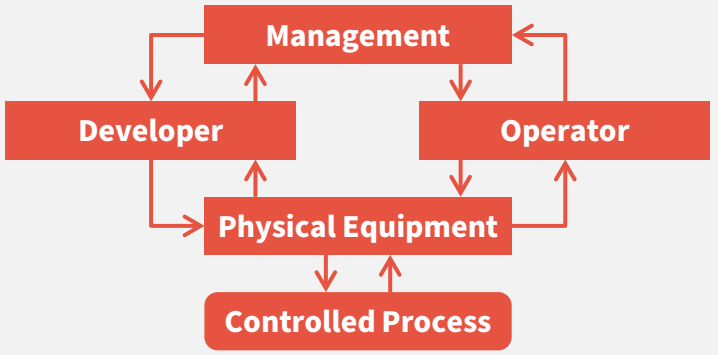
ConAC

(Construction Accident Causation model)

Hierarchical



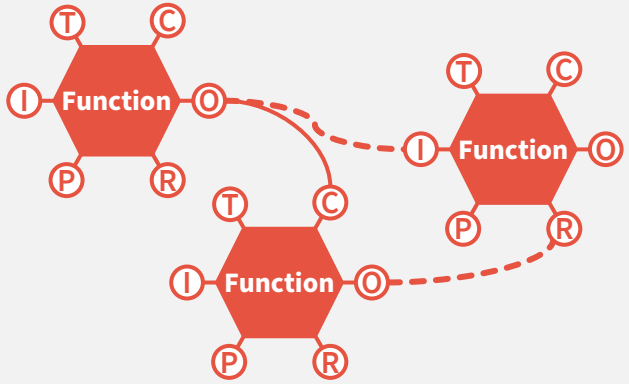
AcciMap



STAMP

(Systems Theoretic Accident Model and Processes)

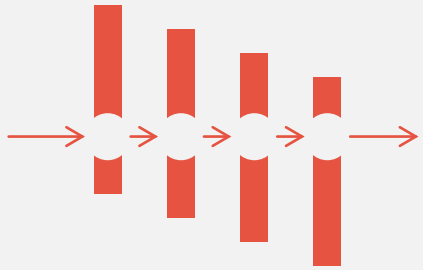
Network graph



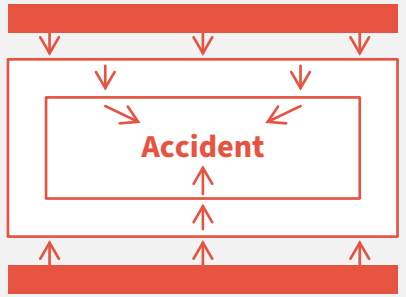
FRAM

(Functional Resonance Analysis Method)

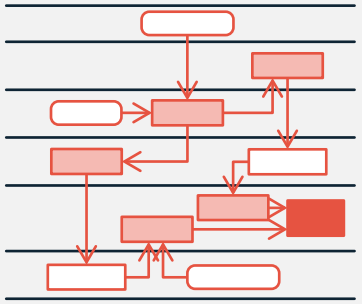
Existing accident causation models



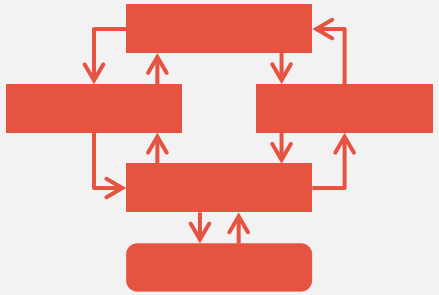
Swiss Cheese Model



ConAC



AcciMap



STAMP

FRAM

Time dimension

Dynamic organizational network structure

Project-based coalition of temporary multi-organizations

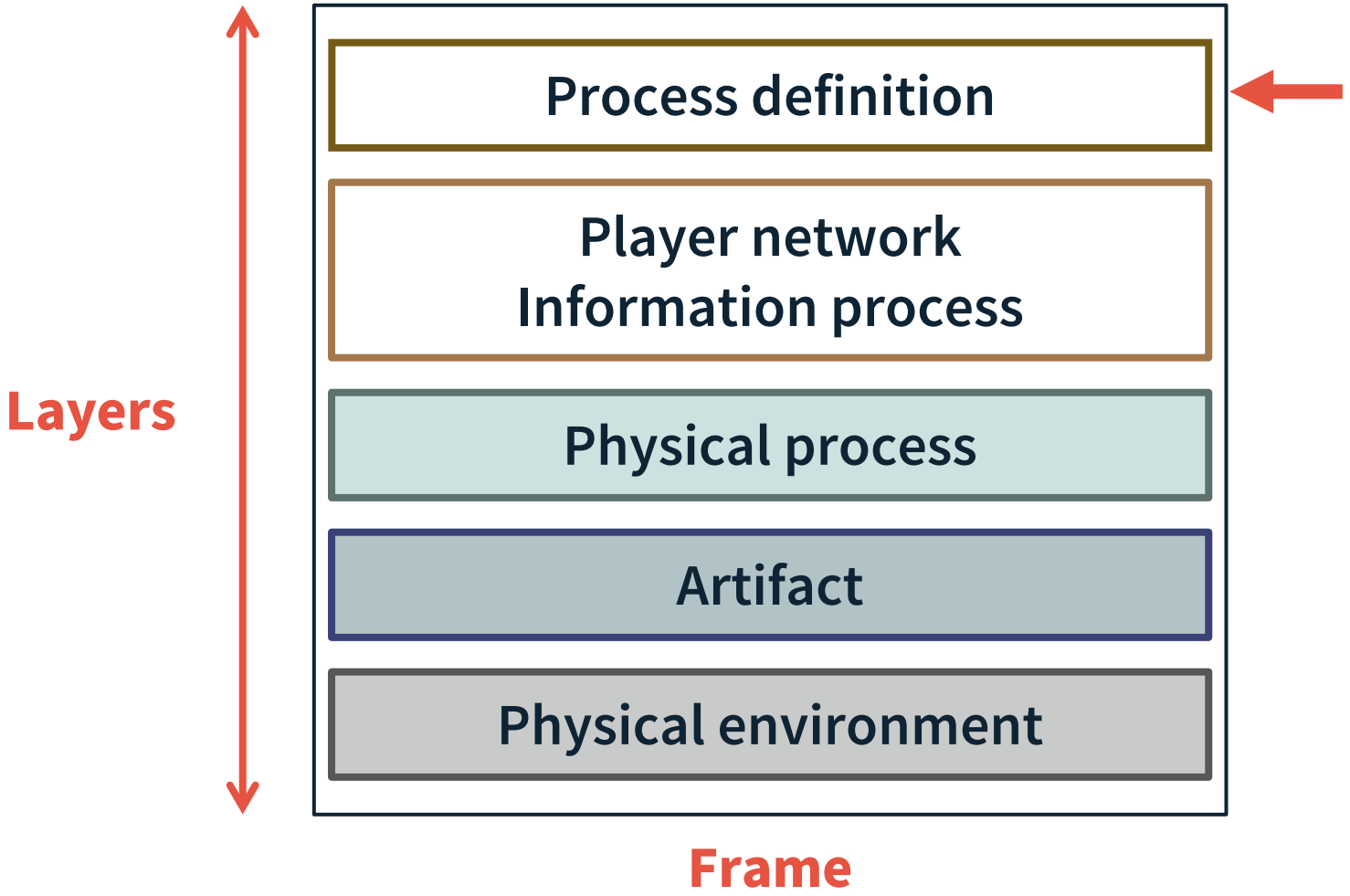
Embedded pathogens persisting over time

Inspection and maintenance work failing to remove the pathogen

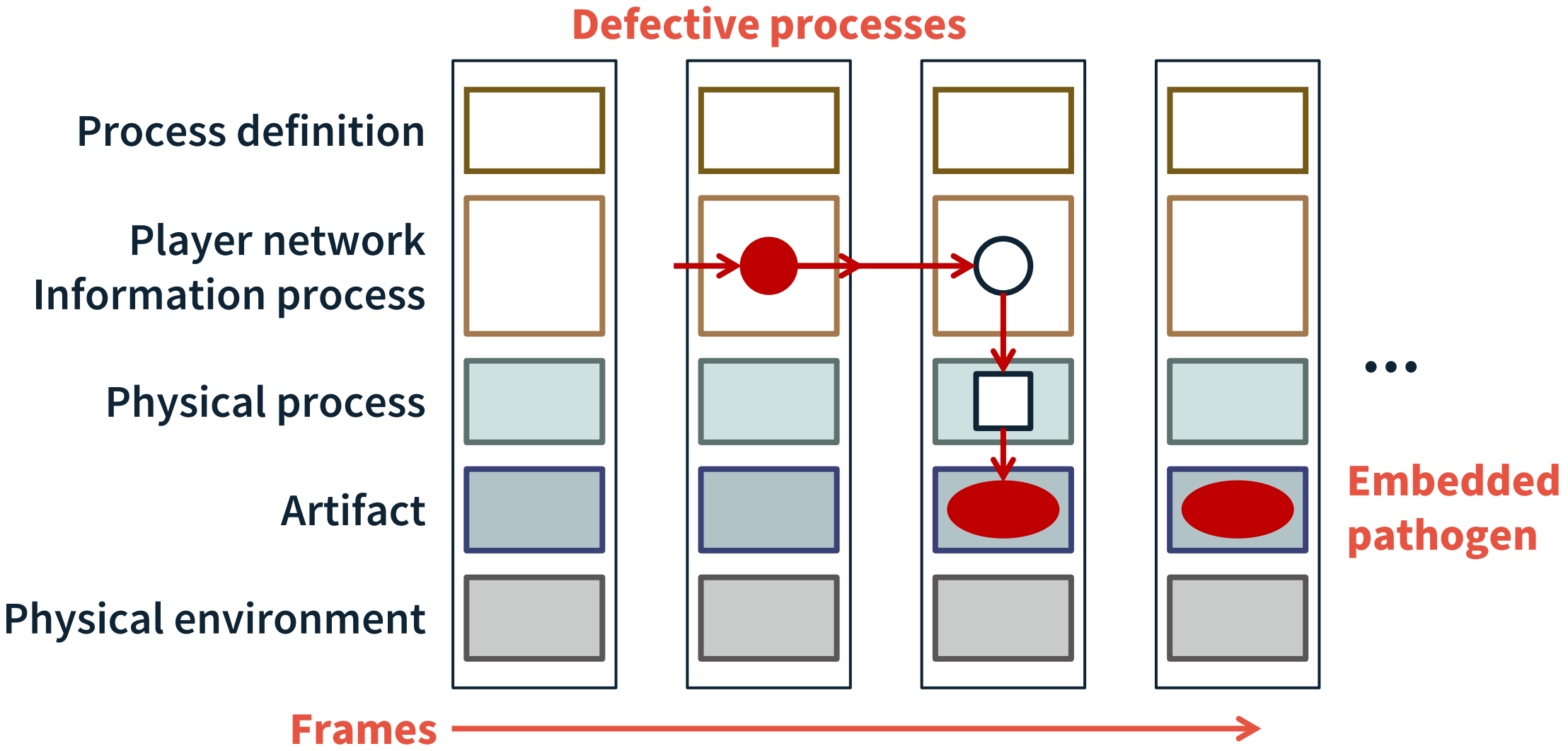
Permanent vs. temporary quality control structure

Regulatory/industrial standards vs. project-specific specifications

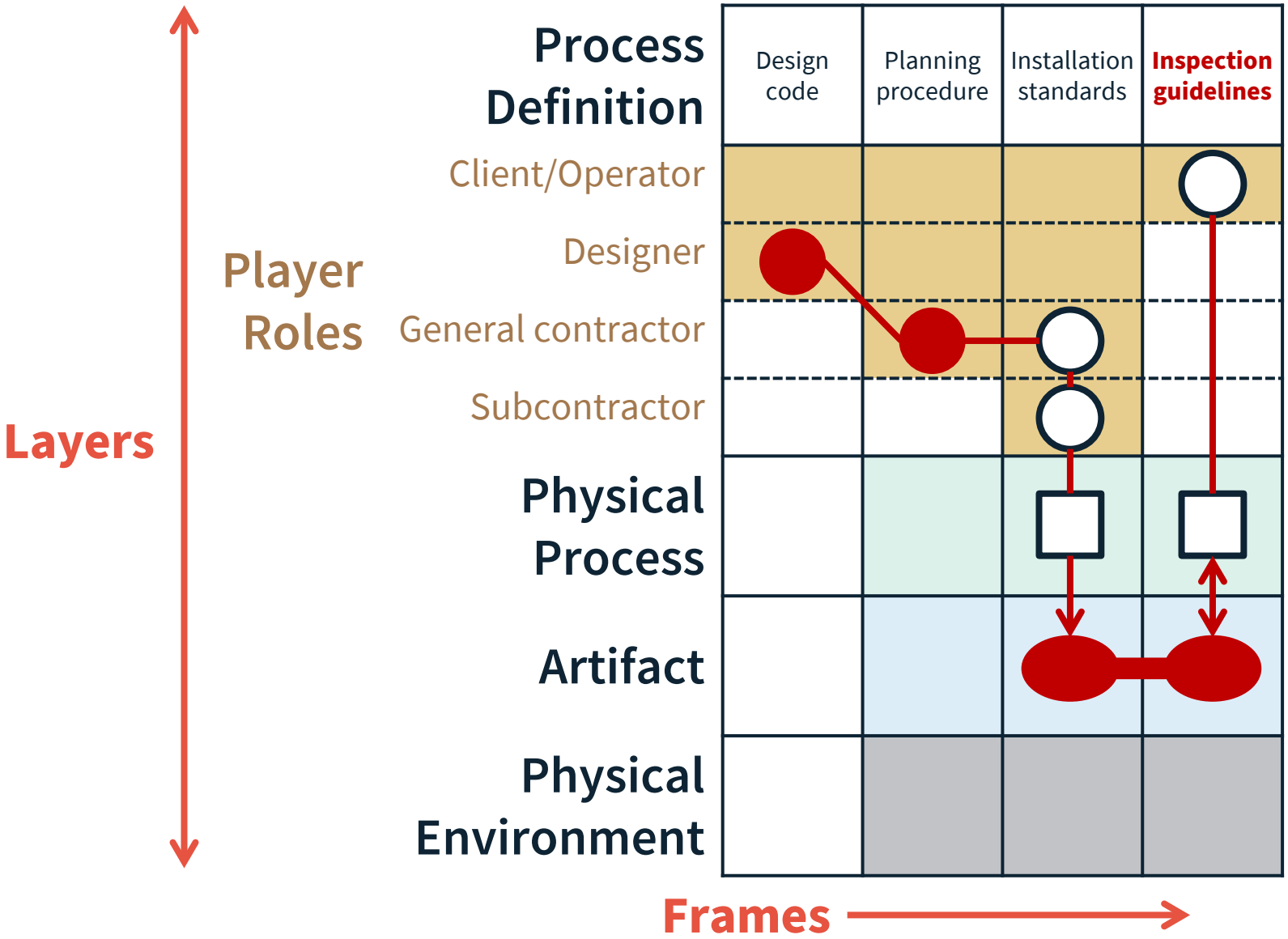
Framed-and-layered accident pathogen propagation model (FLAPP model)



Framed-and-layered accident pathogen propagation model (FLAPP model)



FLAPP Matrix



Inspection guidelines **Inadequate definition**

Incorrect process execution

Wrong input executed correctly

Installation of inadequate design

Embedded pathogen

Inadequate feedback

FLAPP Matrix demonstration

Sasago Tunnel ceiling collapse

MILT Japan (2013) *Report of the Research & Examination Committee for Tunnel Ceiling Collapse Incident* [Japanese].

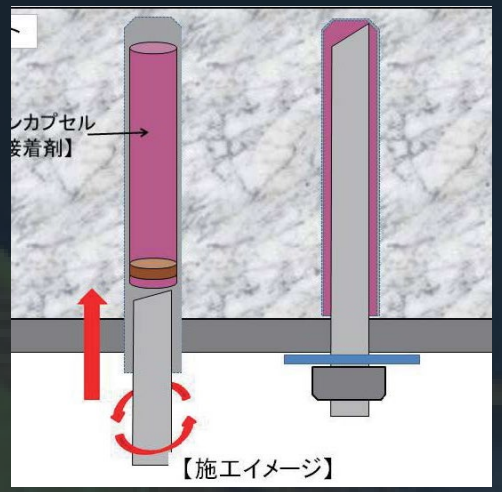
Sasago Tunnel ceiling collapse

Yamanashi, Japan

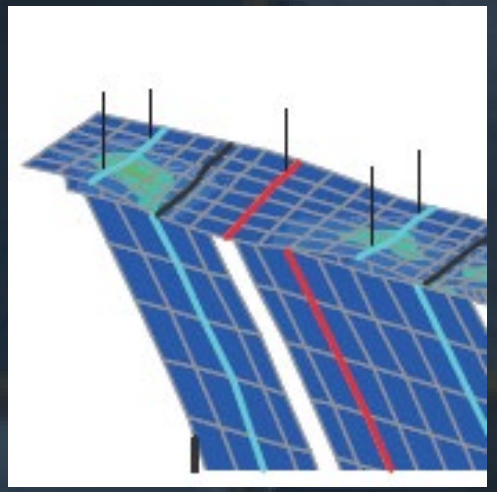
Completed & opened to traffic in 1977

A 130-m section of ceiling panels collapsed on December 2, 2012

9 fatalities, 2 injuries



Degradation of anchor bolt adhesives



Calculation error of load distribution

No acoustic inspection for >10 years

MILT Japan (2013) *Report of the Research & Examination Committee for Tunnel Ceiling Collapse Incident* [Japanese].

Sasago Tunnel ceiling collapse

FLAPP Matrix

Layers

Player Roles

Phase	Plan	Design	Constr.	Comm.	Op.
	1967-70	1970-74	1976-77	1977	1977-2012
Process Definition					
Client/Operator	■	■	■	■	■
Designer		■	■	■	
General contractor		■	■	■	
Subcontractor			■		
Anchor bolt supplier		■			
Maintainer					■
Physical Process					
Artifact					
Physical Environment			Sasago Pass underground	Sasago Pass underground	Sasago Pass underground

Project phases

- Planning
- Design
- Construction
- Commissioning
- Operation

Participating player

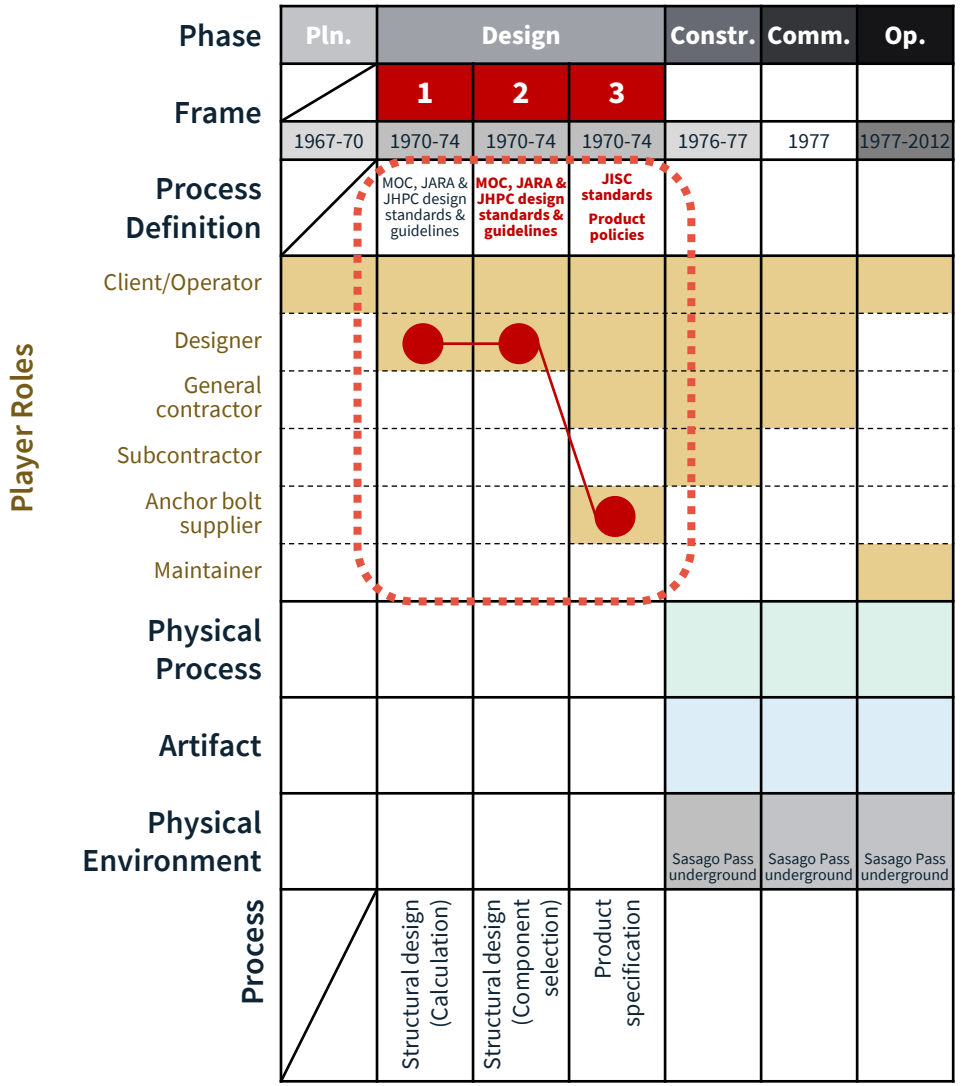
■ Active player

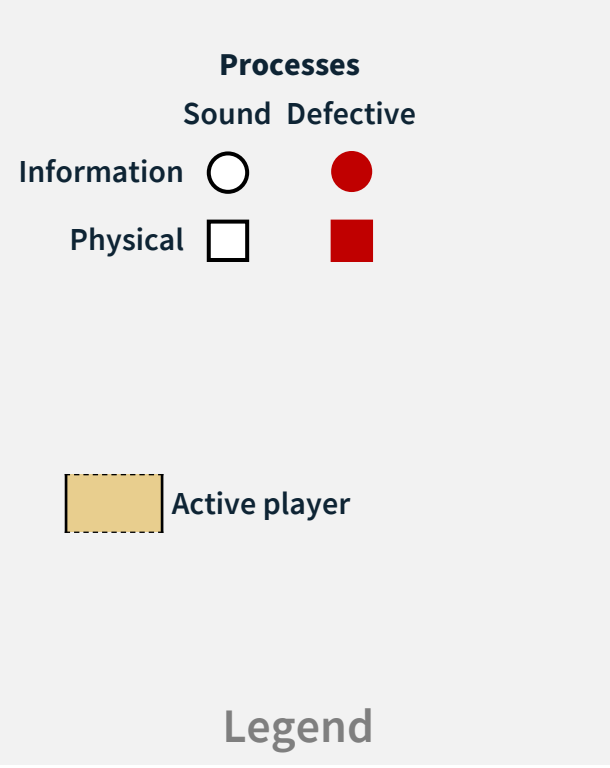
Legend

MILT Japan (2013) *Report of the Research & Examination Committee for Tunnel Ceiling Collapse Incident* [Japanese].

Sasago Tunnel ceiling collapse

FLAPP Matrix





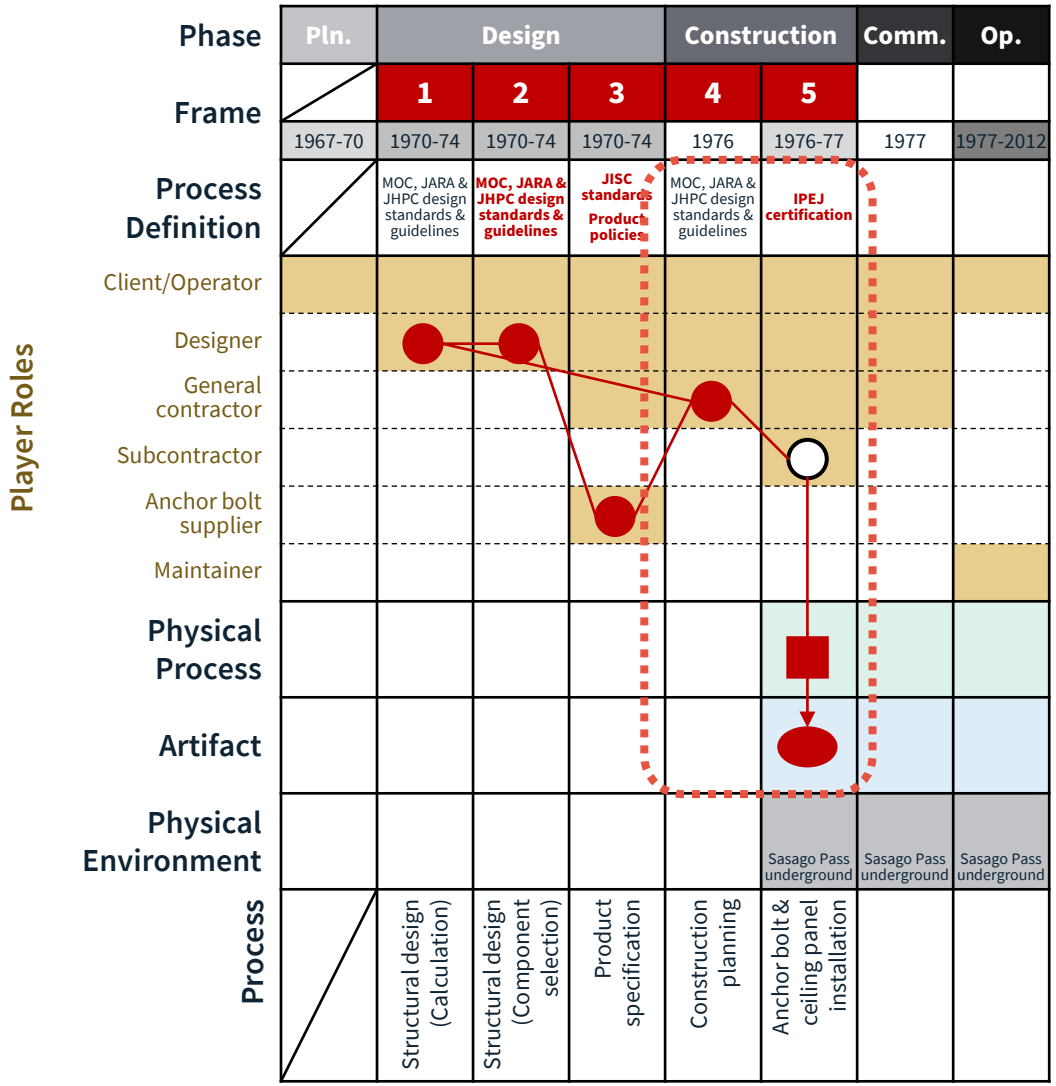
Inadequate structural design

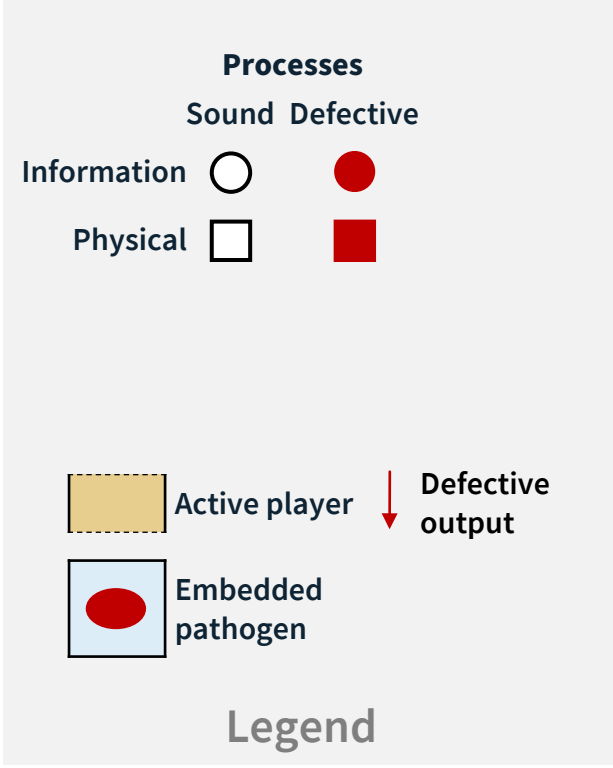
- Structural calculation
- Choice of product
- Product specifications
- Product quality standards

MILT Japan (2013) *Report of the Research & Examination Committee for Tunnel Ceiling Collapse Incident* [Japanese].

Sasago Tunnel ceiling collapse

FLAPP Matrix





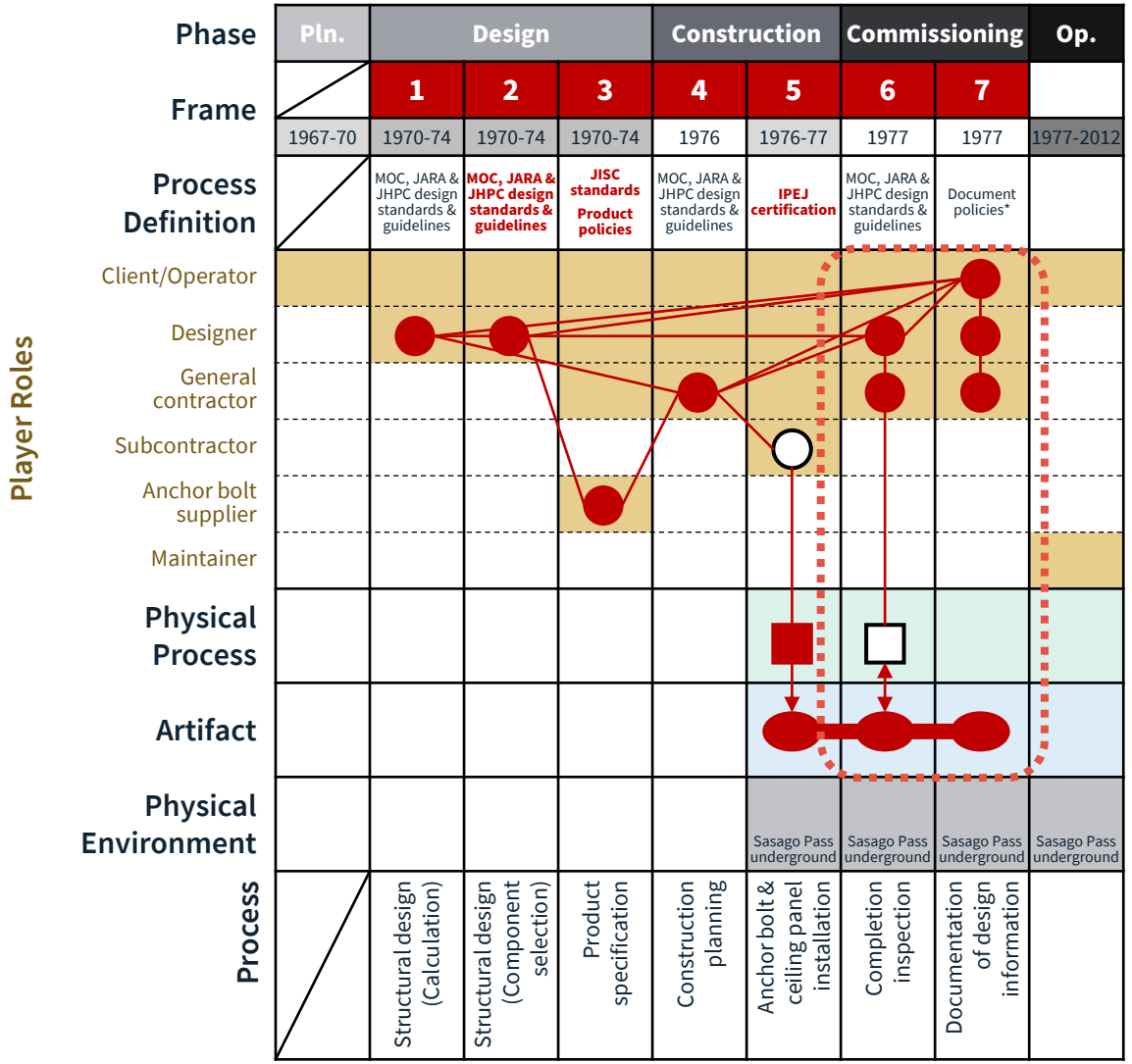
Inadequate anchor bolt installation

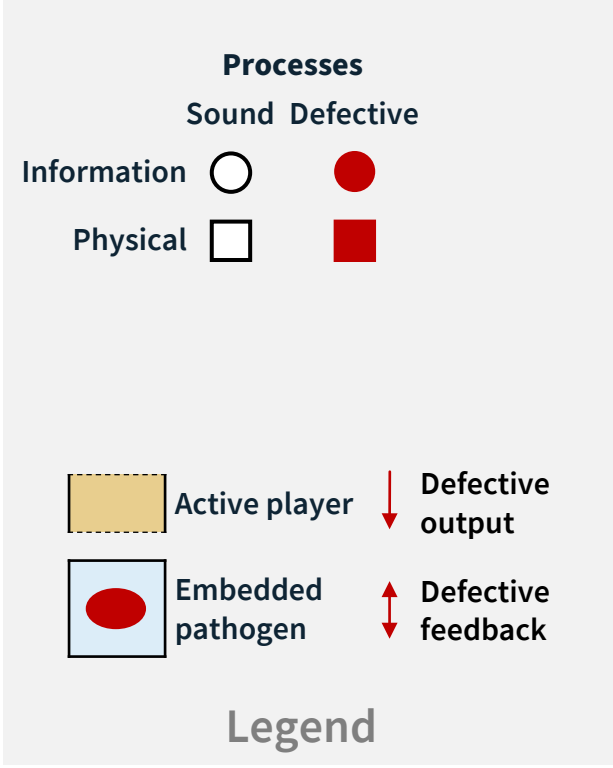
- Procedure specification
- Installation quality
- Ceiling panels installed as designed

MILT Japan (2013) *Report of the Research & Examination Committee for Tunnel Ceiling Collapse Incident* [Japanese].

Sasago Tunnel ceiling collapse

FLAPP Matrix





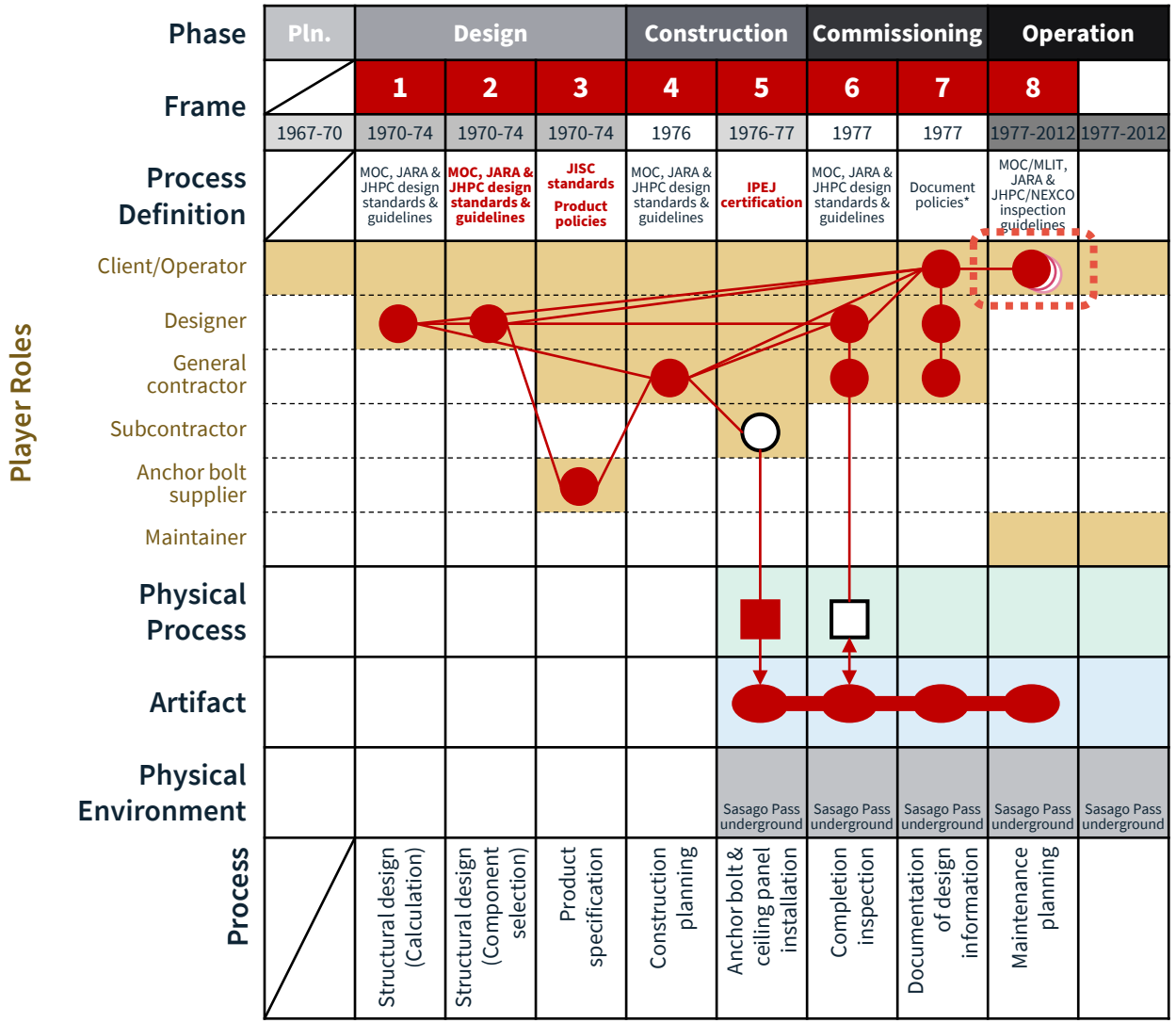
Inadequate commissioning

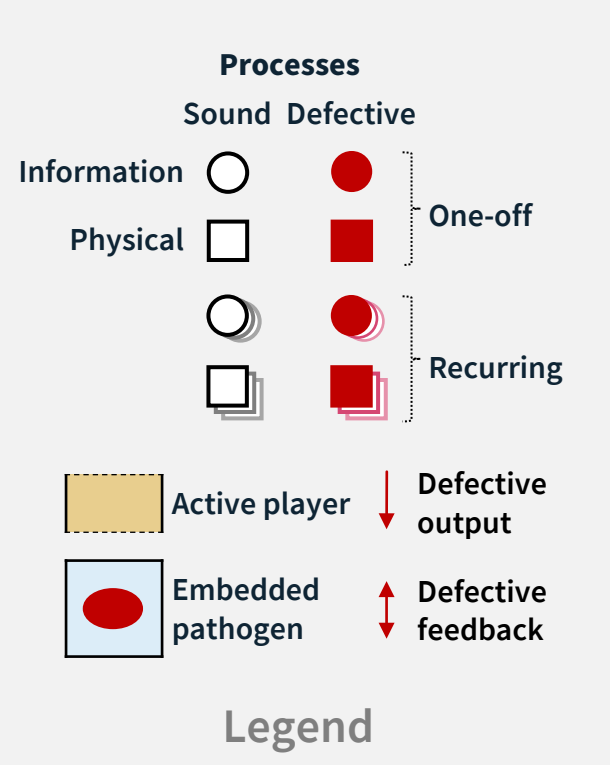
- Completion inspection
- Documentation

MILT Japan (2013) *Report of the Research & Examination Committee for Tunnel Ceiling Collapse Incident* [Japanese].

Sasago Tunnel ceiling collapse

FLAPP Matrix





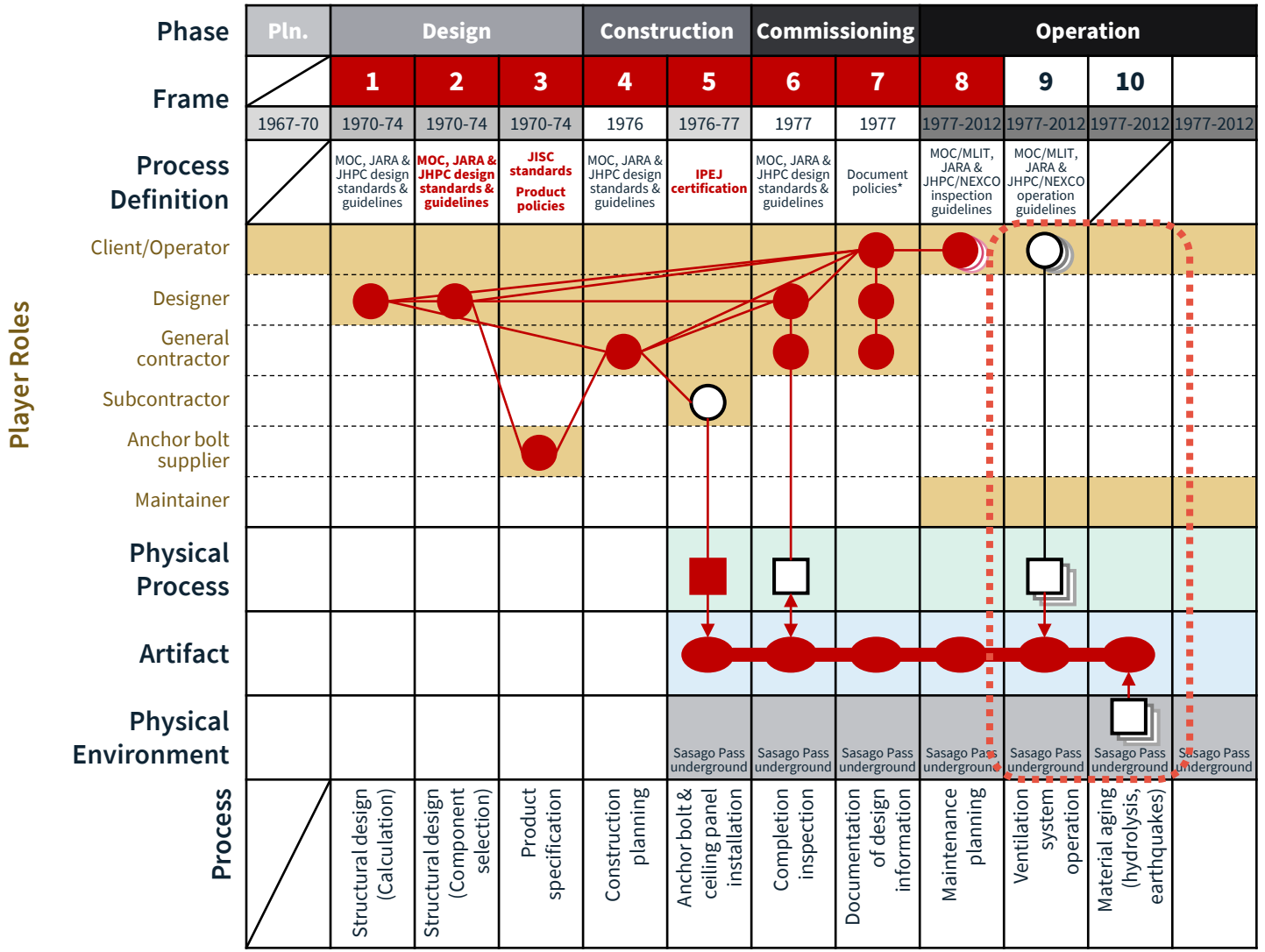
Inadequate maintenance planning

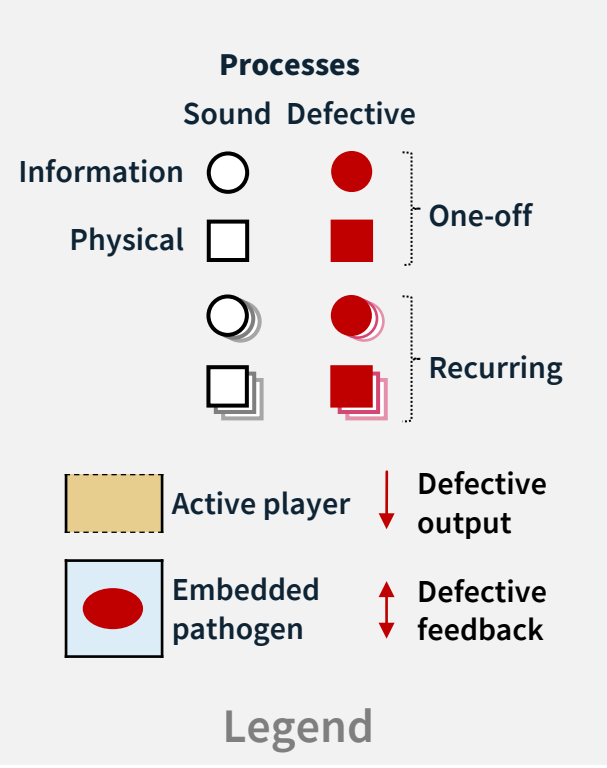
- Inspection & repair history
- Recurring process

MILT Japan (2013) *Report of the Research & Examination Committee for Tunnel Ceiling Collapse Incident* [Japanese].

Sasago Tunnel ceiling collapse

FLAPP Matrix





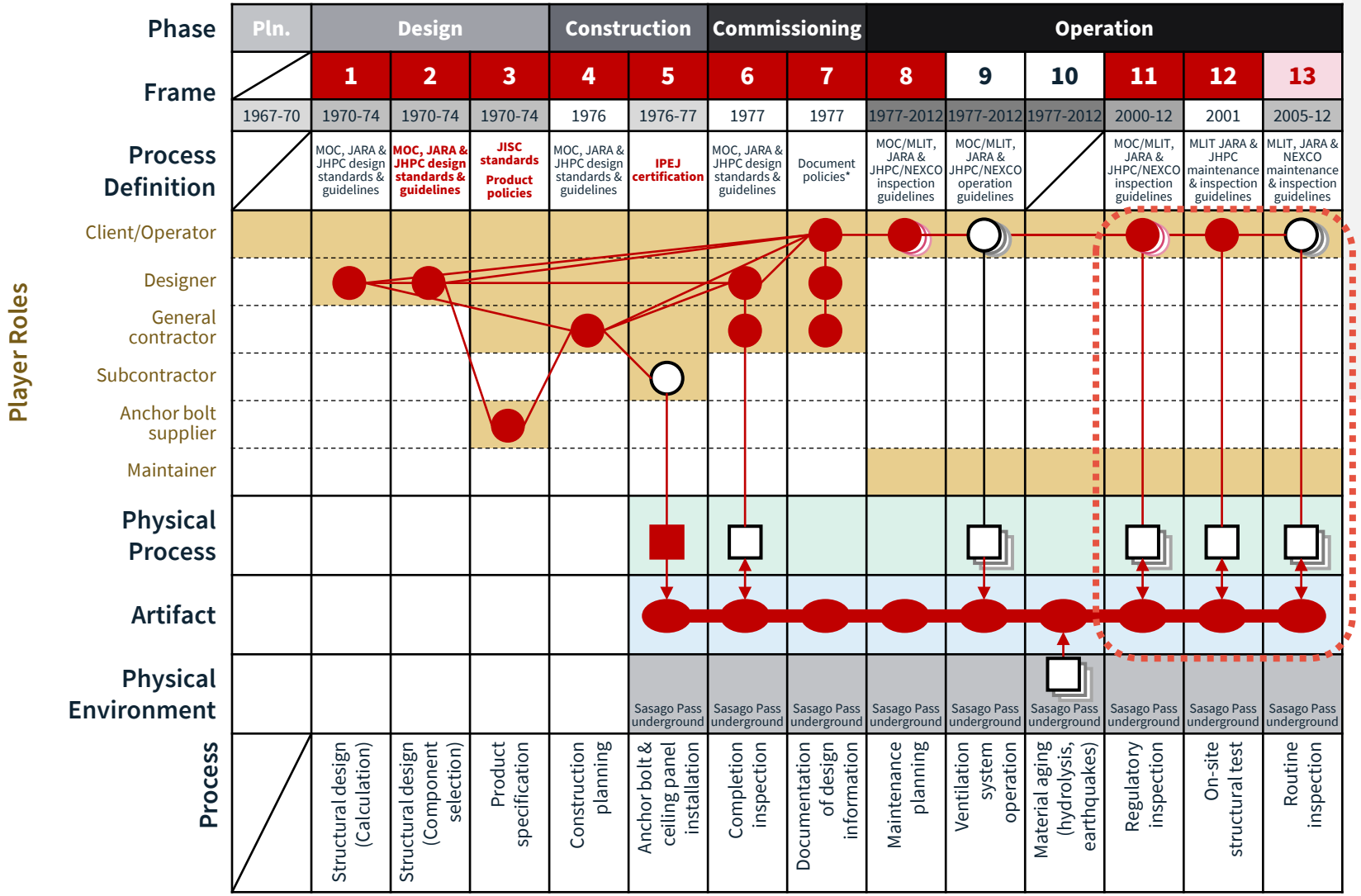
Normal tunnel operation

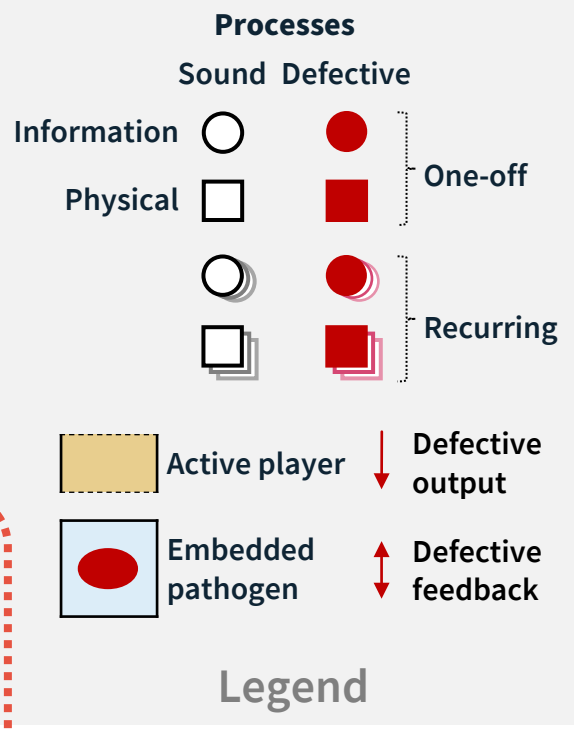
- Ventilation system
- Natural material aging

MILT Japan (2013) *Report of the Research & Examination Committee for Tunnel Ceiling Collapse Incident* [Japanese].

Sasago Tunnel ceiling collapse

FLAPP Matrix





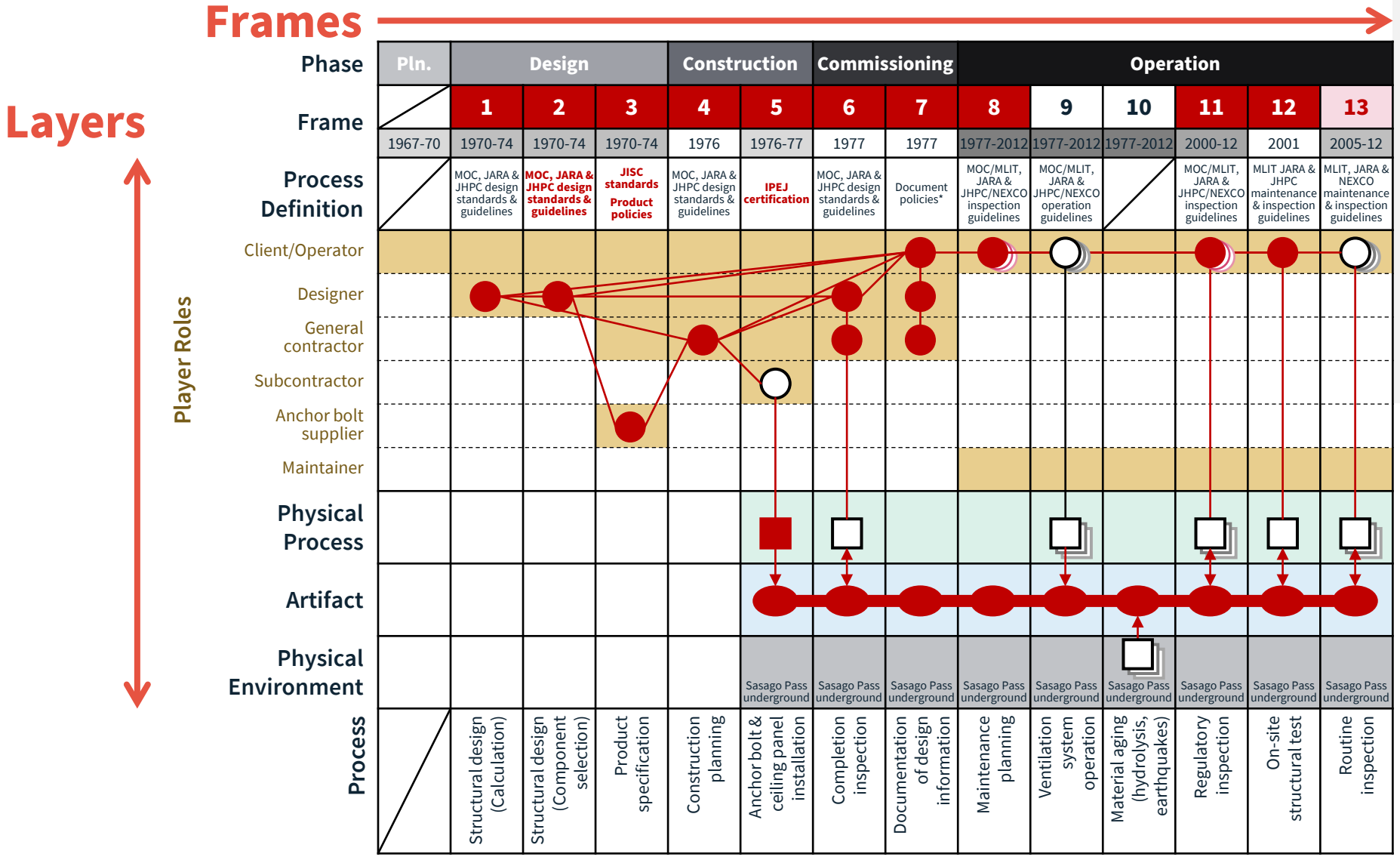
Insufficient testing & inspections

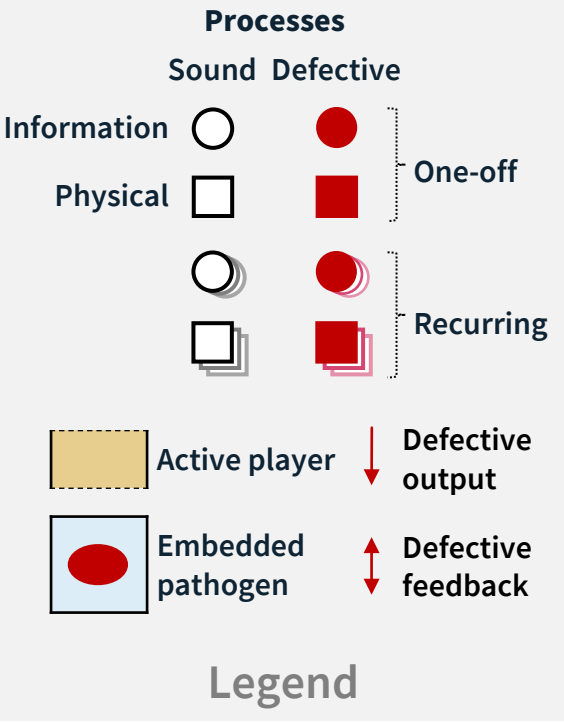
- Routine inspections
- On-site pull-out testing

MILT Japan (2013) *Report of the Research & Examination Committee for Tunnel Ceiling Collapse Incident* [Japanese].

Sasago Tunnel ceiling collapse

FLAPP Matrix





MILT Japan (2013) *Report of the Research & Examination Committee for Tunnel Ceiling Collapse Incident* [Japanese].

Outline

- FLAPP model
- **Sample cases of construction system accidents**
- Model application results
- Discussion & conclusion

Publicly available & detailed documentation

A sample set of accident cases

Cases with high public attention

→ Cases with significant consequences

Kings Bridge collapse

1961-1962

Melbourne, Australia

Arecibo Telescope collapse

1963-2020

Puerto Rico, United States

Minneapolis I-35W highway bridge collapse

1967-2007

Minneapolis, United States

Structural failures

Sasago Tunnel ceiling collapse

1977-2012

Yamanashi, Japan

Kansas City Hyatt Regency walkway bridge collapse

1980-1981

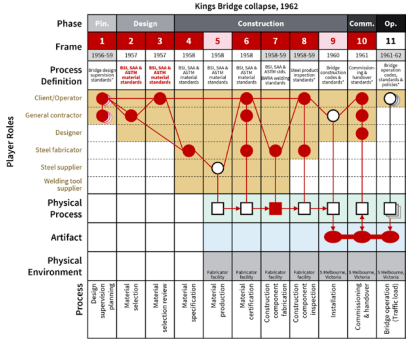
Kansas City, United States

Algo Centre Mall roof collapse

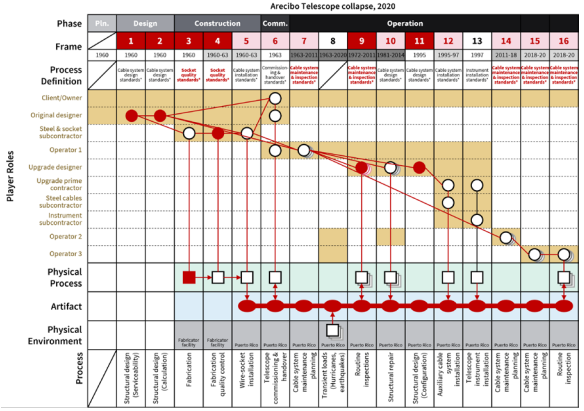
1980-2012

Elliot Lake, Canada

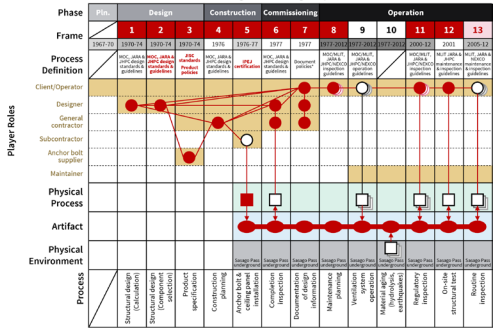
Kings Bridge collapse
1961-1962



Arecibo Telescope collapse
1963-2020

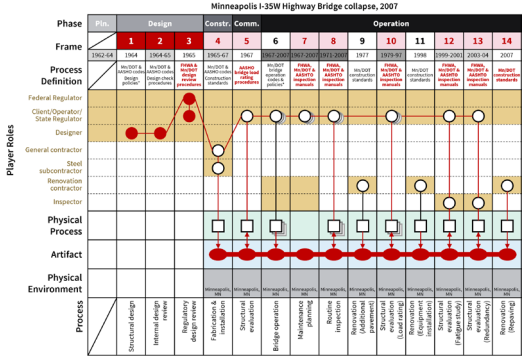


Minneapolis I-35W highway bridge collapse
1967-2007

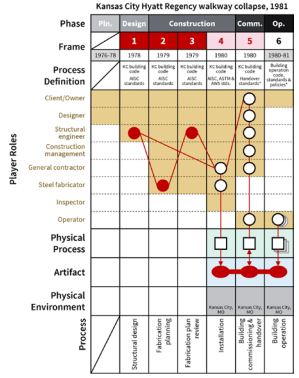


FLAPP Matrix

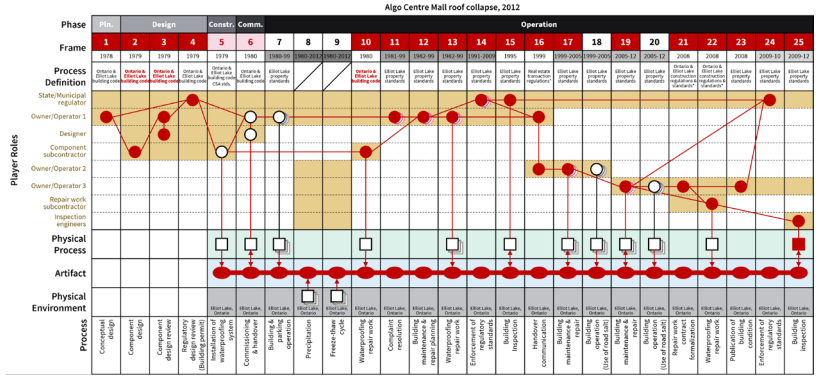
Sasago Tunnel ceiling collapse
1977-2012



Kansas City Hyatt Regency walkway bridge collapse
1980-1981

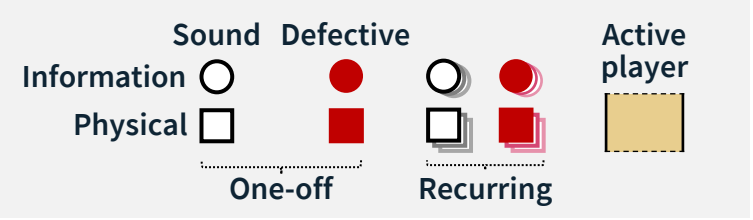


Algo Centre Mall roof collapse
1980-2012



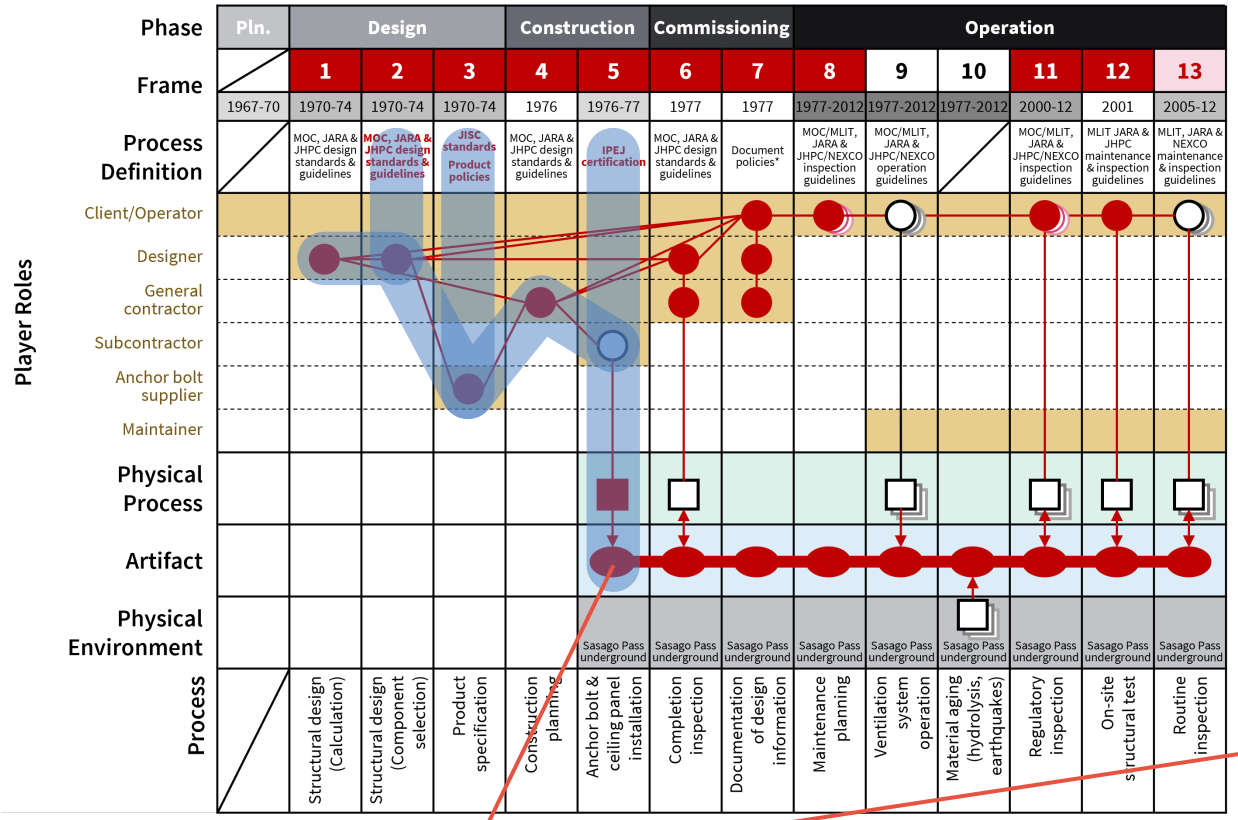
Outline

- FLAPP model
- Sample cases of construction system accidents
- **Decomposition of pathogen propagation**
- Discussion & conclusion

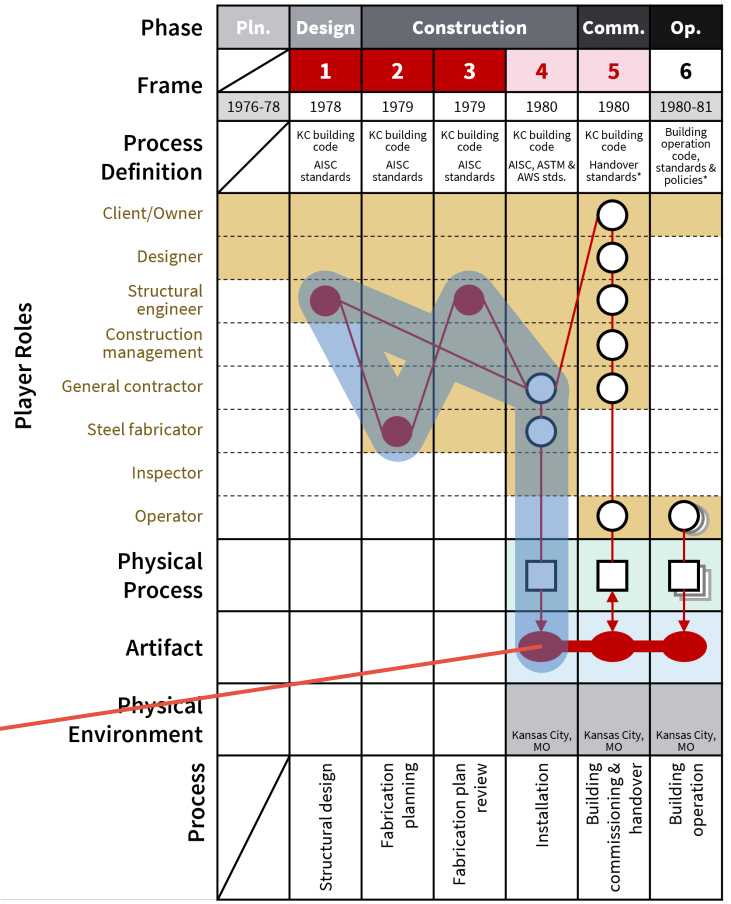


Pathogen threads

Sasago Tunnel ceiling collapse

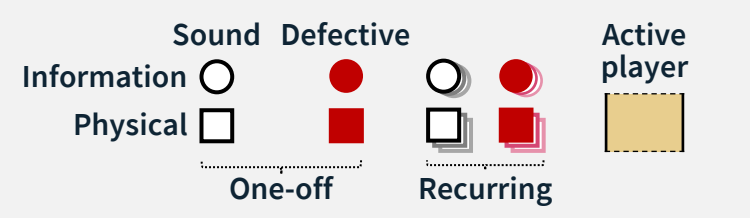


Kansas City Hyatt Regency walkway bridge collapse



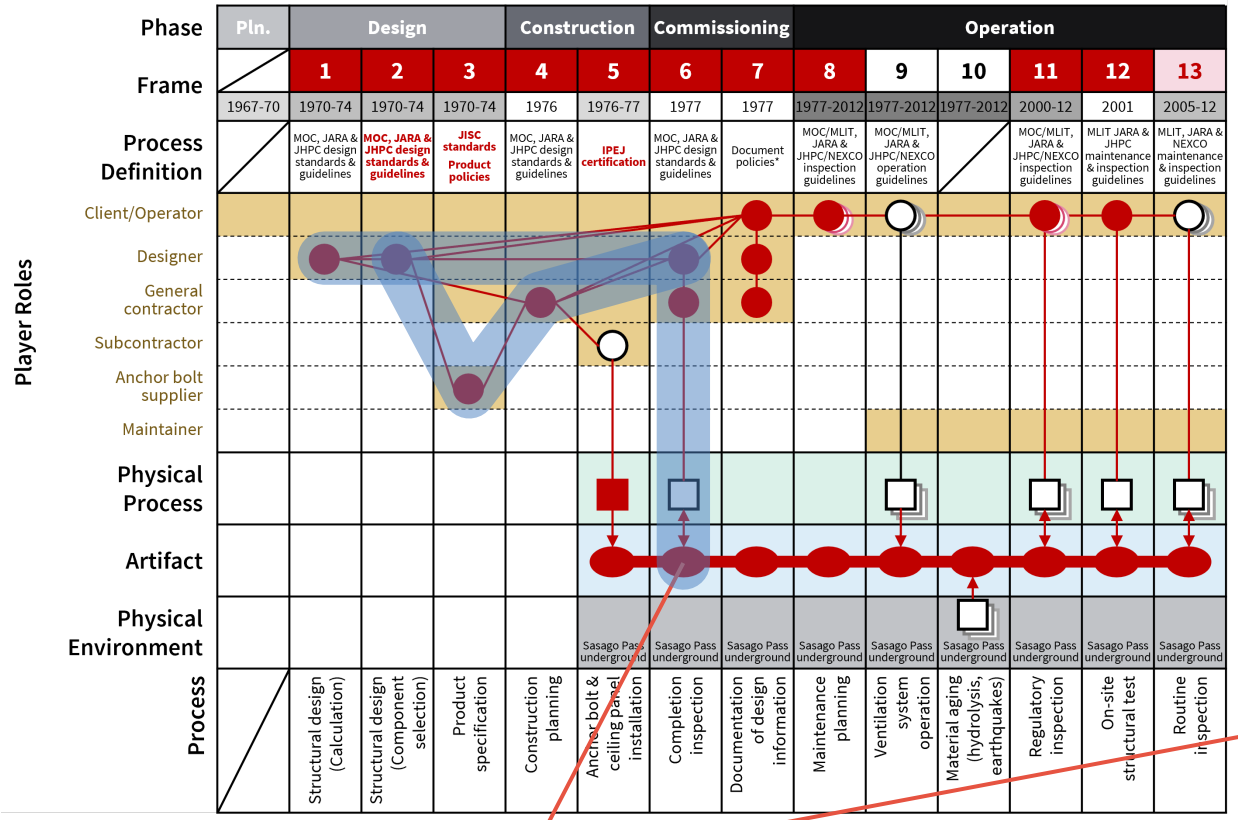
1. **Initial injection**

   Design, fabrication & installation

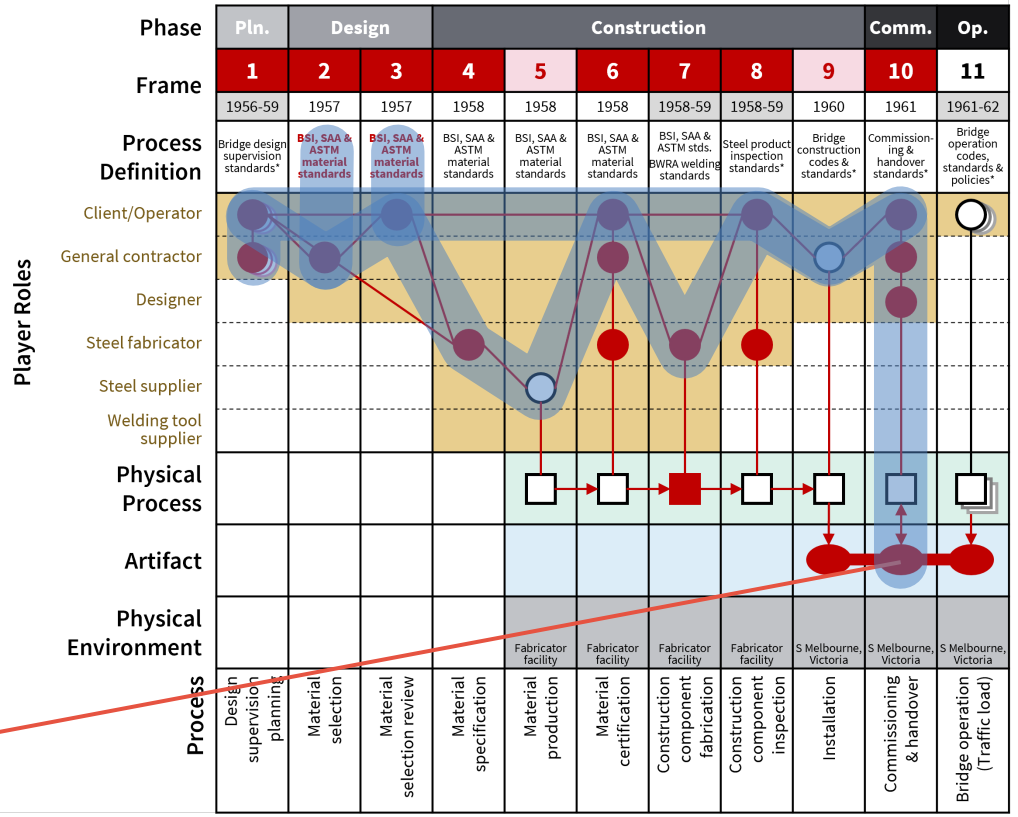


Pathogen threads

Sasago Tunnel ceiling collapse

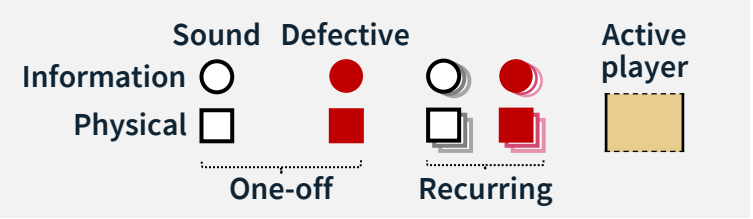


Kings Bridge collapse



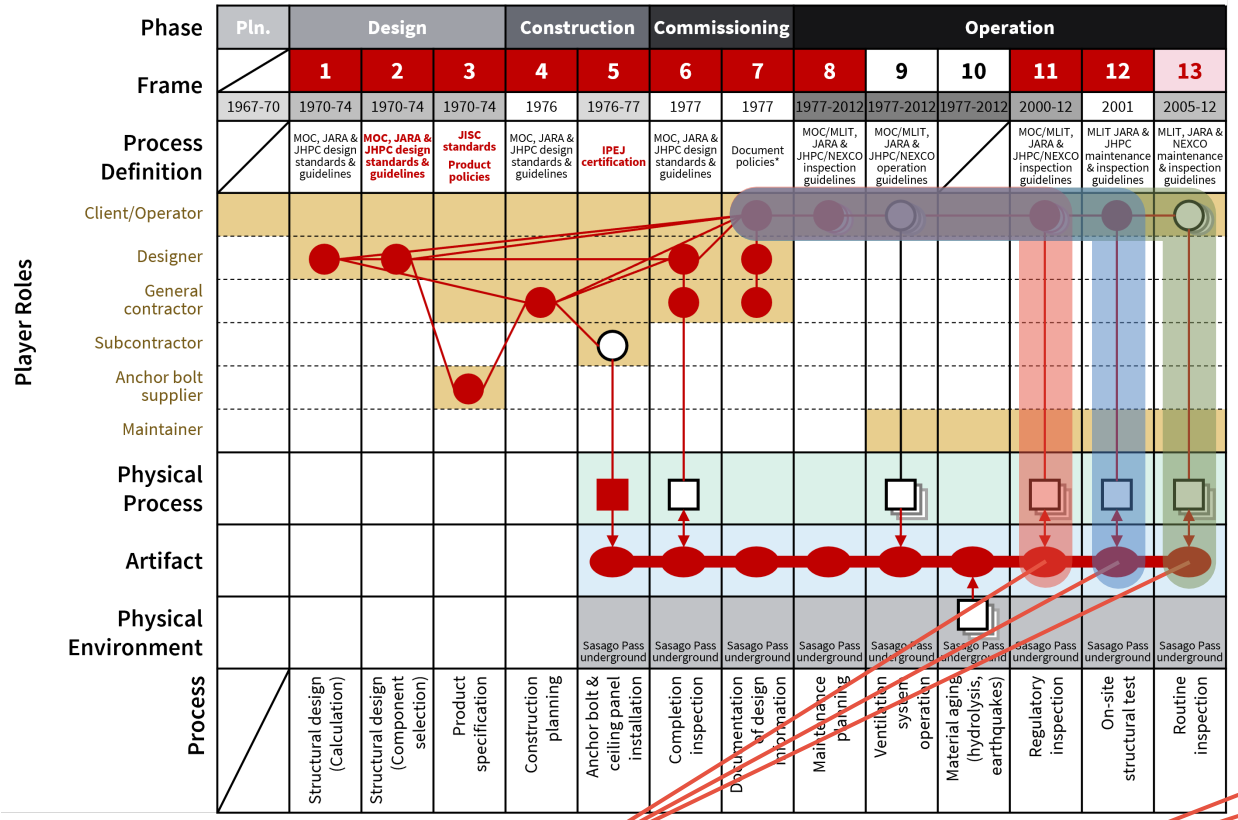
2. Pathogen exposure

Completion inspection, system verification

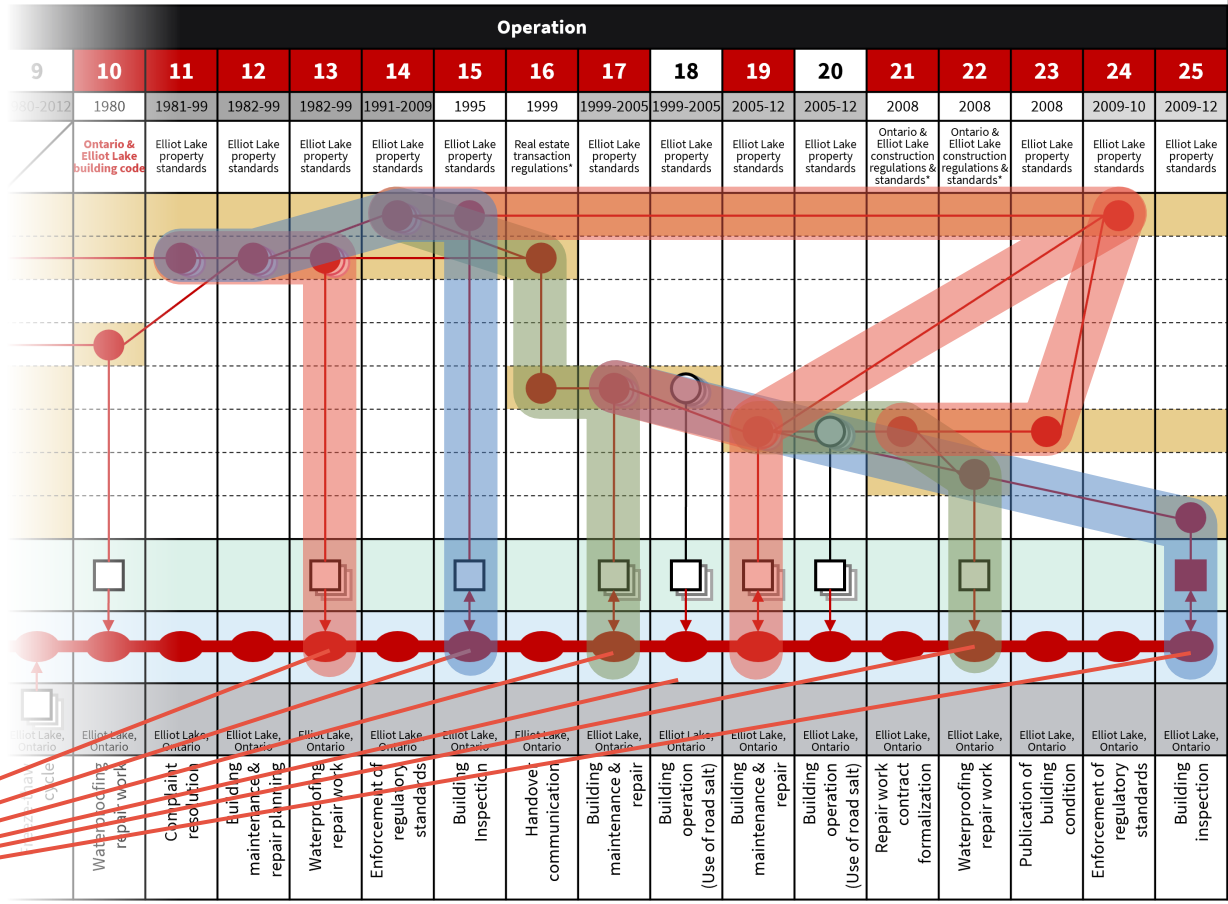


Pathogen threads

Sasago Tunnel ceiling collapse

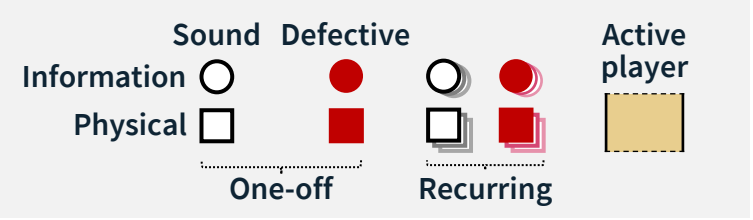


Algo Centre Mall roof collapse



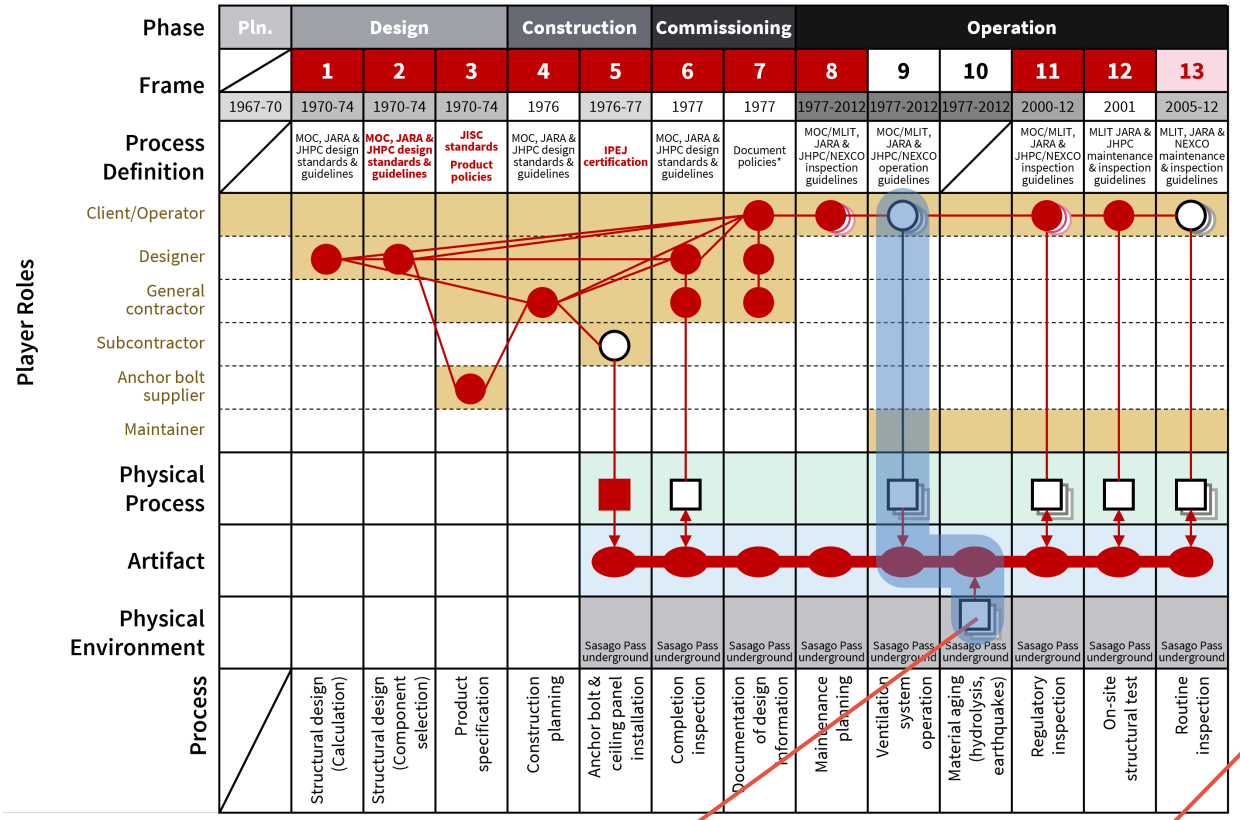
3. Missed opportunities

Routine inspections, maintenance & repair work

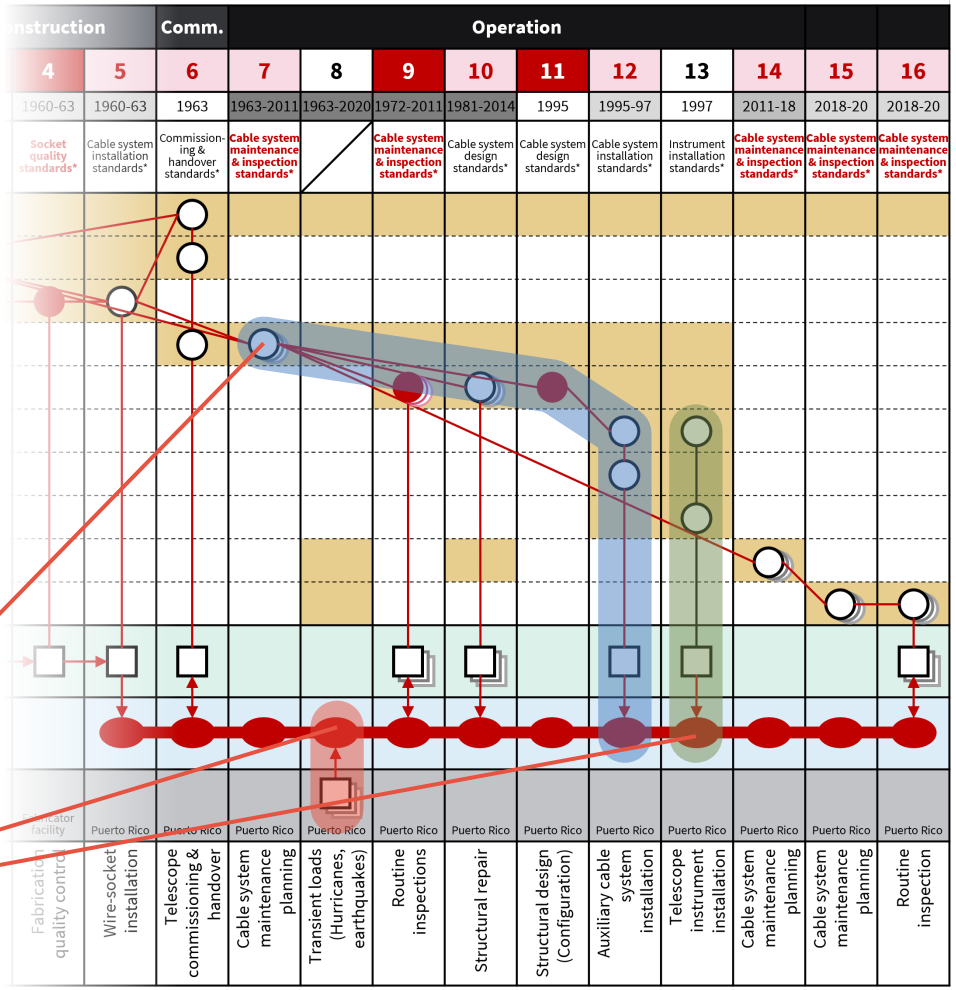


Pathogen threads

Sasago Tunnel ceiling collapse

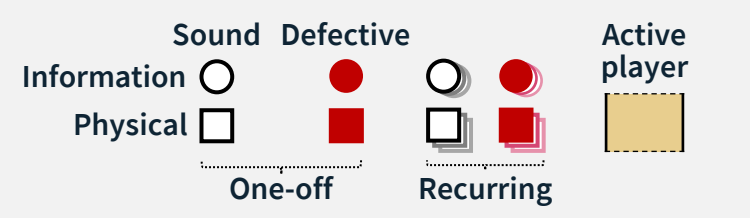


Arecibo Telescope collapse



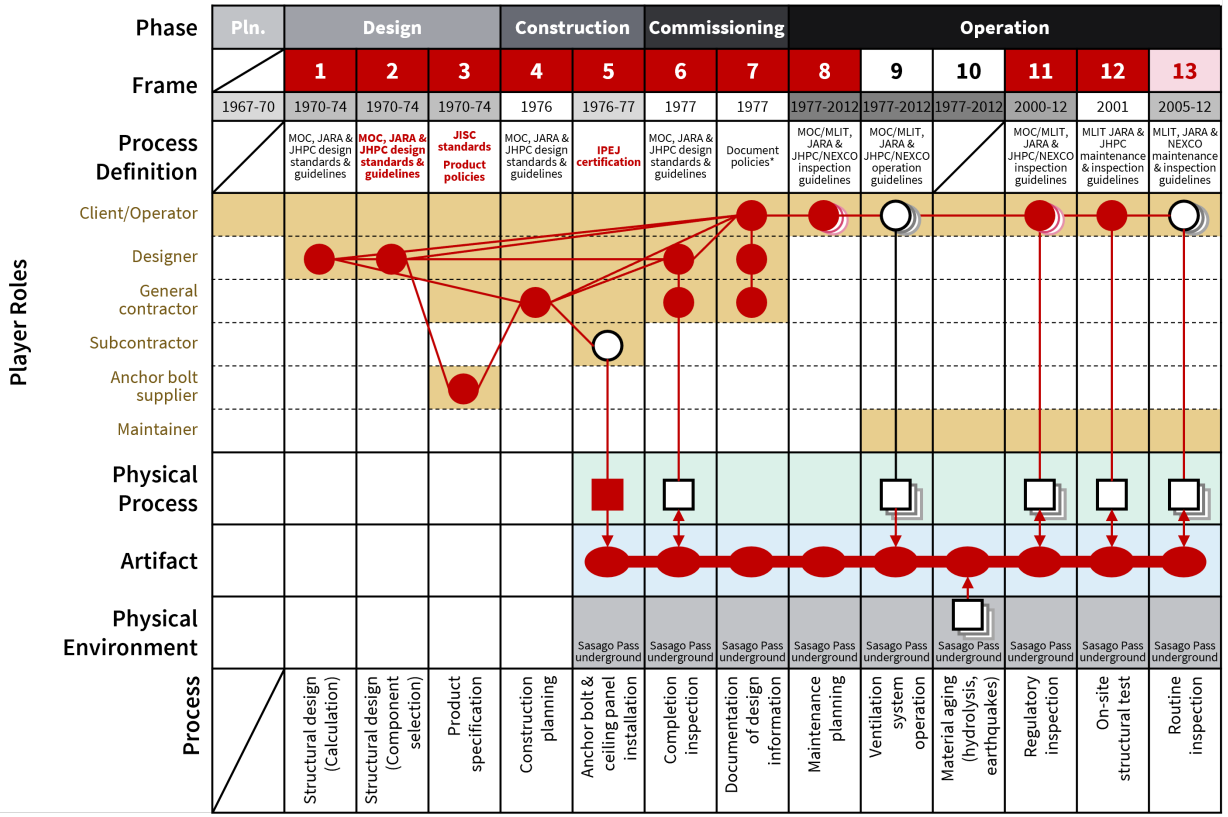
4. Well-intended aggravation

Nominal operations, renovations

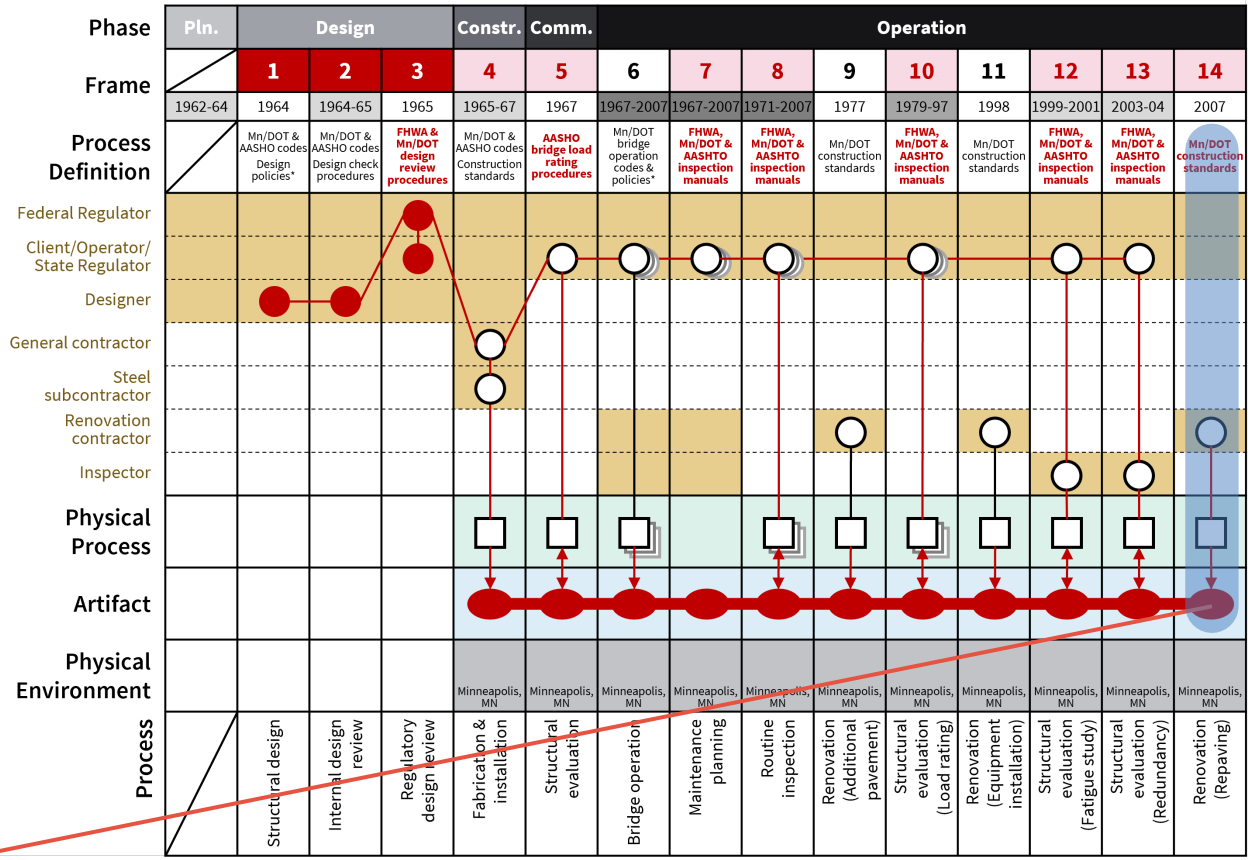


Pathogen threads

Sasago Tunnel ceiling collapse

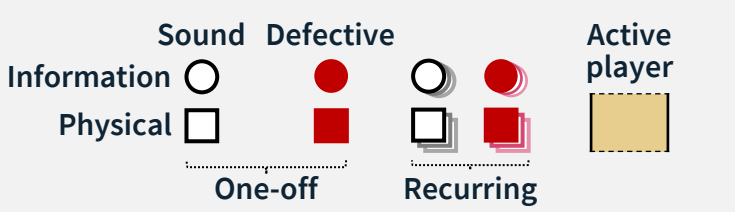


Minneapolis I-35W highway bridge collapse



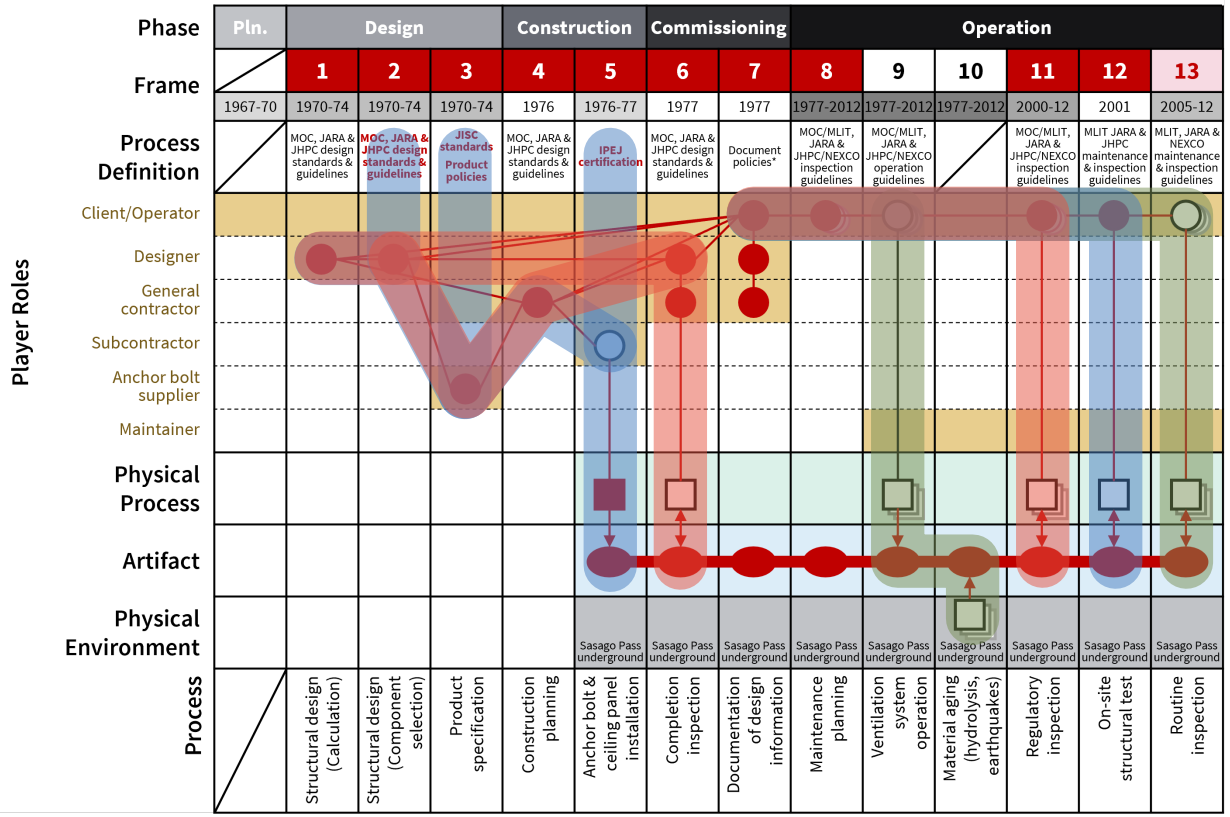
5. Pathogen activation

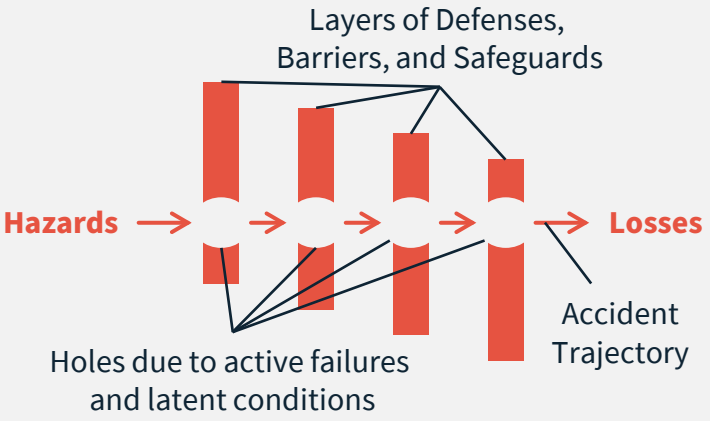
Final, local trigger of the accident



Pathogen threads

Sasago Tunnel ceiling collapse





Swiss Cheese Model

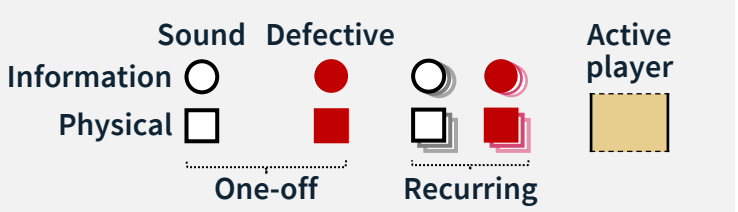
Tangible examples of the metaphors:

“resident pathogen”

“accident trajectory”

1. Initial injection
2. Pathogen exposure
3. Missed opportunities
4. Well-intended aggravation
5. Pathogen activation

Reason, J. (1990). The contribution of latent human failures to the breakdown of complex systems. *Philosophical Transactions of the Royal Society of London. Series B*, *327*(1241), 475–484.

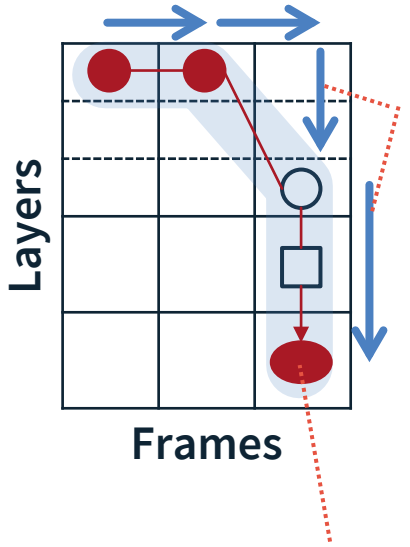


Pathogen thread elements

Sasago Tunnel ceiling collapse

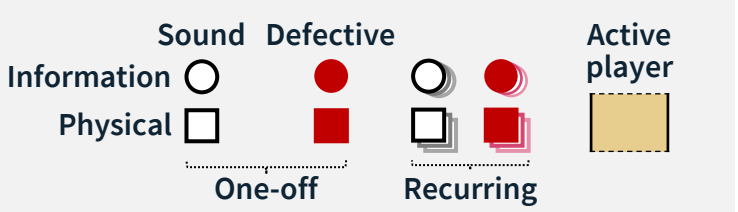
Phase	Pln.	Design			Construction		Commissioning		Operation					
Frame		1	2	3	4	5	6	7	8	9	10	11	12	13
	1967-70	1970-74	1970-74	1970-74	1976	1976-77	1977	1977	1977-2012	1977-2012	1977-2012	2000-12	2001	2005-12
Process Definition		MOC, JARA & JHPC design standards & guidelines	**MOC, JARA & JHPC design standards & guidelines**	**JISC standards Product policies**	MOC, JARA & JHPC design standards & guidelines	**IPEJ certification**	MOC, JARA & JHPC design standards & guidelines	Document policies*	MOC/MLIT, JARA & JHPC/NEXCO inspection guidelines	MOC/MLIT, JARA & JHPC/NEXCO operation guidelines		MOC/MLIT, JARA & JHPC/NEXCO inspection guidelines	MLIT JARA & JHPC maintenance & inspection guidelines	MLIT, JARA & NEXCO maintenance & inspection guidelines
Player Roles: Client/Operator														
Player Roles: Designer														
Player Roles: General contractor														
Player Roles: Subcontractor														
Player Roles: Anchor bolt supplier														
Player Roles: Maintainer														
Physical Process														
Artifact														
Physical Environment						Sasago Pass underground	Sasago Pass underground	Sasago Pass underground	Sasago Pass underground	Sasago Pass underground	Sasago Pass underground	Sasago Pass underground	Sasago Pass underground	Sasago Pass underground
Process		Structural design (Calculation)	Structural design (Component selection)	Product specification	Construction planning	Anchor bolt & ceiling panel installation	Completion inspection	Documentation of design information	Maintenance planning	Ventilation system operation	Material aging (hydrolysis, earthquakes)	Regulatory inspection	On-site structural test	Routine inspection

Trans-frame thread elements



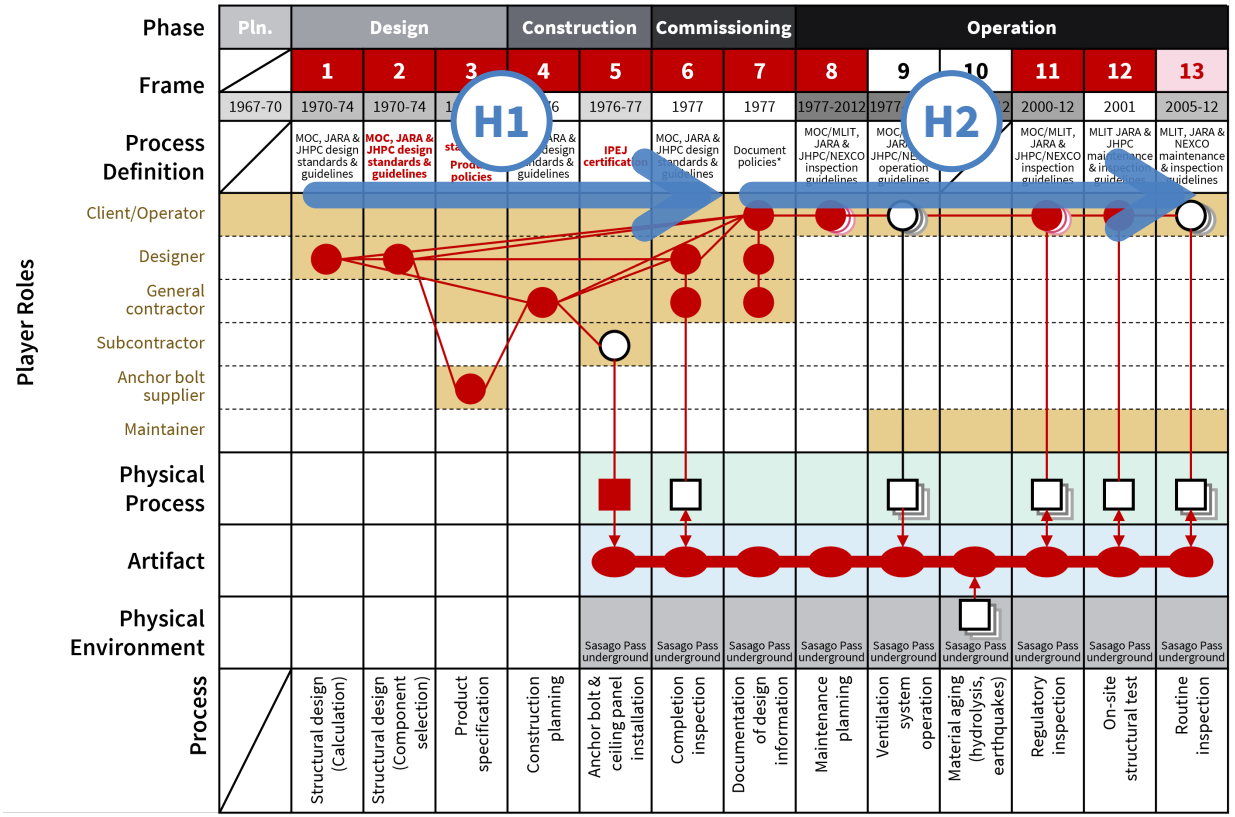
Trans-layer thread elements

Pathogen thread



Pathogen thread elements

Sasago Tunnel ceiling collapse

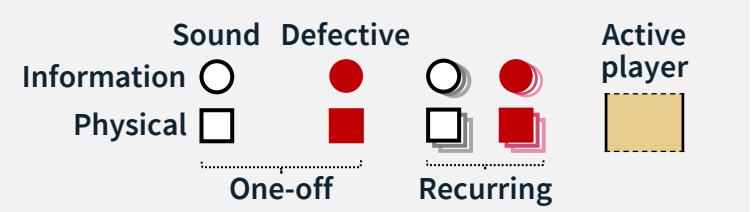


Horizontal (trans-frame) elements

1. Inadequate information reviews
2. Inadequate knowledge transfer

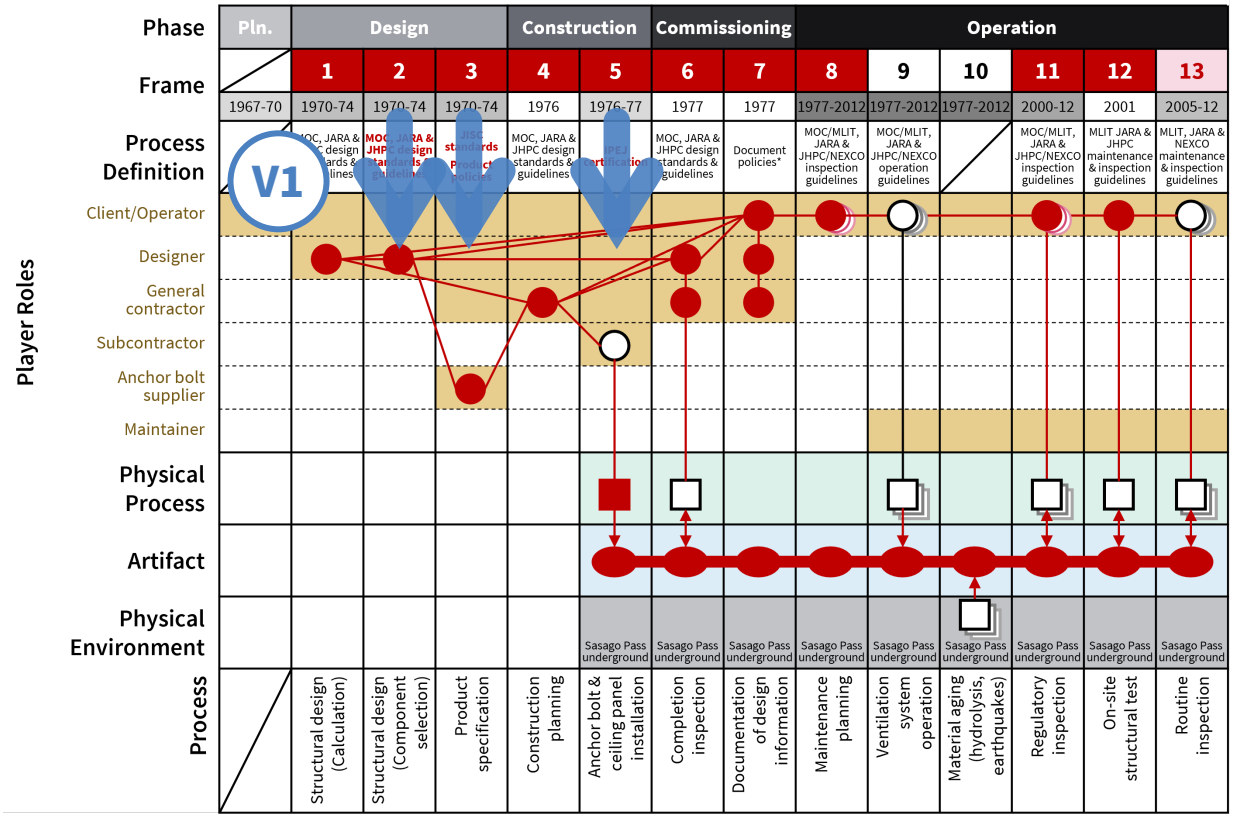
- Design review
- Regulatory approval

- Documentation
- Record maintenance
- Knowledge management



Pathogen thread elements

Sasago Tunnel ceiling collapse



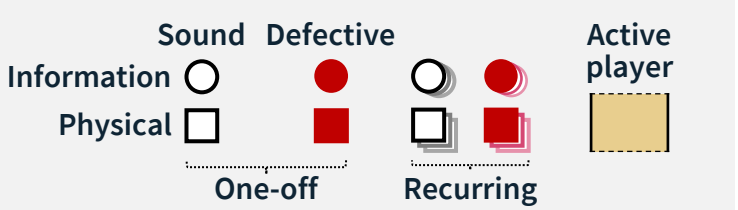
Horizontal (trans-frame) elements

1. Inadequate information reviews
2. Inadequate knowledge transfer

Vertical (trans-layer) elements

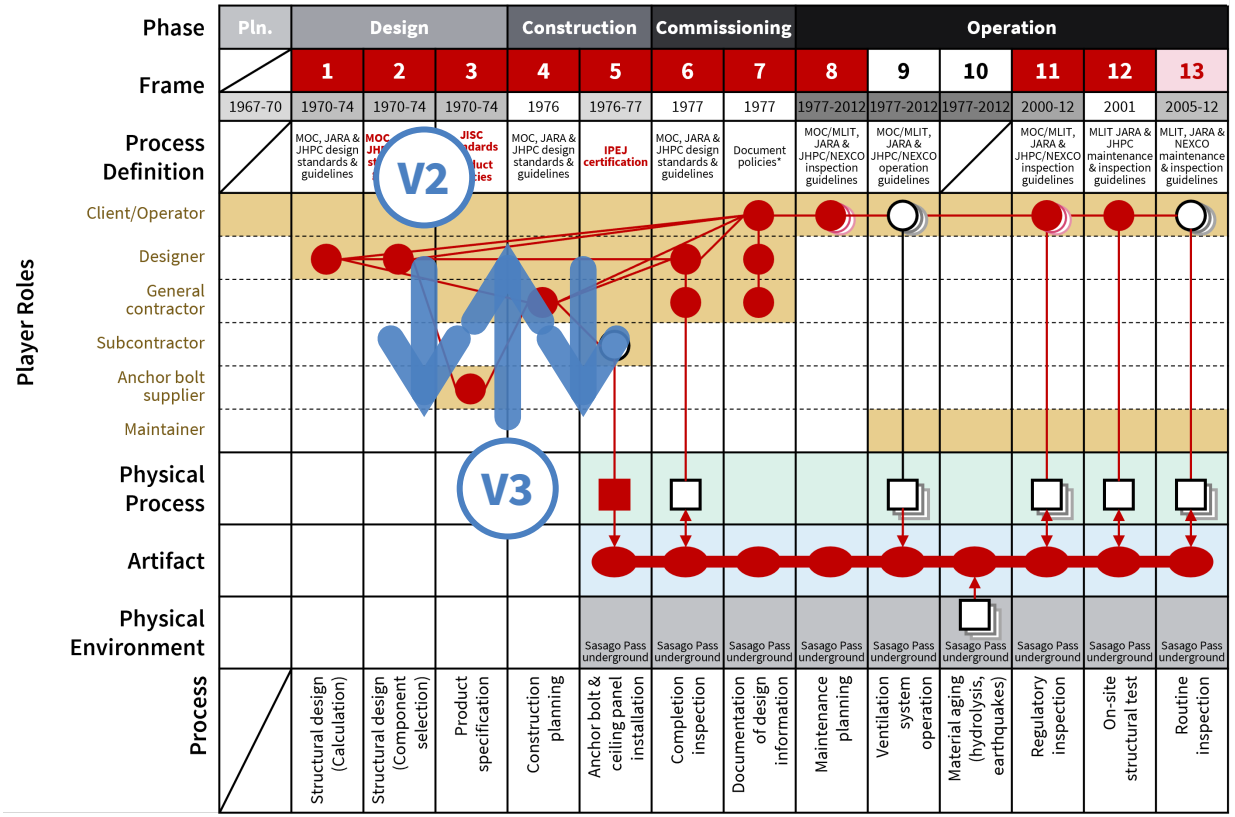
1. Inadequate process definitions

- Design codes, regulations
- Industrial standards
- Internal policies, standard procedures



Pathogen thread elements

Sasago Tunnel ceiling collapse



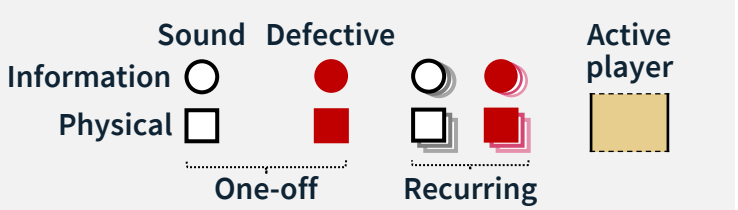
Horizontal (trans-frame) elements

1. Inadequate information reviews
2. Inadequate knowledge transfer

Vertical (trans-layer) elements

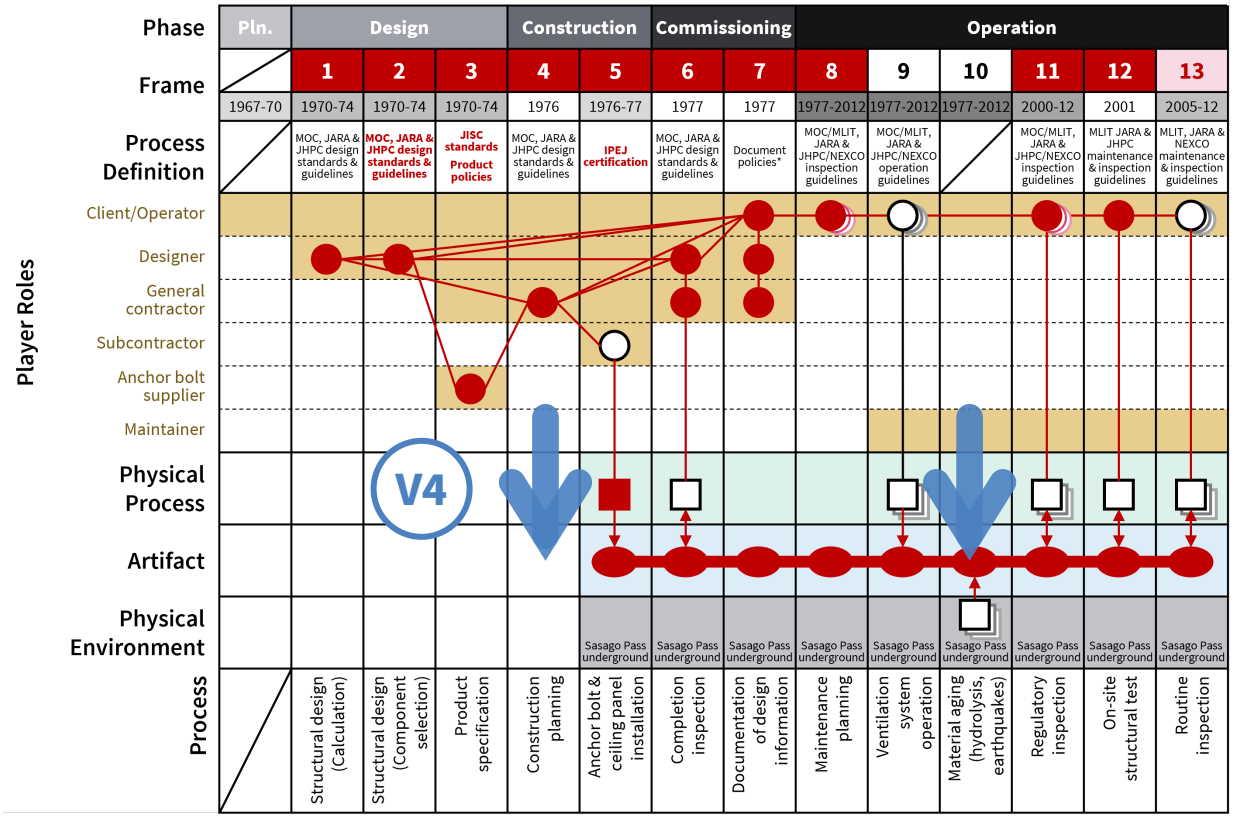
1. Inadequate process definitions
2. Miscommunication of critical high-level information
3. Miscommunication of domain knowledge

- System requirements
- Fabrication/installation procedures
- Subsystem/component performance specifications
- Fabrication/installation status reports



Pathogen thread elements

Sasago Tunnel ceiling collapse



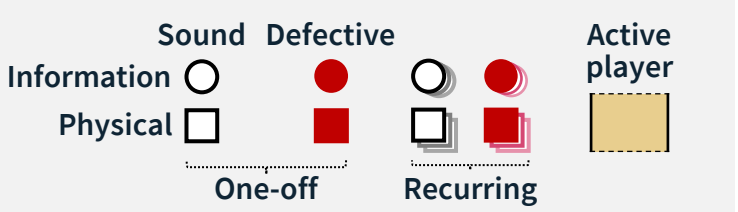
- Physical processes
- Fabrication, installation, modification, etc.

Horizontal (trans-frame) elements

1. Inadequate information reviews
2. Inadequate knowledge transfer

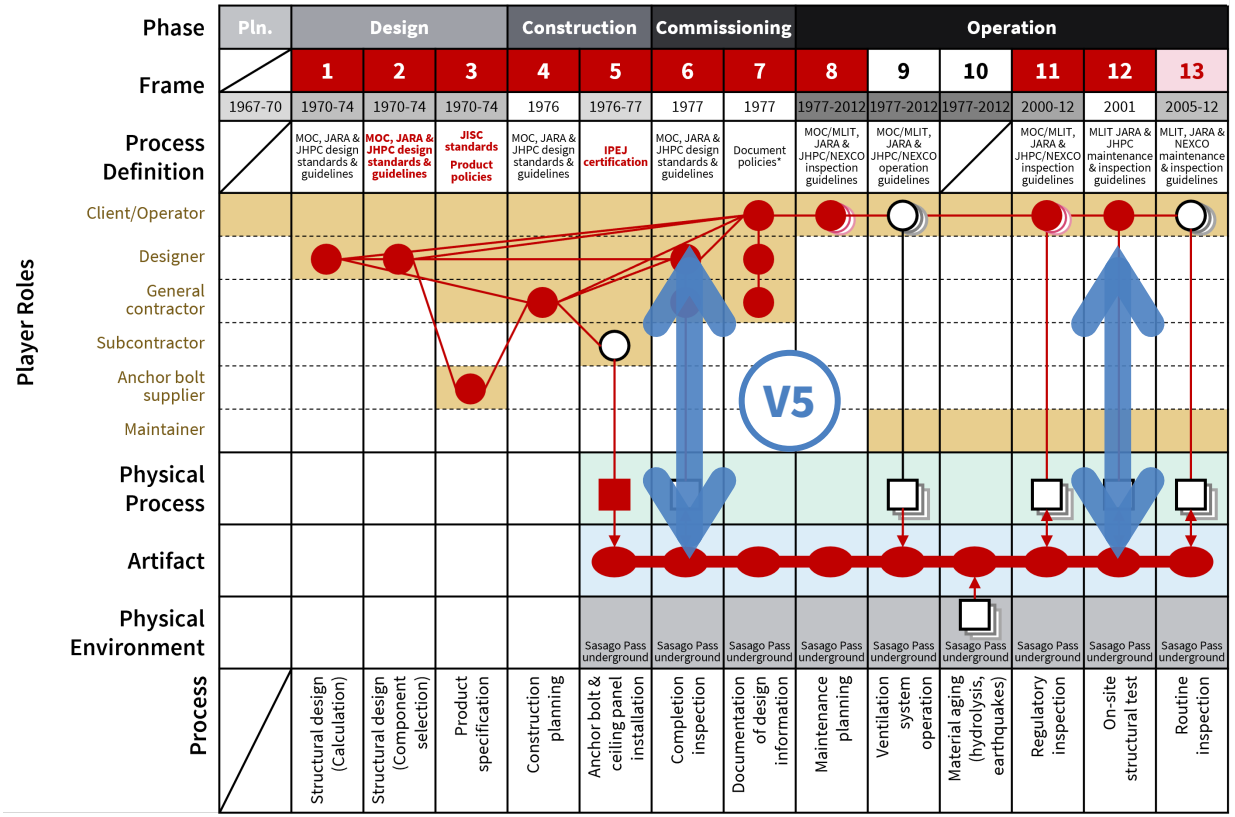
Vertical (trans-layer) elements

1. Inadequate process definitions
2. Miscommunication of critical high-level information
3. Miscommunication of domain knowledge
4. Inadequate establishment or alteration of the artifact



Pathogen thread elements

Sasago Tunnel ceiling collapse



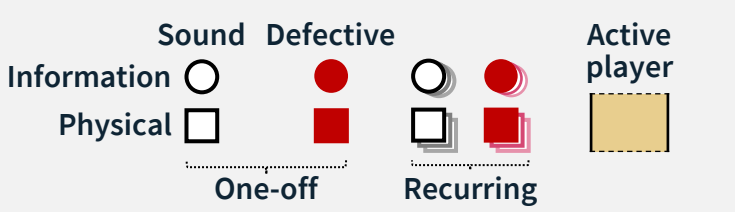
- Physical feedback
- Inspection, monitoring, etc.

Horizontal (trans-frame) elements

1. Inadequate information reviews
2. Inadequate knowledge transfer

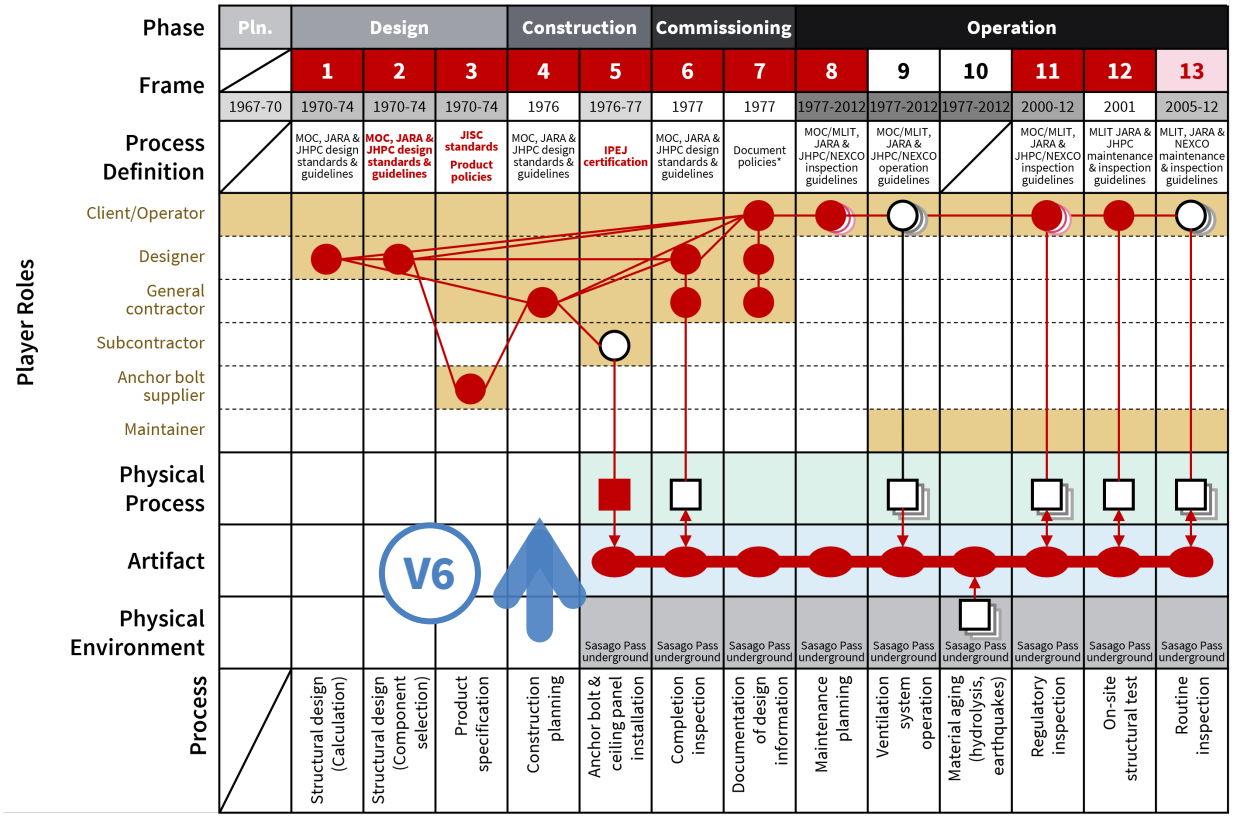
Vertical (trans-layer) elements

1. Inadequate process definitions
2. Miscommunication of critical high-level information
3. Miscommunication of domain knowledge
4. Inadequate establishment or alteration of the artifact
5. Inadequate perception of the artifact



Pathogen thread elements

Sasago Tunnel ceiling collapse



- Physical environmental effects (expected)
- Weather, earthquakes, chemical process, etc.

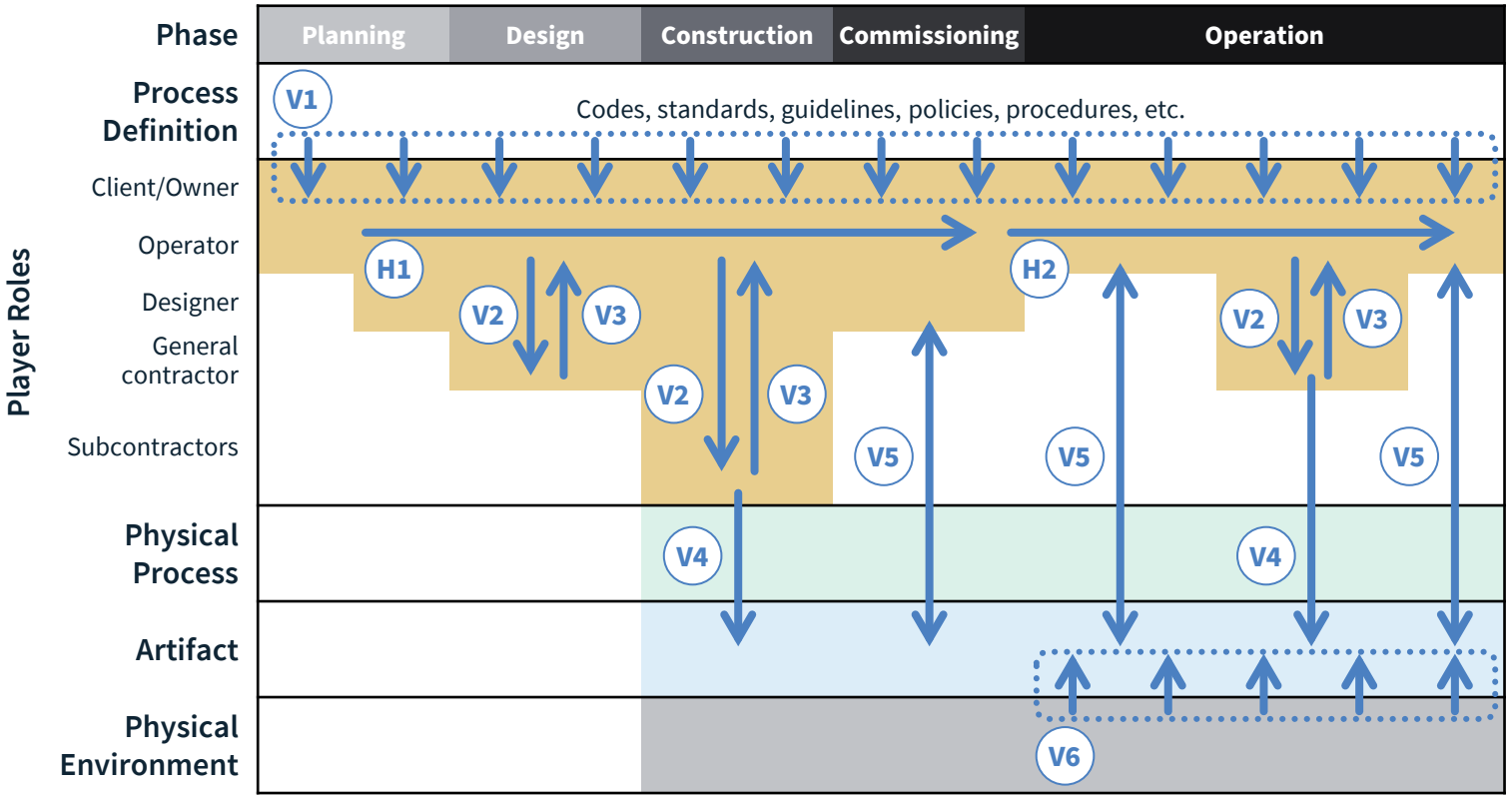
Horizontal (trans-frame) elements

1. Inadequate information reviews
2. Inadequate knowledge transfer

Vertical (trans-layer) elements

1. Inadequate process definitions
2. Miscommunication of critical high-level information
3. Miscommunication of domain knowledge
4. Inadequate establishment or alteration of the artifact
5. Inadequate perception of the artifact
6. Adverse effects of benign environmental effects and processes

Pathogen thread elements



Horizontal (trans-frame) elements

1. Inadequate information reviews
2. Inadequate knowledge transfer

Vertical (trans-layer) elements

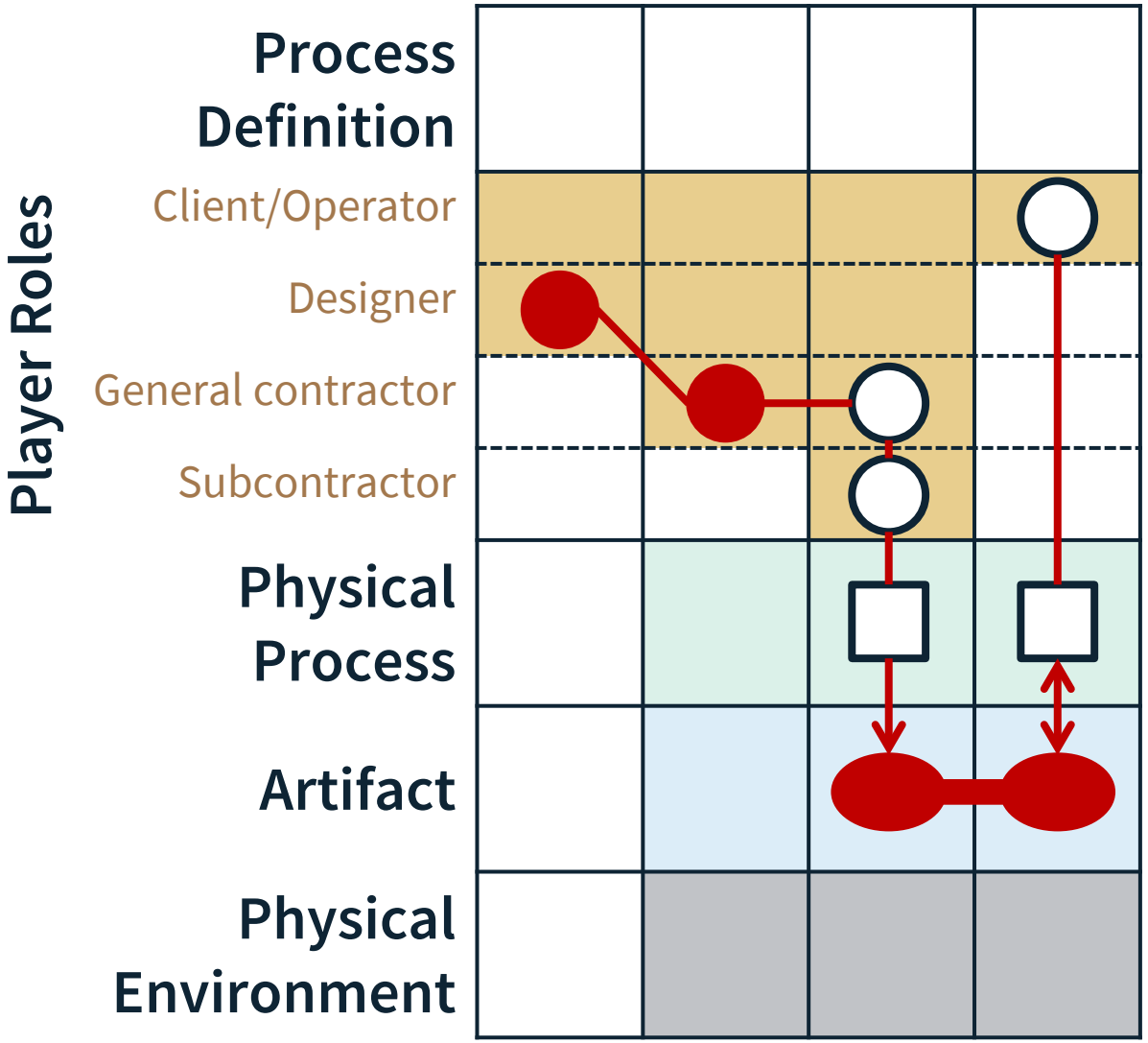
1. Inadequate process definitions
2. Miscommunication of critical high-level information
3. Miscommunication of domain knowledge
4. Inadequate establishment or alteration of the artifact
5. Inadequate perception of the artifact
6. Adverse effects of benign environmental effects and processes

A generic FLAPP Matrix

- A typical transition of organizational network across project phases
- Any of the thread elements can occur at any point in the system lifecycle

Why do pathogen threads appear?

FLAPP Model's conceptual explanation



Pathogen susceptibility

- What makes the matrix cells susceptible to "red" elements
- Field property of the time-organization continuum
- Human/organizational factors and external pressures

Pathogen transmissibility

- Easiness of the "red" elements to transmit through cells
- Certain types of information/components can be more transmissible than others
- Long-lasting regulations/standards, repeatedly referenced information, "invisible" components, etc.

Outline

- FLAPP model
- Sample cases of construction system accidents
- Decomposition of pathogen propagation
- **Discussion & conclusion**

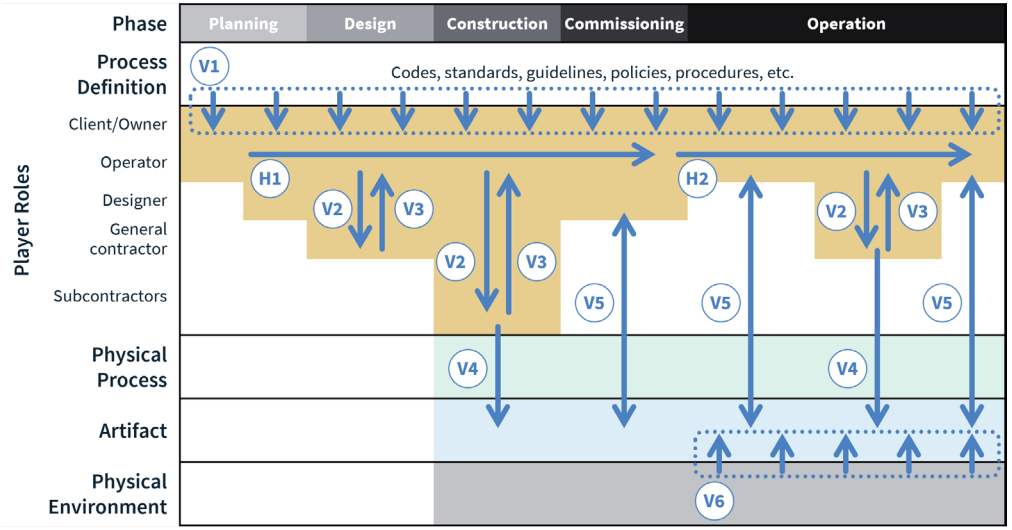
Systems engineering implications

Extension of the SE Vee model

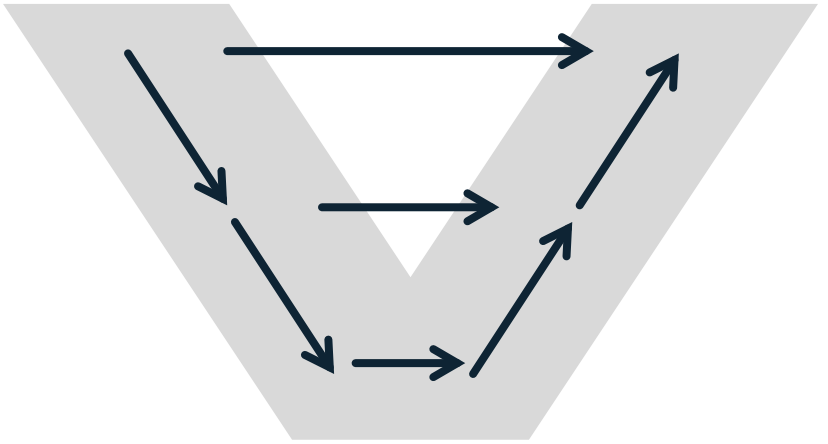
- Additional layers (process definition, physical process, environment)
- Communication across multiple Vee's

Anchor points for monitoring and detecting accident pathogens

- Focus on the intersections of vertical (hierarchical) and horizontal (temporal) communication paths
- Failures can creep into the system from any point in the lifecycle



A generic FLAPP Matrix

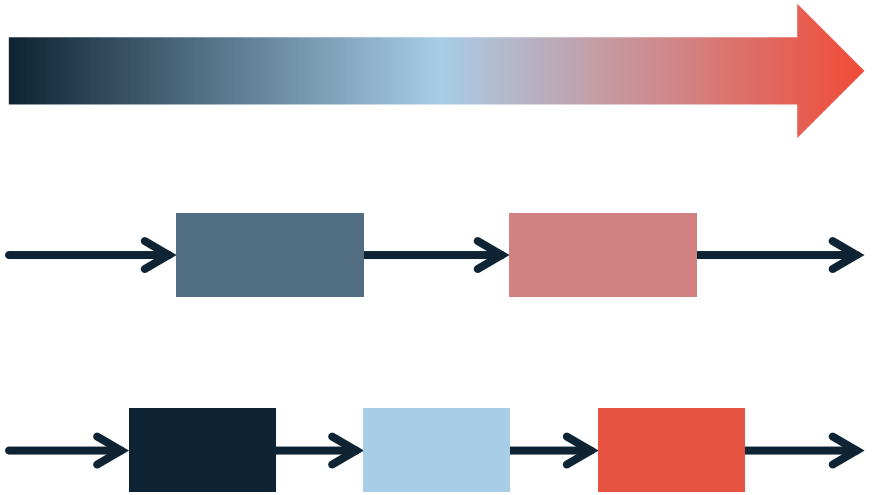


The SE Vee

Limitations & future work

Node-edge representation

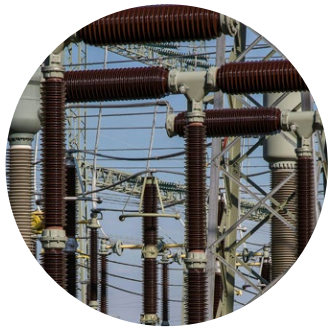
- Discrete and binary abstraction
- Exist/not exist, defective/non-defective
- Difficult to capture continuous, uncertain, or ambiguous phenomena and relationships



Extend to non-structural failures

- Cases with different types of failures
- Cases with detailed records

Quality defect



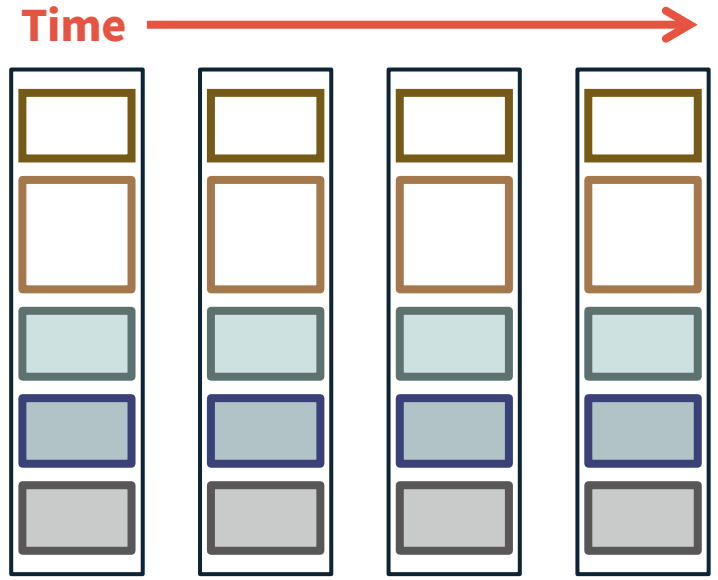
Malfunctioning

Uncontrolled release of energy

Conclusion

Addition of time dimension

- Simple modification of hierarchical models
- Unfolds the critical aspect of accident causation in construction systems

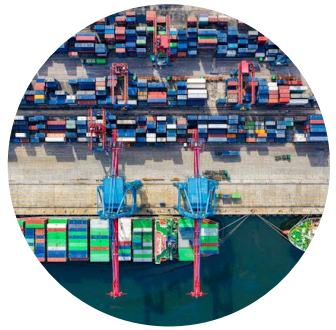


Taxonomy of propagation structure

- Potential applications outside construction
- Systems with long lifespans involving dynamic network of project organizations

Aerospace

Software



Supply chain

34th Annual INCOSE international symposium

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July 2 - 6, 2024

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