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Construction System Failures: Frame Notation of Project Pathogens and their Propagation Across Time and System Hierarchy

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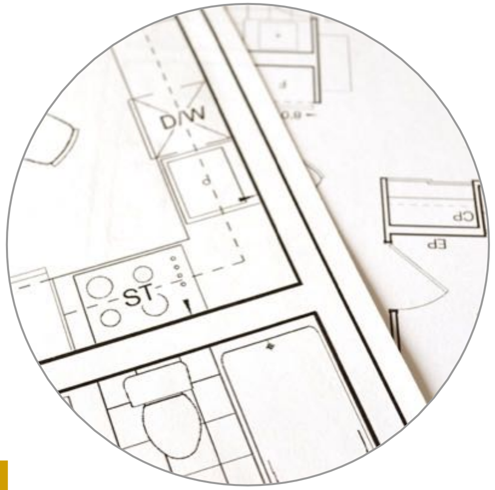
Construction systems

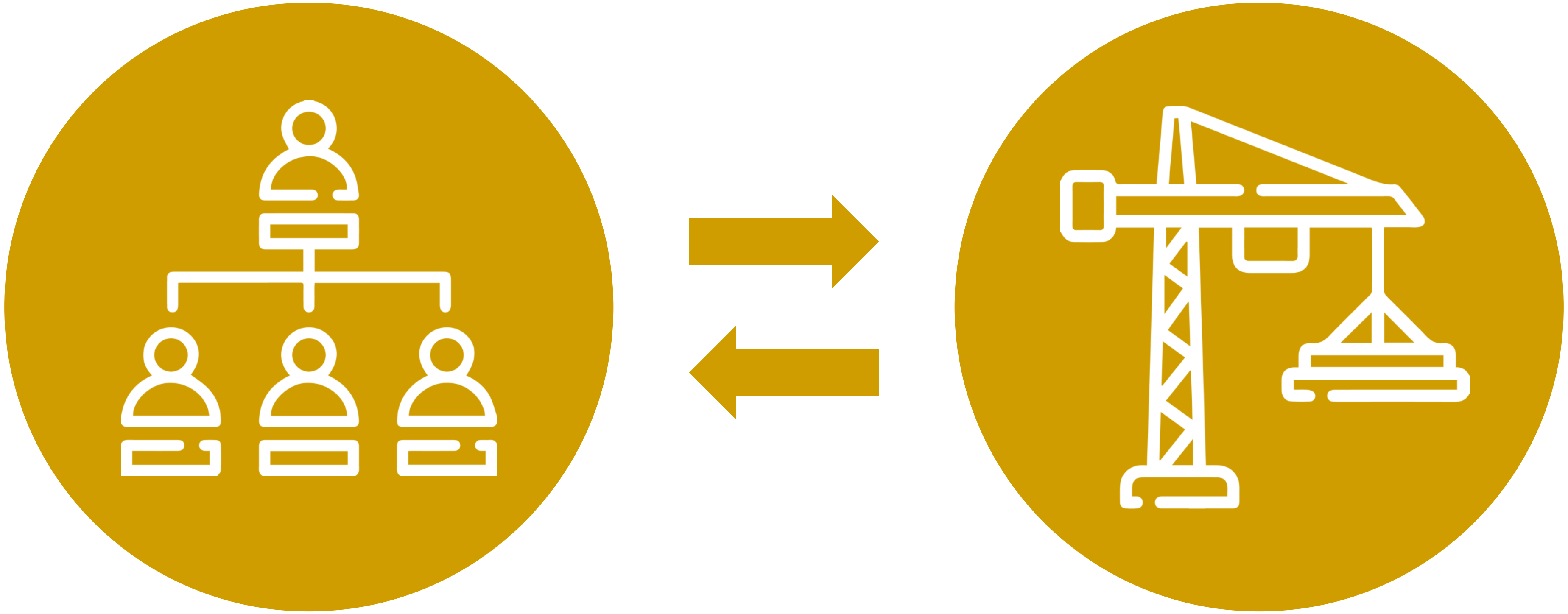

Constructed systems

Design specifications

Materials, equipment

Construction systems as complex sociotechnical systems



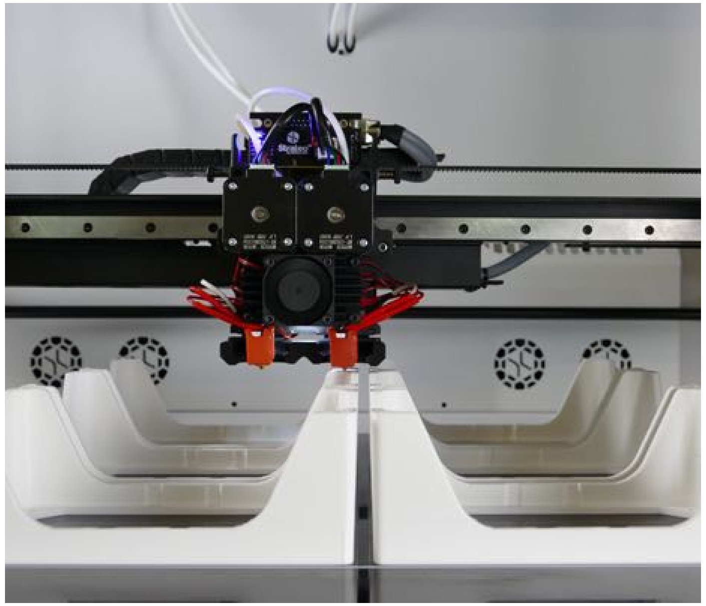
Social

- Organizational process
- Regulations
- Management

Technical

- Technical process
- On-site work
- Physical materials

Expanding contexts of construction



Digital fabrication

Additive manufacturing

Smart/integrated buildings, cities & infrastructure

Extraterrestrial application

Construction system failures

Kansas City Hyatt Regency
Walkway bridge collapse, 1981[1]

Minneapolis I-35W
Highway bridge collapse, 2007[2]

Safety research across domains




- Ceaseless effort of safety studies in various domains
- Learning from failures and planning ahead to prevent future failures
- Various frameworks, models, methodologies to analyze failures

Accident models

Accident/System failures

Accident model

- Causation analysis
- Factors and conditions

Learnings

Models can be improved

- Are system-wide factors and complex interactions considered in construction safety literature?
- Models developed outside of construction not necessarily suited for construction system failures

Designing a prototype model

- Accident model designed specifically for construction system failures
- Capture failures across a wide spectrum of severity
- Learn from failures in the past to prevent ones in the future

Designing a prototype model

Look at existing models in the literature

Apply to an actual accident case

Accident Case

Developing a Prototype Notation

Model Application

Learnings

Concluding Comments

Accident Case

Developing a Prototype Notation

Model Application

Learnings

Concluding Comments

Minneapolis I-35W highway bridge collapse, 2007

- August 1, 2007
- ~1,000-ft span collapsed
- 111 vehicles involved
- 145 injuries, 13 fatalities
- Repaving work underway
- Bridge opened in 1967

Aerial view of the collapsed bridge[2]

Reported causes, contributing factors

NTSB Accident Report[2]

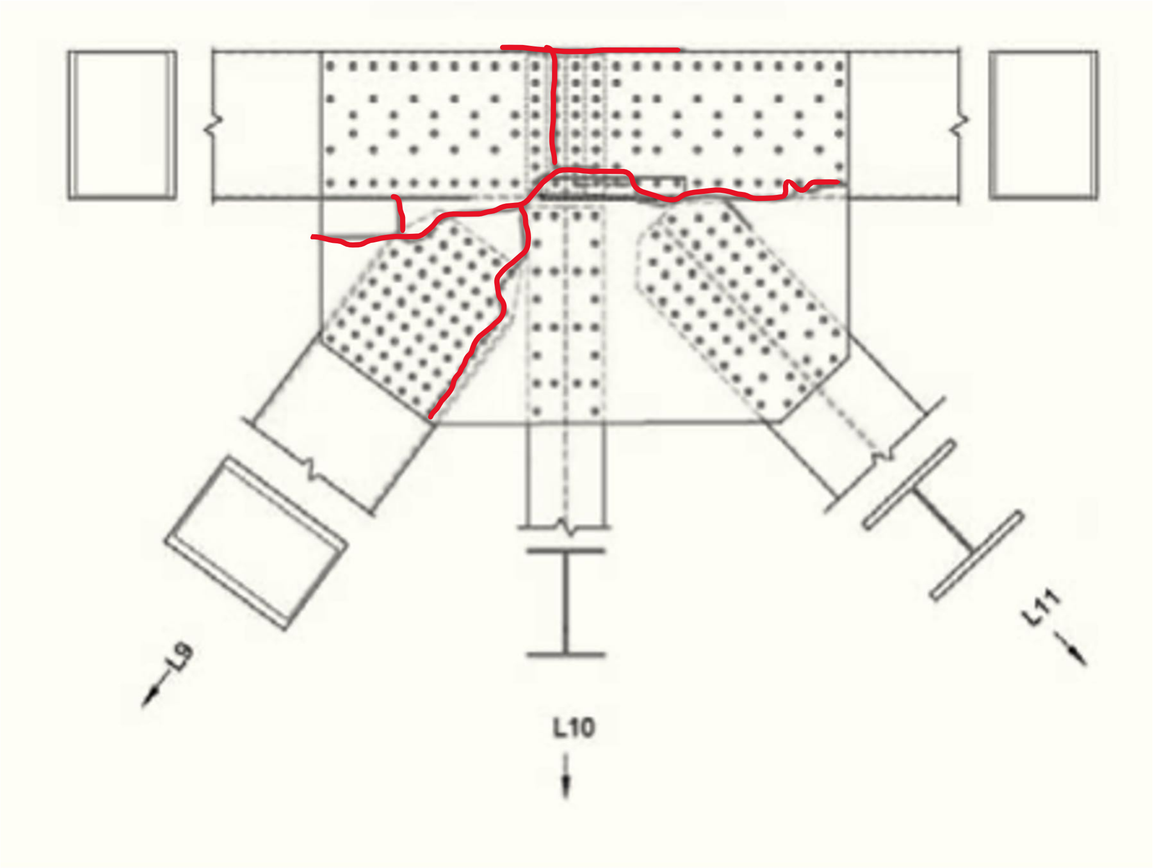
1. **Defective gusset plates**
    - Insufficient load capacity
    - Omission of calculations

Typical gusset plate of the bridge[2]

Reported causes, contributing factors

NTSB Accident Report[2]

1. **Defective gusset plates**
   - Insufficient load capacity
   - Omission of calculations
2. **Failed inspections**
   - Gusset plate excluded from inspection guidelines



Gusset plate with fractures [2]

Reported causes, contributing factors

NTSB Accident Report[2]

1. **Defective gusset plates**
    - Insufficient load capacity
    - Omission of calculations
2. **Failed inspections**
    - Gusset plate excluded from inspection guidelines
3. **Additional load**
    - Renovation and repaving work increased bridge weight

Reported causes, contributing factors

NTSB Accident Report[2]

1. **Defective gusset plates**
   - Insufficient load capacity
   - Omission of calculations
2. **Failed inspections**
   - Gusset plate excluded from inspection guidelines
3. **Additional load**
   - Renovation and repaving work increased bridge weight

Bridge collapsed during repaving[2]

Accident Case

Developing a Prototype Notation

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Concluding Comments

Accident model

- Helps understanding of accident causation
- Frames and organizes relevant information
- Sets perspectives, guides the scope of investigation
- Ultimately determines how to approach safety management

e.g.

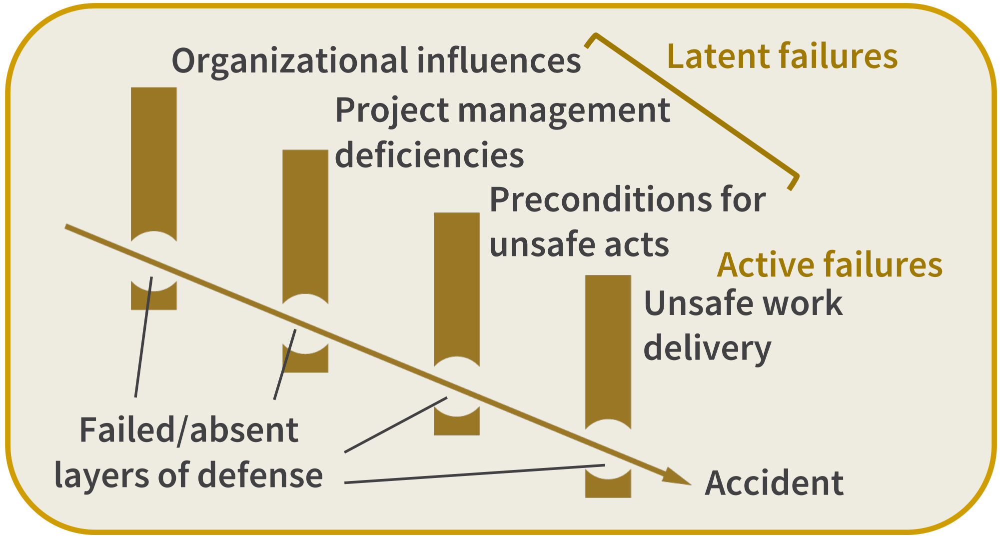
Domino model

Swiss Cheese Model [3]

Systems-Theoretic Accident Model and Process (STAMP) [4]

"Linear" and "nonlinear" models in the literature [5]

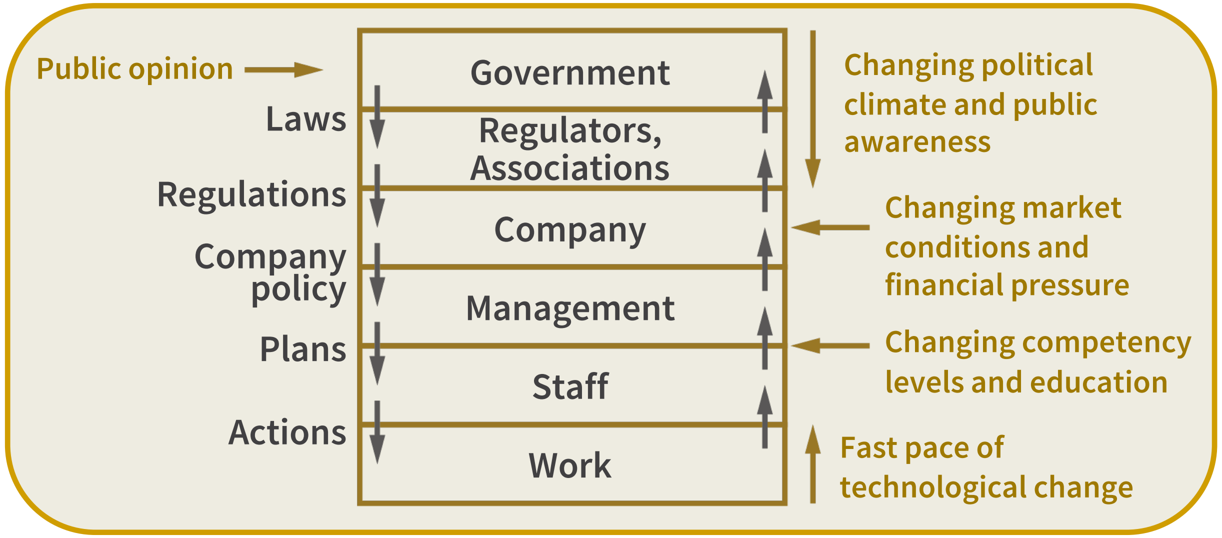
Complex linear models



Swiss Cheese Model[3]

- Prevalent in construction studies
- Reliant on a sequence of events
- Limited scope on system factors
- Relatively easy to handle

Complex nonlinear models

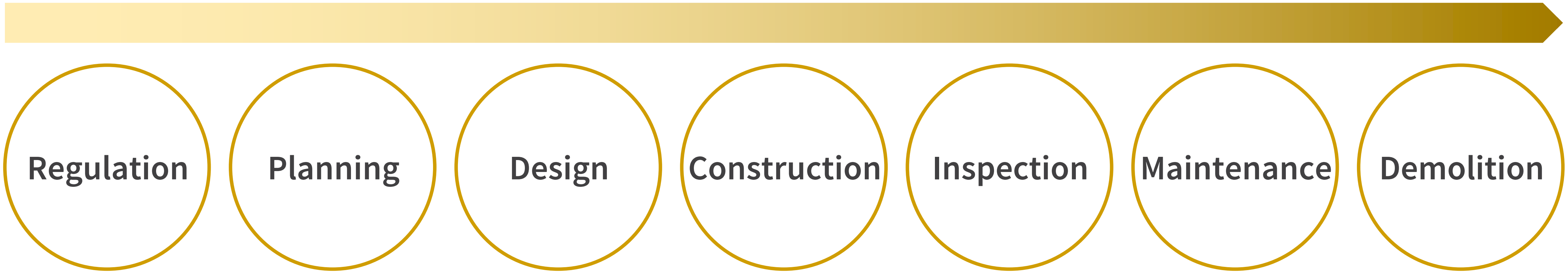


Risk Management Framework (RMF)[6]

- System-wide perspective
- Complex interactions of individuals
- Few applications in construction

Key feature of construction projects

Time dimension

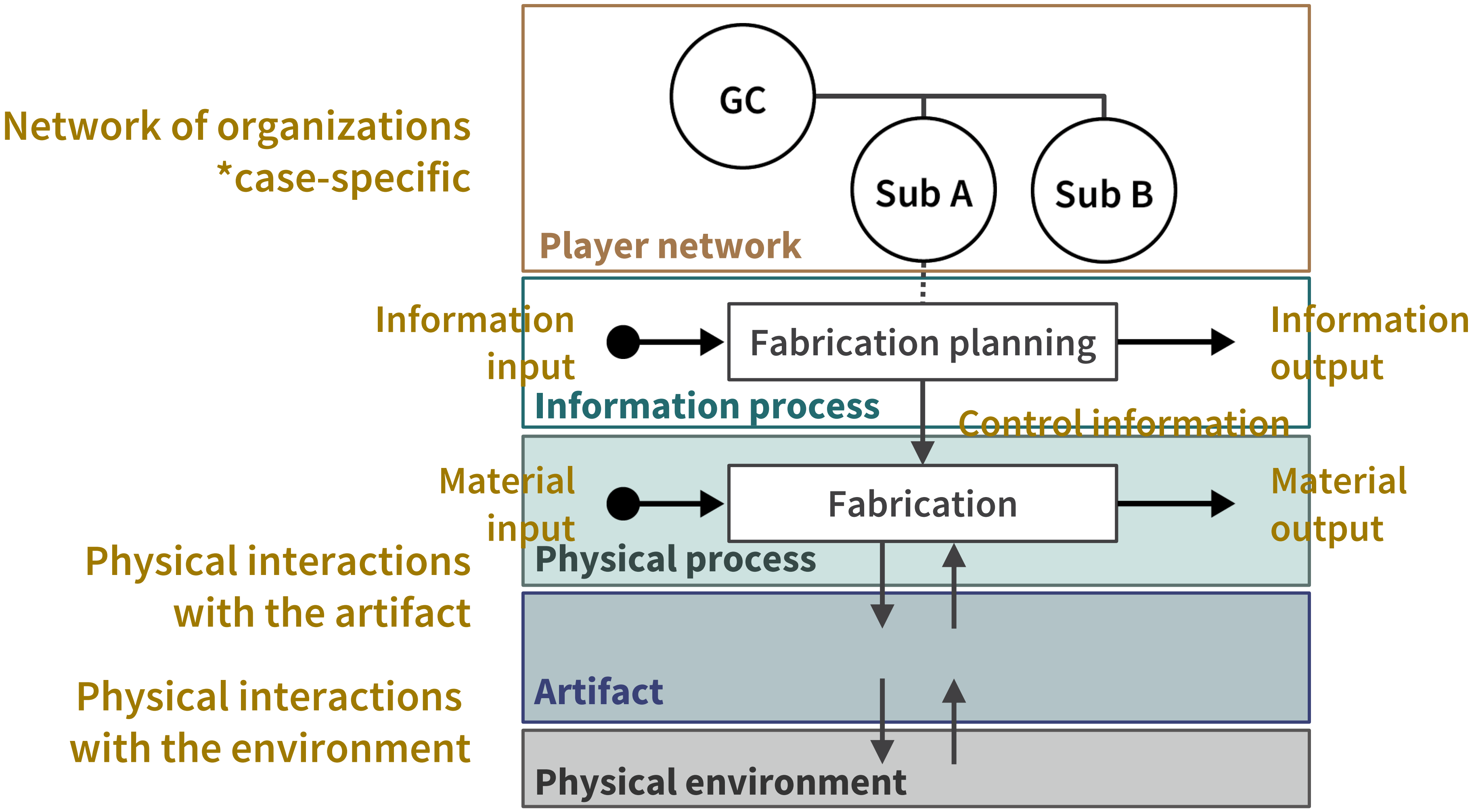


Temporary multiple organization[7]

- Temporary formed project teams
- Dynamic and ephemeral nature of organizational network
- Different players come and go throughout project lifecycle

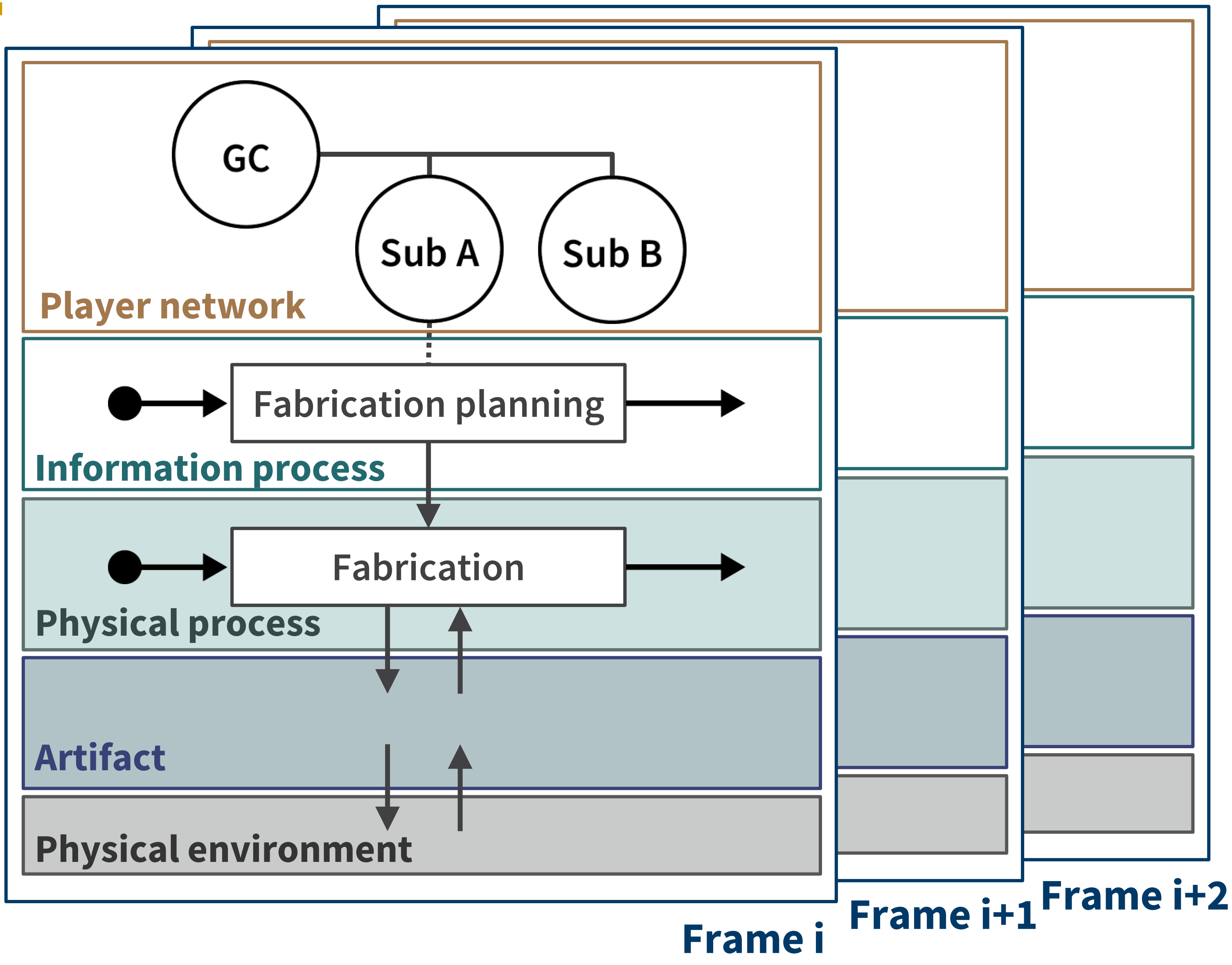
Developing a prototype notation

Basic graphical elements



Developing a prototype notation

Basic graphical elements

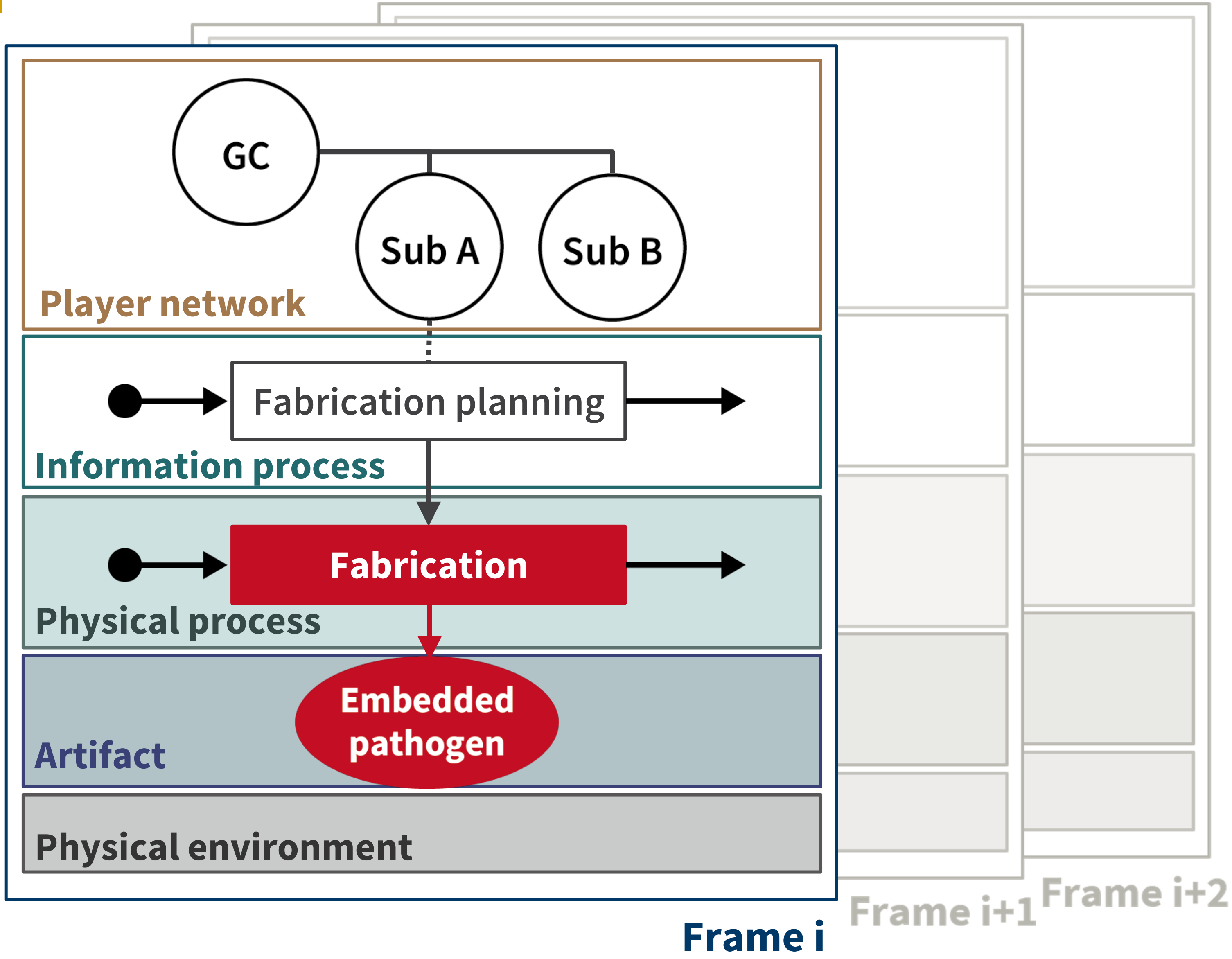


Developing a prototype notation

Basic graphical elements

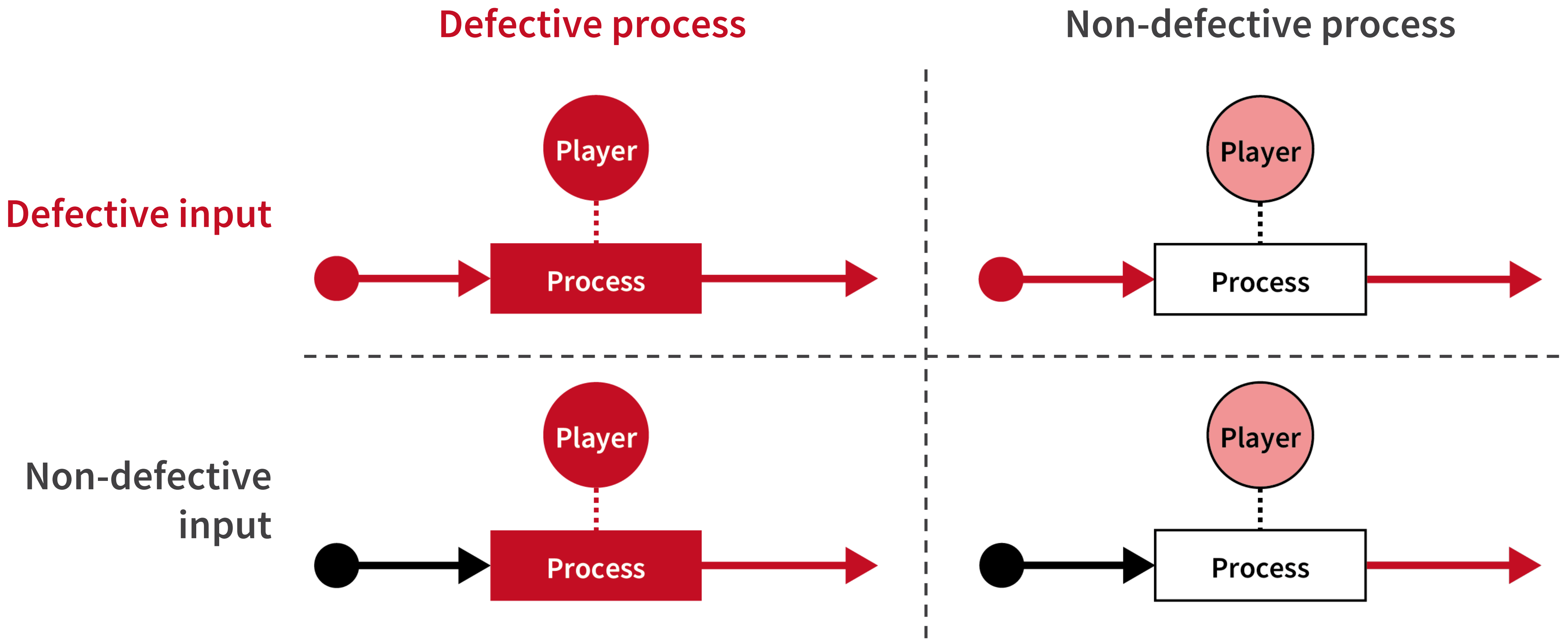
Defective process

Pathogen injection



Pathogens in a system

Latent failures = “Pathogens”



Accident Case

Developing a Prototype Notation

Model Application

Learnings

Concluding Comments

Constructing each frame

1. **Identify a defective process**
    - From investigation documents

NTSB (2008) *Collapse of I-35W Highway Bridge: Minneapolis, Minnesota, August 1, 2007*

↓

Examples of defective processes identified from the document

- Inappropriate structural calculations
- Inadequate design review procedures
- Fabricated defective gusset plates
- Inadequate load rating requirements
- …

Constructing each frame

1. **Identify a defective process**
    - From investigation documents
    - One defective process per frame

- Inappropriate structural calculations
- **Inadequate design review procedures**
- Fabricated defective gusset plates
- Inadequate load rating requirements
- …

Constructing each frame

1. **Identify a defective process**
   - From investigation documents
   - One defective process per frame

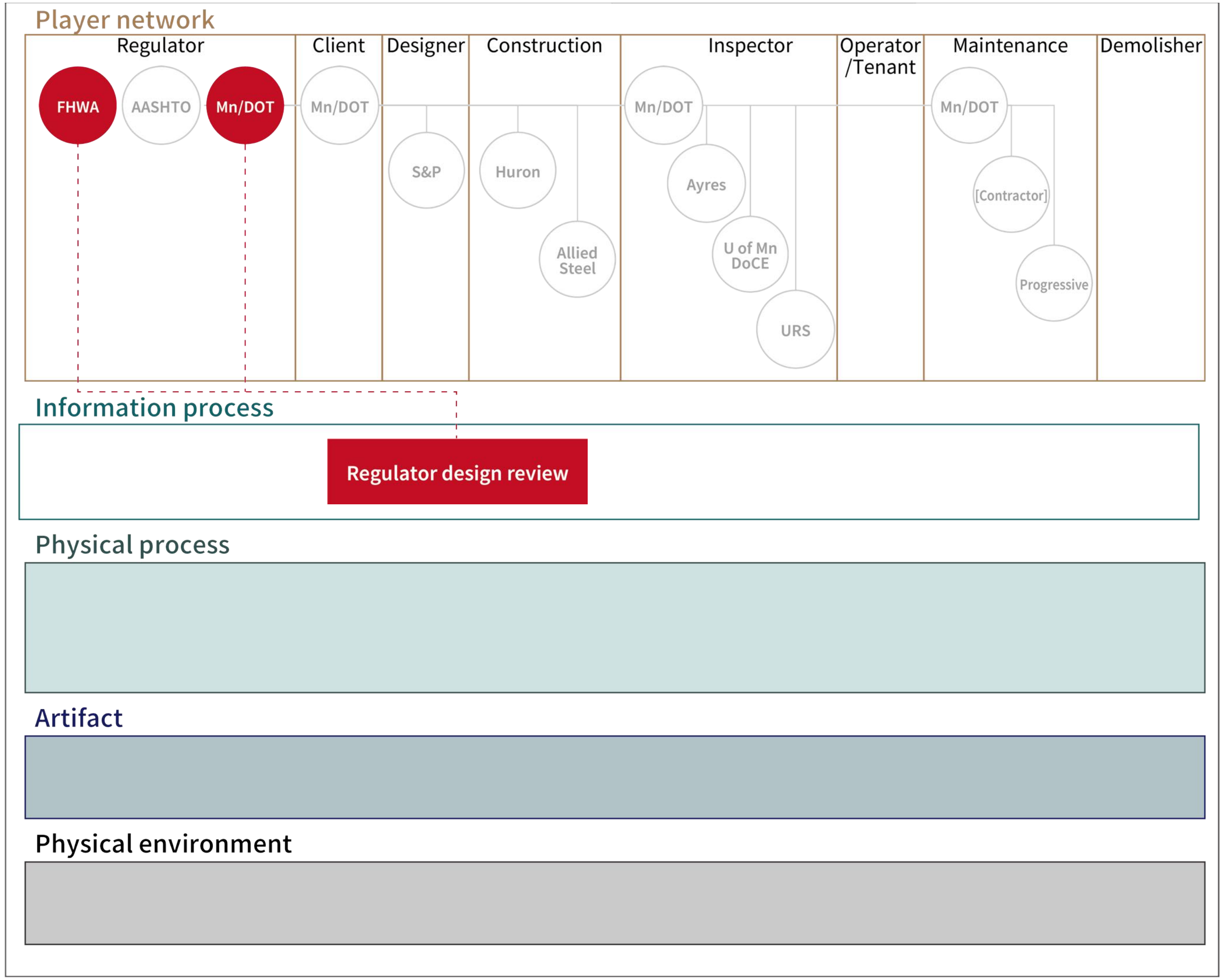
- **Inadequate design review procedures**

Regulator design review

Constructing each frame

1. **Identify a defective process**
   - From investigation documents
   - One defective process per frame
2. **Illustrate the player network**
   - Mark the players in charge of the defective processes

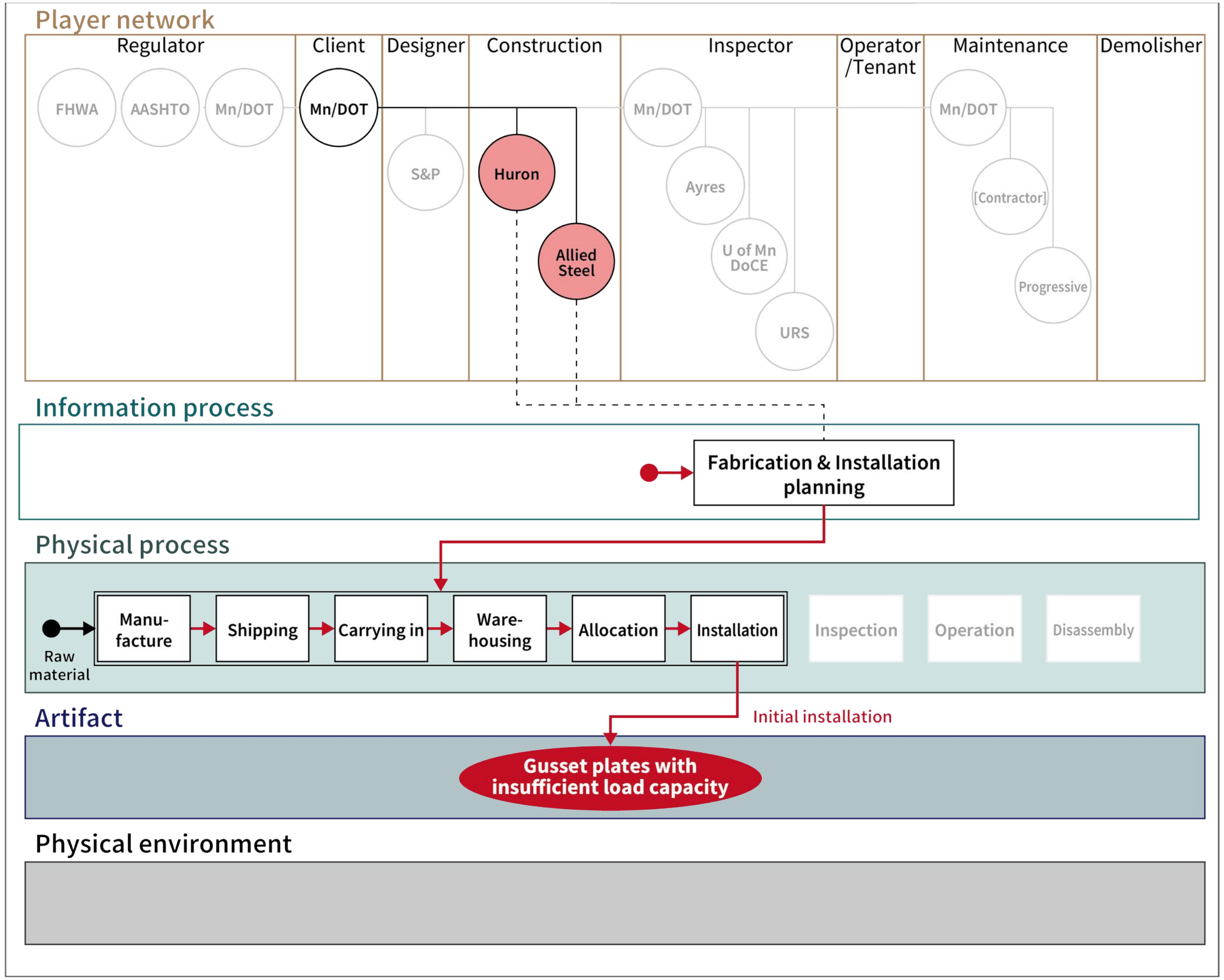
- Inadequate design review procedures



Constructing each frame

1. **Identify a defective process**
   - From investigation documents
   - One defective process per frame
2. **Illustrate the player network**
   - Mark the players in charge of the defective processes
3. **Draw the information & physical processes within the same frame**
   - Mark the defective elements

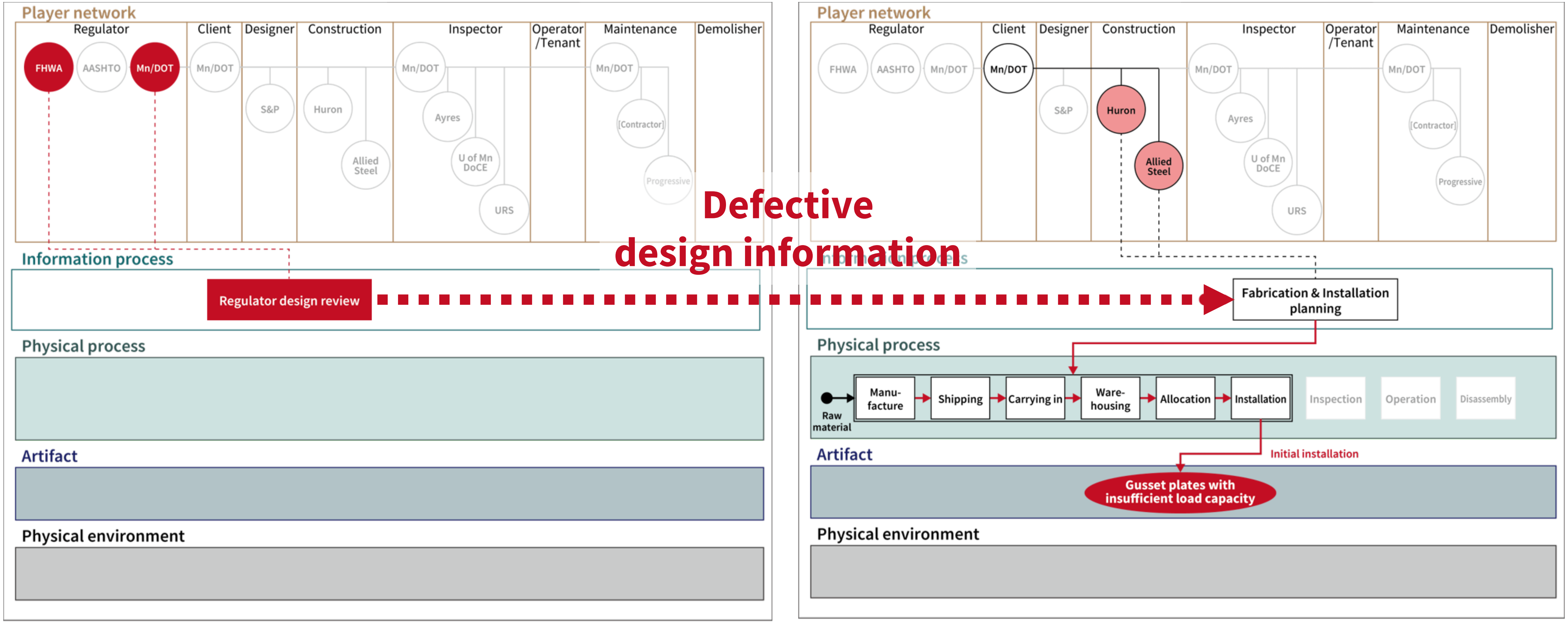
- **Fabricated and installed as specified; gusset plates with insufficient capacity**



Model application

Sequence of frames

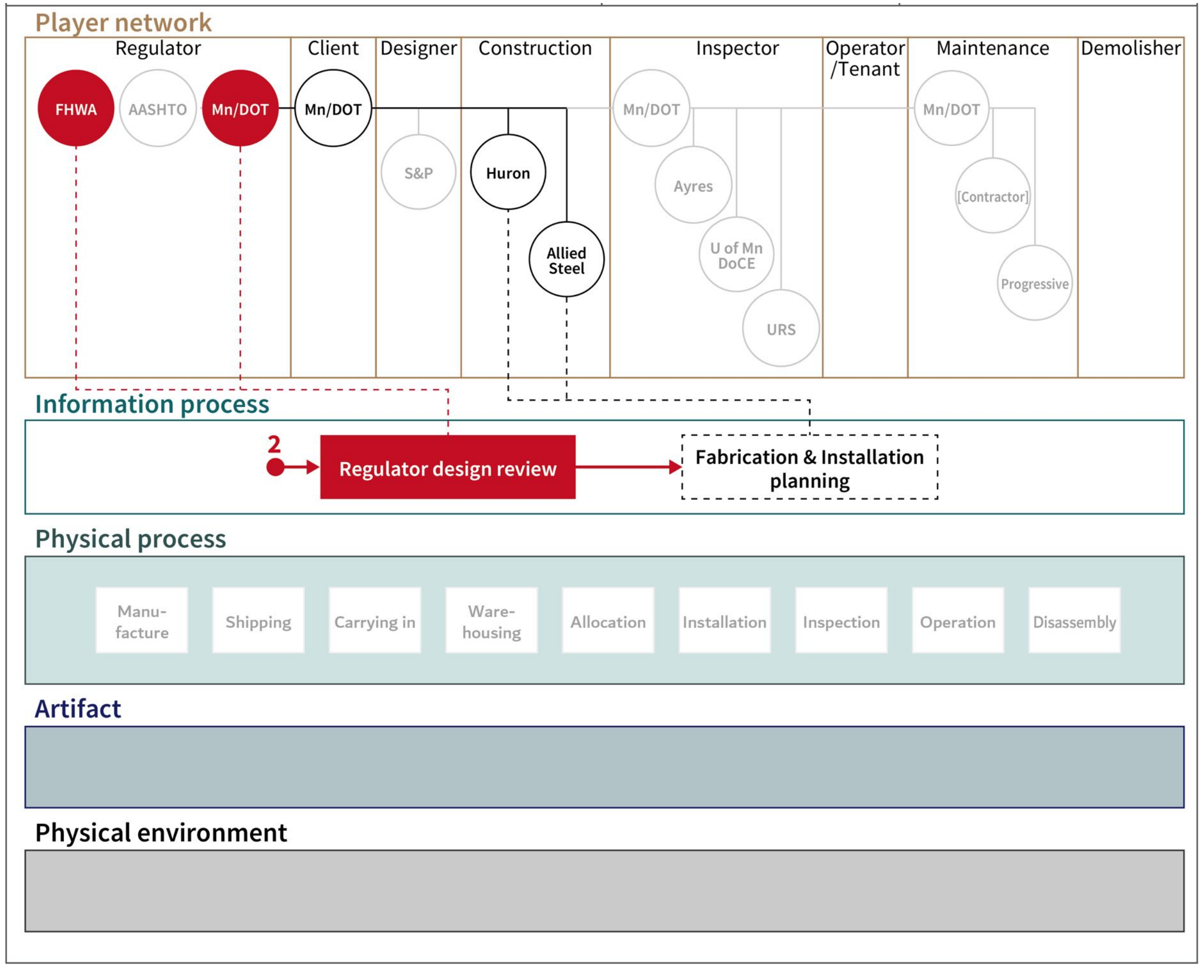
- Inadequate design review procedures
- Fabricated and installed as specified; gusset plates with insufficient capacity



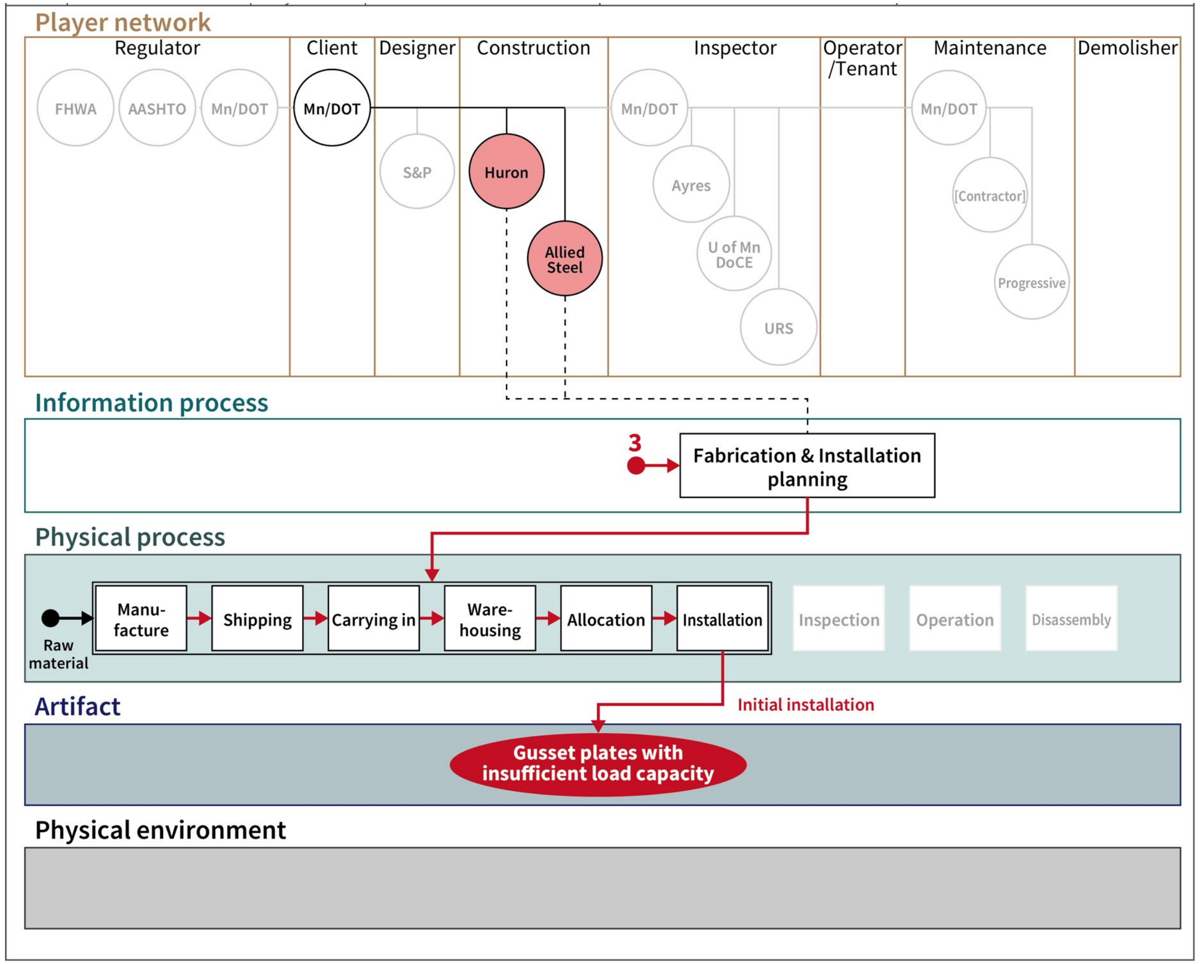
Model application

Sequence of frames

- Inadequate design review procedures



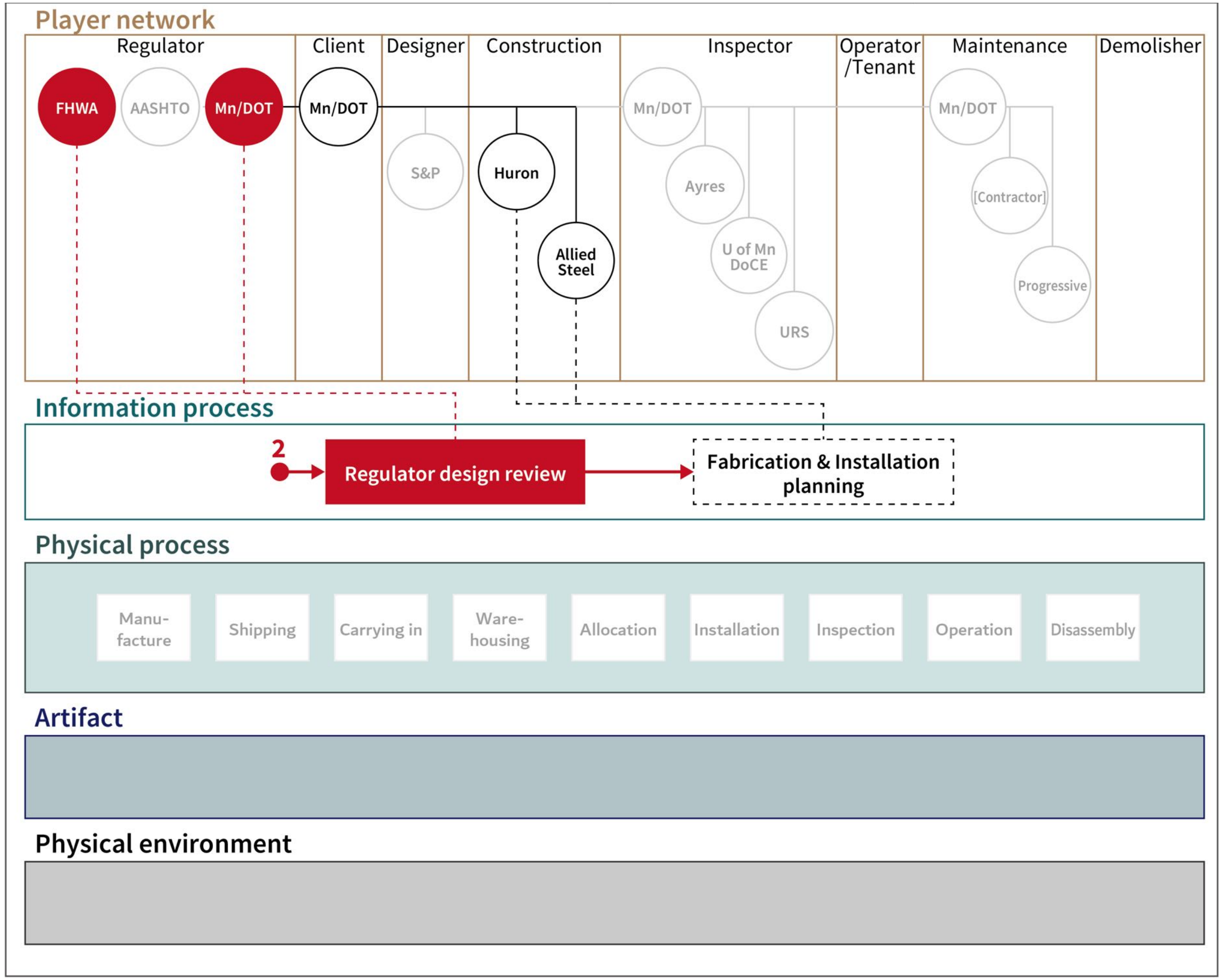
- Fabricated and installed as specified; gusset plates with insufficient capacity



Constructing each frame

1. Identify a defective process
   - From investigation documents
   - One defective process per frame
2. Illustrate the player network
   - Mark the players in charge of the defective processes
3. Draw the information & physical processes within the same frame
   - Mark the defective elements
4. **Establish links with preceding and succeeding frames**
   - Annotate the input arrow
   - Succeeding process

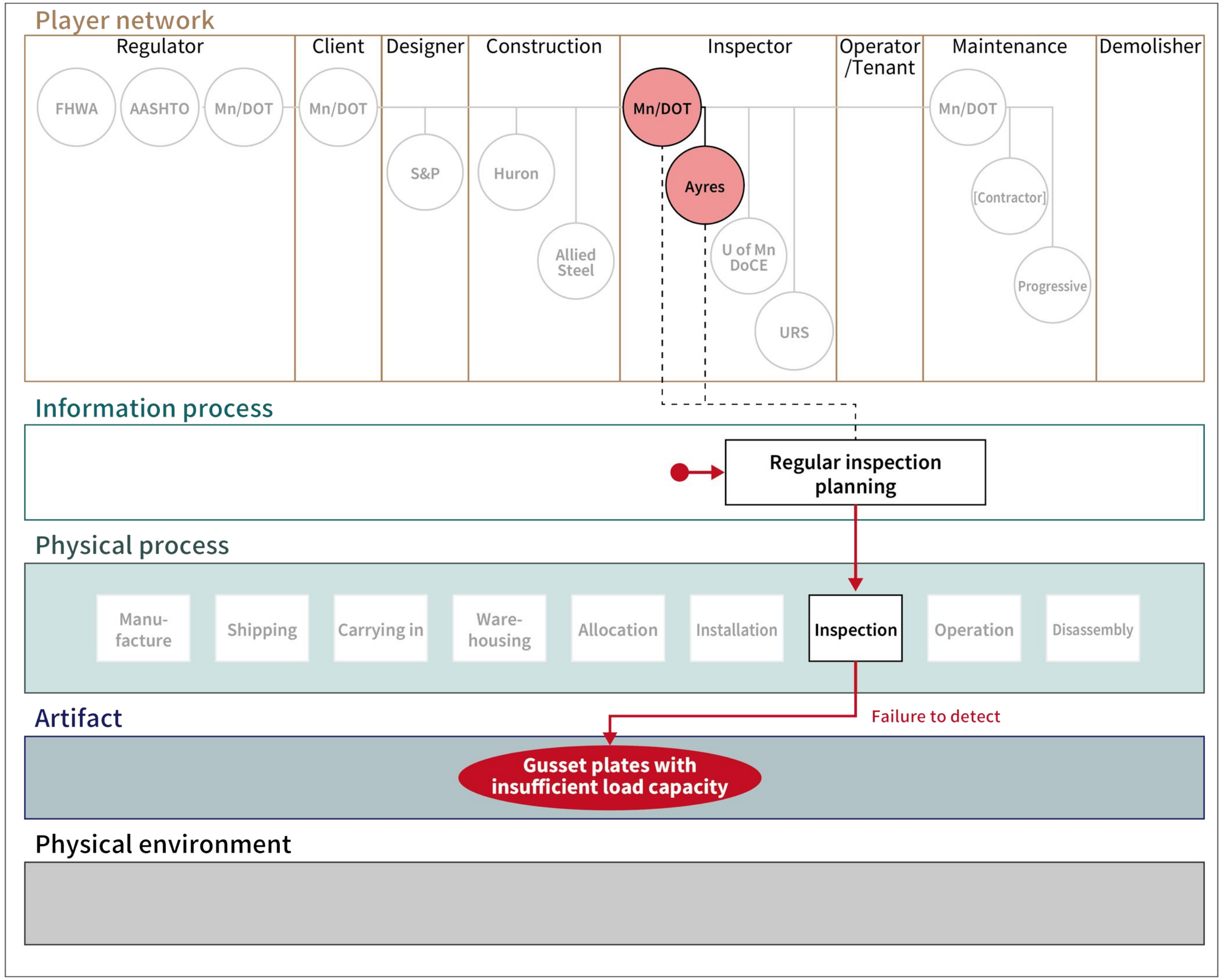
- **Inadequate design review procedures**



Other frames

Required inspections repeatedly failing to detect defective gusset plate design

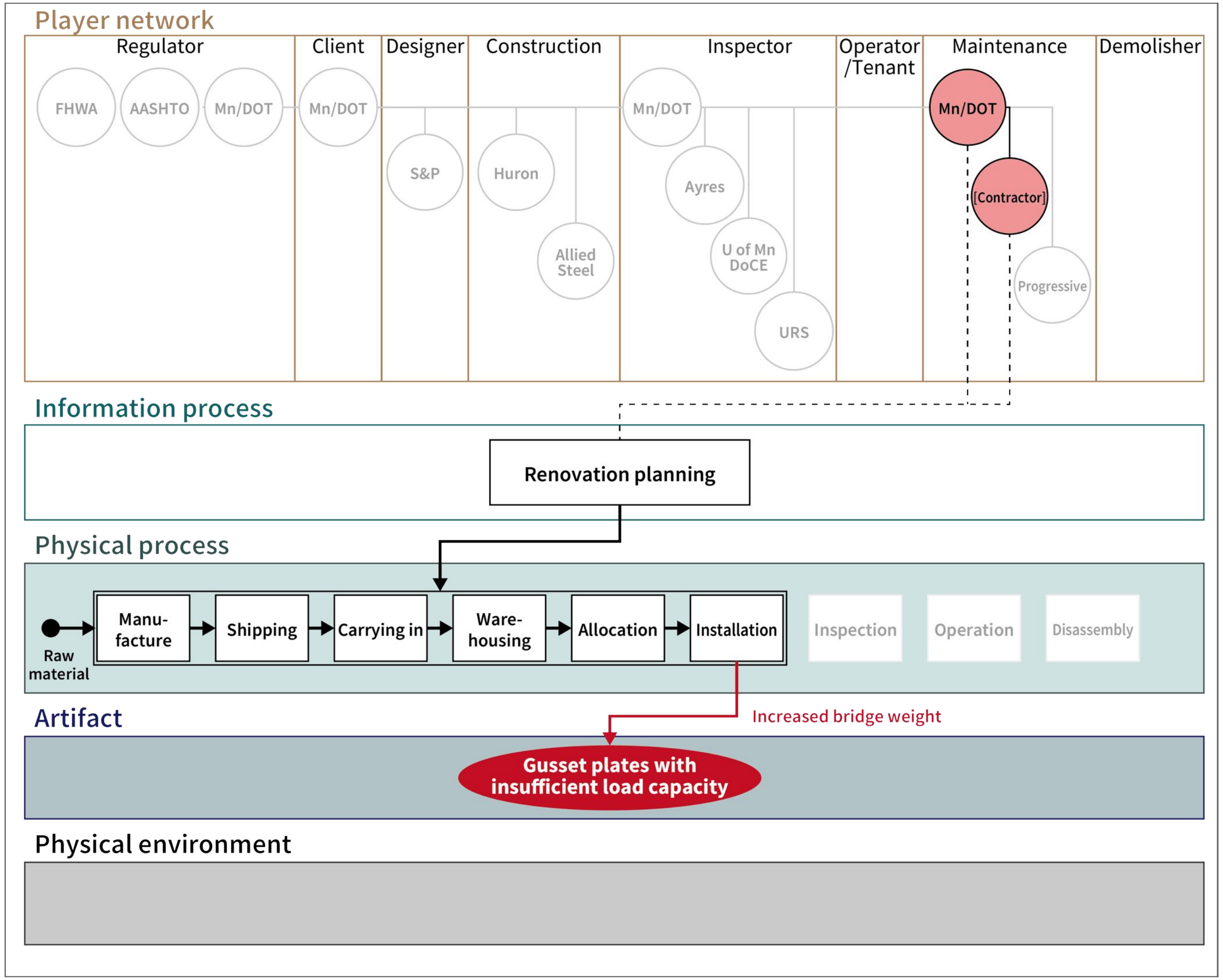
- Required annual inspections 1971-2007
- Gusset plates excluded from inspection guidelines
- Inspection work executed according to the guidelines
- Failing to detect the flaw in the gusset plates for ~40 years



Other frames

Renovation increased deck thickness

- Renovation work in 1977,1998
- Addition of median barriers, traffic railings & anti-icing system
- Both increased the weight of the bridge for justifiable purposes
- Unknowingly worsened the situation



Model application

List of frames

Players

Frames

Roles

Frame	Year	Defective process	Successive Frame	Regulator			Client	Designer	Construction		Inspector				Operator/ Tenant	Maintenance		Demolisher
				FHWA	AASHTO	Mn/DOT	Mn/DOT	Sverdrup & Parcel	Huron, Inc.	Allied Steel	Mn/DOT	Ayres Associates	U of Mn DoCE	URS		Contractor of Mn/DOT	PCI	
1	1963	Inappropriate structural calculations, not in accordance with AASHO specifications	2															
2	1964-65	Inadequate design quality control, did not detect and correct the error in design of the gusset plates	3															
3	1965	Inadequate design review procedures	4															
4	1965-67	Fabricated and installed as specified, gusset plates with insufficient capacity for the expected loads																
5	(not found)	Inadequate load rating requirements	6,7,8															
6	1967	Failing to conduct load rating before opening																
7	1979	Bridge load rating failing to address gusset plates																
8	1998	Bridge load rating failing to address gusset plates																
9	1977	Renovation increased deck thickness																
10	1998	Renovation increased dead load with the median barrier, traffic railings, and anti-icing system																
11	(not found)	Absence of gusset plates in inspection guidelines, manuals, and inspector training	12,13,14															
12	2001	Fatigue assessment not including gusset plates																
13	2003	Fatigue evaluation only inspecting gusset plates via visual methods																
14	1971-2007	Required inspections repetitively failing to detect the inadequacy of the gusset plate design																
15	(not found)	Lack of appropriate guidance for construction material storage on bridges	16															
16	2007	Repaving work with insufficient consideration of load concentration																

Model application

List of frames

				Roles														
				Regulator			Client	Designer	Construction		Inspector				Operator/ Tenant	Maintenance		Demolisher
Frame	Year	Defective process	Successive Frame	FHWA	AASHTO	Mn/DOT	Mn/DOT	Sverdrup & Parcel	Huron, Inc.	Allied Steel	Mn/DOT	Ayres Associates	U of Mn DoCE	URS		Contractor of Mn/DOT	PCI	
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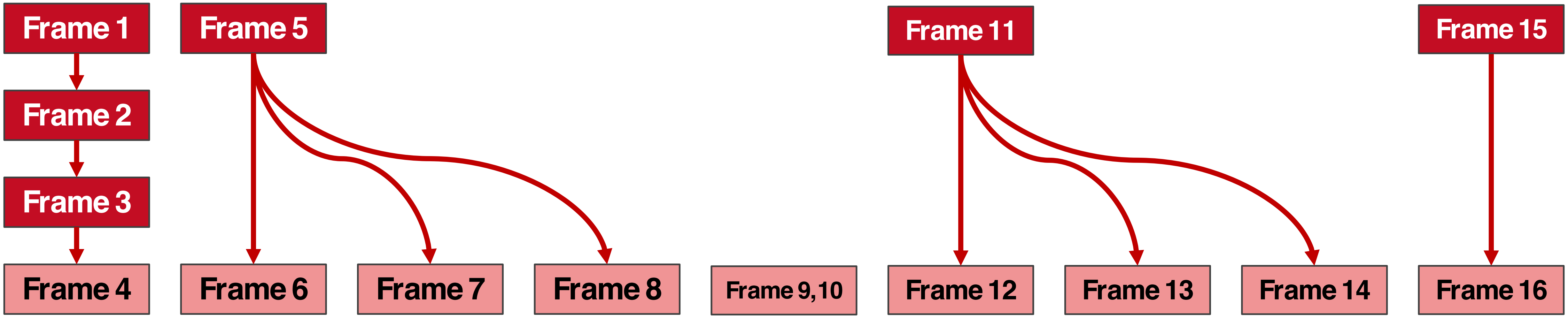
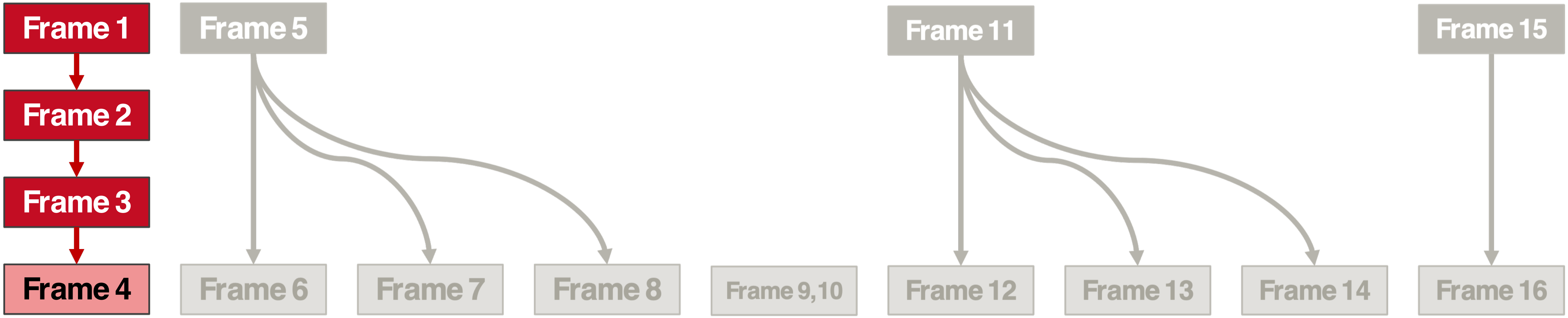
Threads of pathogen propagation



Threads of pathogen propagation

Initial injection: Defectively designed gusset plates fabricated and installed on the bridge



Frame 1 Inappropriate structural calculations, not in accordance with regulations

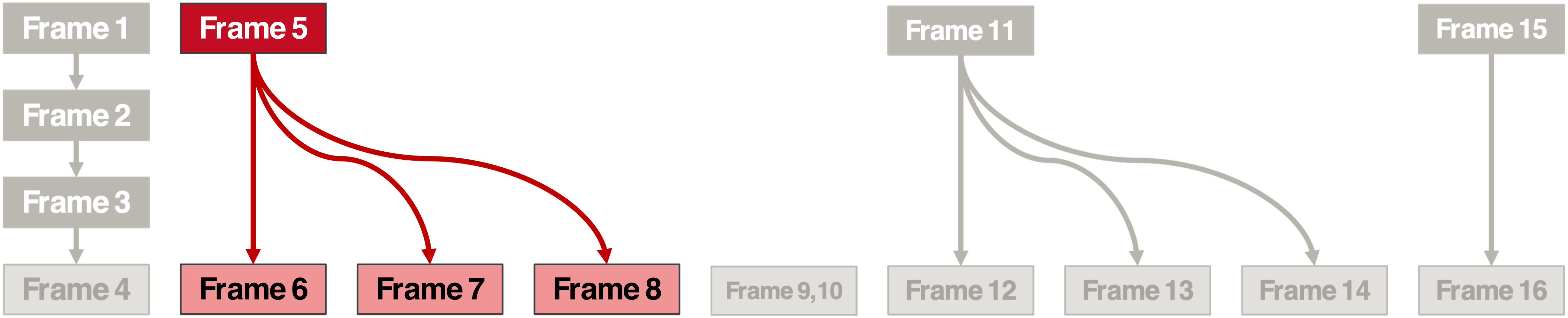
Frame 2 Inadequate internal design quality control

Frame 3 Inadequate regulatory design review procedures

Frame 4 Fabricated and installed as specified

Threads of pathogen propagation

Pathogen exposure: Failed bridge load rating before and after opening to public



Frame 5 Inadequate load rating requirements

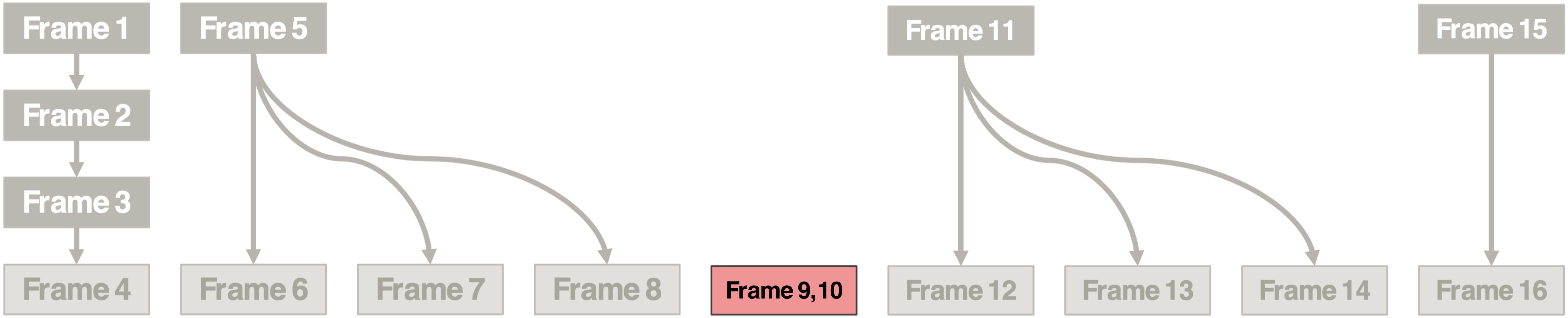
Frame 6 Failing to conduct load rating before bridge opening

Frame 7 Bridge load rating failing to address gusset plates (1979)

Frame 8 Bridge load rating failing to address gusset plates (1998)

Threads of pathogen propagation

Well-intended aggrevation: Renovation work unknowingly increased bridge weight

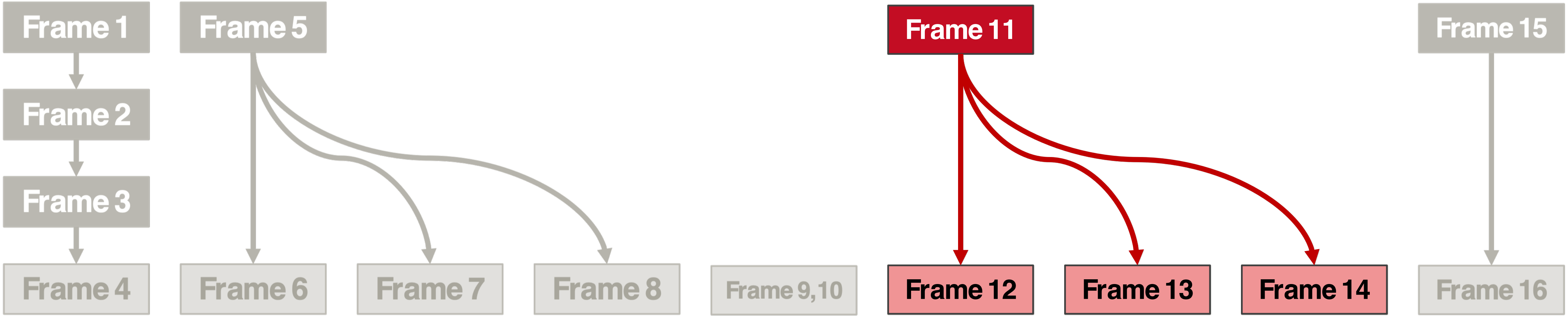


Frame 9 Renovation increased deck thickness (1977)

Frame 10 Renovation increased dead load with median barrier, traffic railings & anti-icing system (1998)

Threads of pathogen propagation

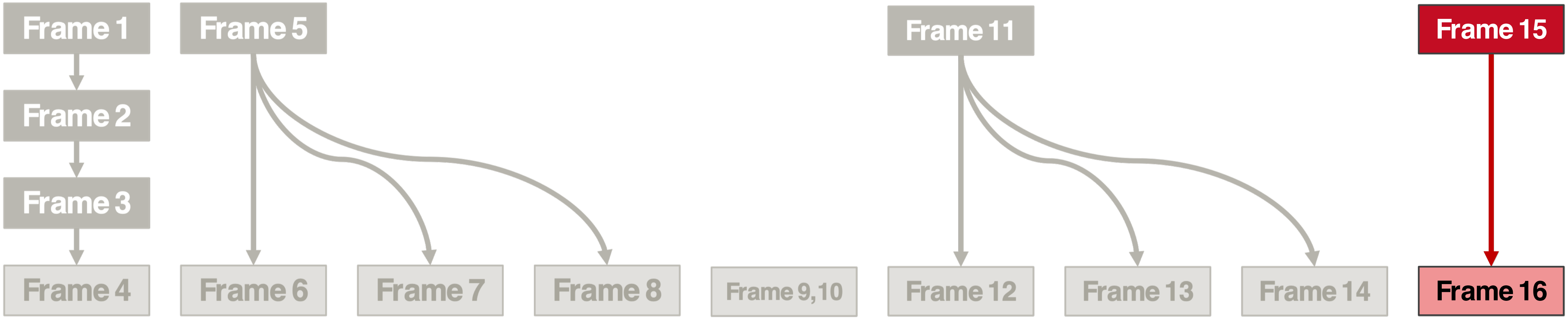
Missed opportunities: Routine inspections failing to detect flawed gusset plates



Frame 11	Absence of gusset plates in inspection guidelines
Frame 12	Fatigue assessment not including gusset plates
Frame 13	Fatigue evaluation only inspecting gusset plates via visual methods
Frame 14	Required inspections repeatedly failing to detect the inadequate design

Threads of pathogen propagation

Pathogen activation: Repaving work added weight, triggering the collapse



Frame 15	Lack of appropriate guidance for construction material storage on bridges
Frame 16	Repaving work with insufficient consideration of load concentration

Learnings

What the prototype model enabled us to see/think

1. **Emphasis on the time dimension**
    - The configuration of the player network changes dramatically over time
    - The frame structure can capture such transitions
2. **Illustrating accident causation as pathogen lifecycles**
    - Sequence of defective processes
    - Generation, propagation, injection & activation of pathogens
    - The embedded pathogen can go unnoticed
3. **Different players with different contributions across pathogen lifecycle**
    - Different types of defective processes
4. **Graphical display of multiple threads of pathogen propagation**
    - There can be multiple origins of pathogens
    - All threads contributing to the ultimate consequence = accident

Learnings

What the prototype model enabled us to see/think

1. Emphasis on the time dimension

Scope of this analysis has some limitations…

Only looked at which process failed

- What caused the processes to fail?
- The player network layer can be expanded

High illustration cost

- Information extracted manually
- Low graphical scalability at this point

Dimensions not considered

- Project scale
- Physical location
- Span of each frame, frame interval
- …

4. Graphical display of multiple threads of pathogen propagation
   - There can be multiple origins of pathogens
   - All threads contributing to the ultimate consequence = accident

Accident Case

Developing a Prototype Notation

Model Application

Learnings

Concluding Comments

Summary

- **Designed a prototype accident model for construction system failures**

  A graphical notation based on the frame and layer structure

- **Demonstrated its capabilities and limitations with a case study**

  Depicting the mechanism of accident causation as lifecycle of pathogens

Future work

Semi-automatic illustration

- Assistive tool for extracting information
- Application to more case studies

Expanding the player network layer

- Dynamic behavior of TMOs
- Diving into the "why" dimension

Pathogen archetypes

- Classifying the types of pathogens
- Differences and similarities

Prospective framework

- Learnings to be used for future projects
- Contributing to safety planning/design

References

1. Marshall, RD, Pfrang, EO, Leyendecker, EV, and Woodward, K A 1982, *Investigation of the Kansas City Hyatt Regency Walkways Collapse*. Washington, D.C.
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