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# System Theoretic Safety Analysis of the Sewol-Ho Ferry Accident in South Korea

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# DISCLAIMER:

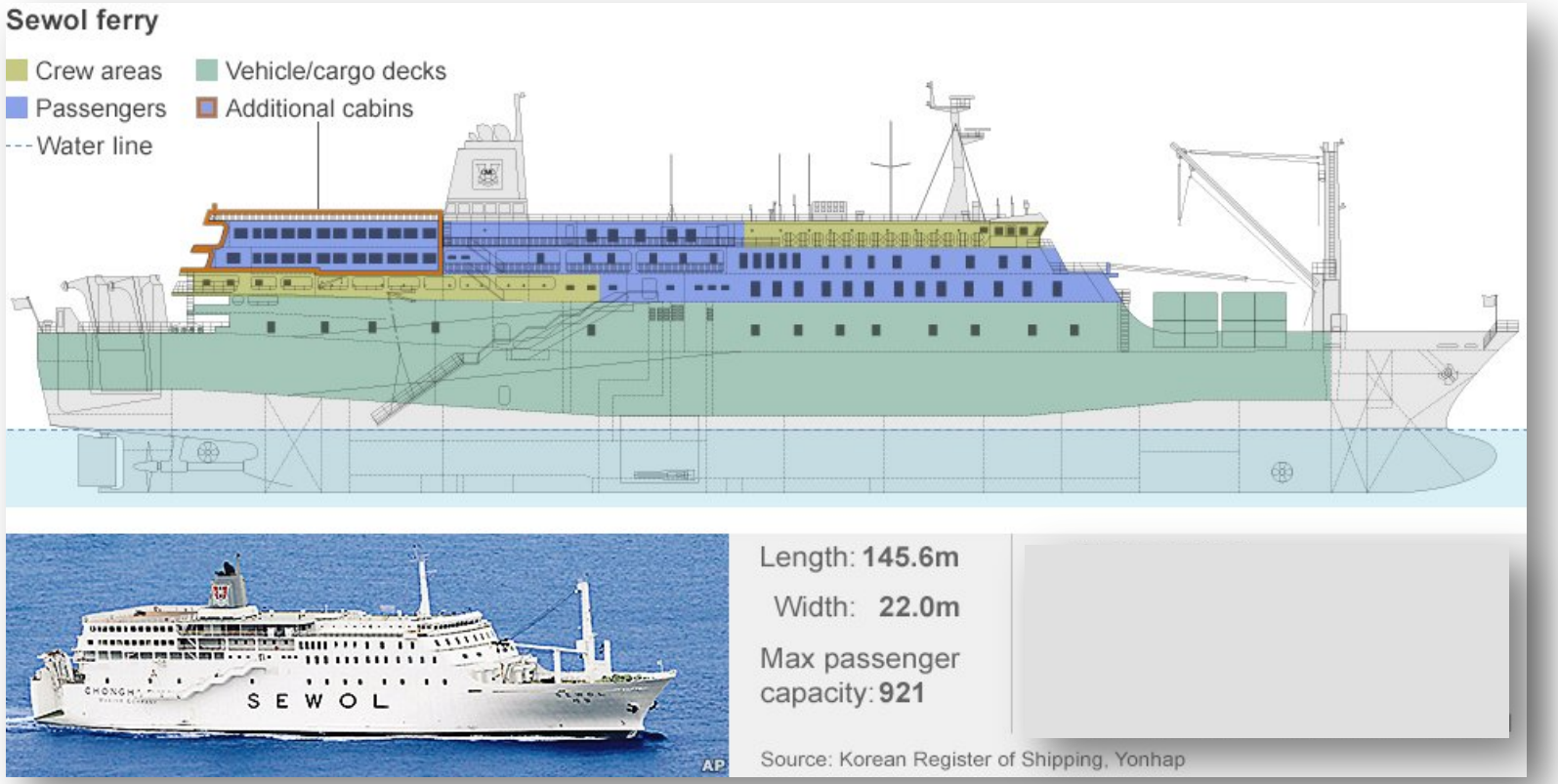
The views expressed in this presentation are those of the presenter and do not reflect the official policy or position of the United Technologies, Otis Elevator or University of Connecticut.

# Jindo Island, South Korea - The sinking

- On April 16, 2014, 08:48 am, a passenger ferry carrying 476 people capsized and then sank near Jindo Island when it made a sharp turn and began to list severely.
- 299 died and 5 people remained missing (07/15/2017).
- One of South Korea's worst maritime disasters

# The state of Sewol-Ho Ferry (1)

- Length: 146m
- Width: 22m
- Height: 24m
- Total weight: 6,825 tons
- Max passenger: 921
- Max load: 1,070 tons
- Max passenger cars: 88
- Max trucks: 60
- Max 10ft cargo: 247
- Required min ballast water: 1,703 tons




http://www.bbc.com/news/world-asia-27342967

# The state of Sewol-Ho Ferry (2)

- It is a Car Ferry, Motor Vessel (MV) or Roll-On/Roll-Off (RORO or ro-ro) Ship.
- The Sewol-Ho's owner, Chonghaejin Marine Company, redesigned the ferry to add cabins to the third, fourth, and fifth decks to accommodate additional 117 passengers, after purchasing it from a Japanese owner in 2012.
- Korean Register of Shipping (KR) approved the modifications with the proviso that it would have to carry much more ballast water and much less cargo to compensate the raised Center of Gravity (0.51m higher).
  - Max allowed load: 1,070 tons from 2,525 tons
  - Required ballast water: 1,703 tons from 370 tons

# The Crew

- Total 34 crew members including Captain
- 19 of the crew, including Captain are a part time member
- Captain: Oversight and command the crew
- 1st Mate: Supervise loading and securing cargo
- 2nd Mate: Maintain operational equipment
- 3rd Mate: Prepare and submit Ferry safety inspection chart

# The Voyage

- 3 round trips per week
- 250 mile-voyage for one way
- 13.5 hours for one way
- Total round trips of 241 times before the accident


http://www.bbc.com/news/world-asia-27342967

# Summary of Events (04/15/2014)

- Logistics team's supervisor directed the loading service company in order to do loading cargo and vehicles.
  - He guided to load 60 8ft cargo containers on the decks where were designed to load and stack only 10ft cargo ones.
- More vehicles arrived, were loaded and improperly secured while the departure had been delayed for two and a half hours due to a thick fog.
- 1st Mate adjusted Ballast Water to satisfy the ferry's Load Line
- At 09:30 pm, Officer at KSA approved the departure with checking Load Line once the fog was lifted.
- After the departure, 3rd Mate called KSA and provided fictitious information about the number of passengers and vehicles and the weight of cargo.

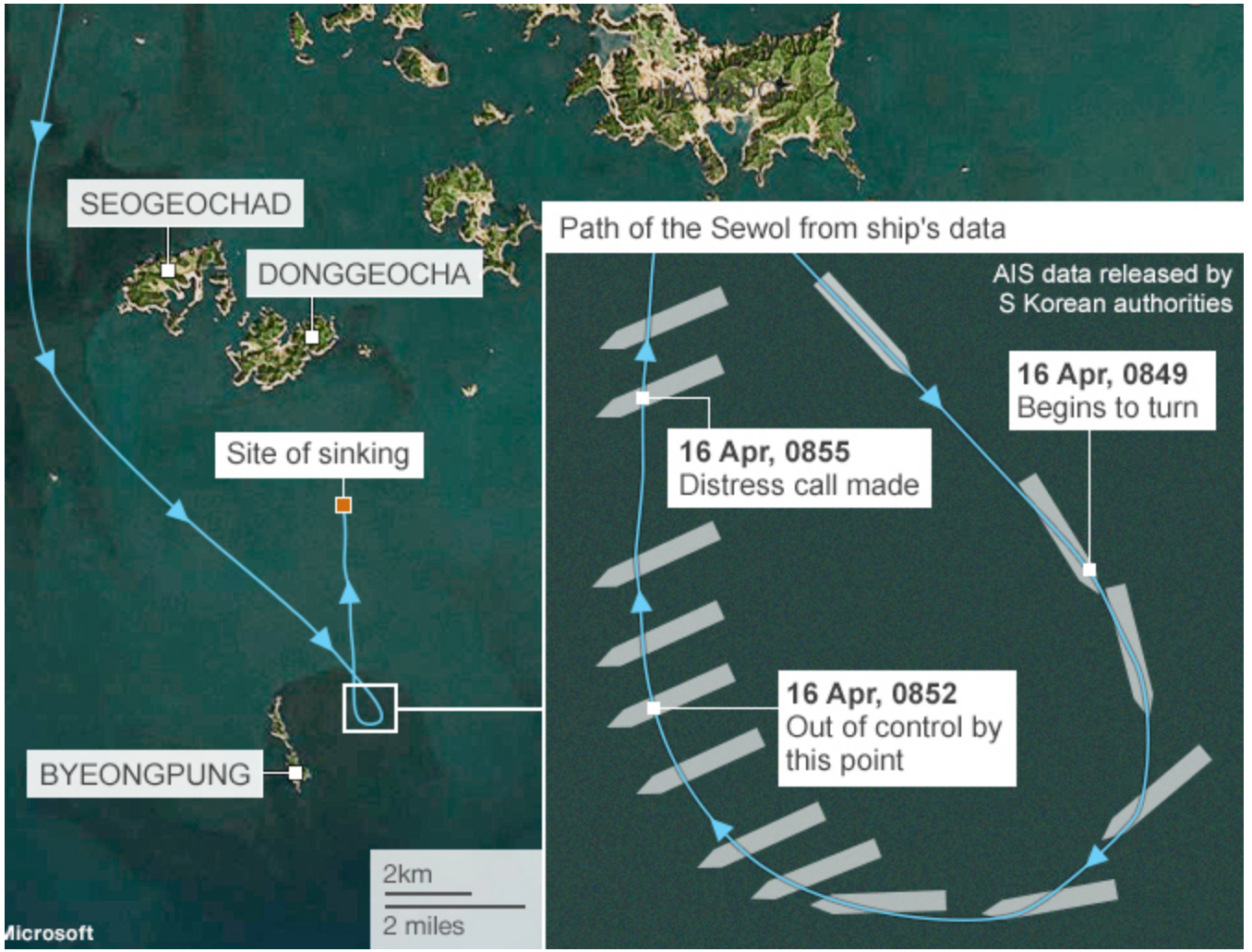
# Summary of Events (04/16/2014, 1/3)

- At 07:00 am, passing near Jindo Island.
- Winds were from a southwesterly direction at 2 to 3 knots; Seas ranged from 1 to 2 feet; Air temperatures were near 59° F or 15° C; Visibility was above 20 nautical miles.
- Helmsman steering the ferry at 135 degree.
- At 08:48 am, 3rd Mate who was monitoring the radar and radio on the bridge, gave two orders to Helmsman to turn the ferry: first to 140 degree and then to 145 degree.
- Helmsman heard the orders and made the first turn of five degrees to starboard. Once the ferry was heading at 140 degree, he steered it to 145 degree, but the ferry was listing sharply to port (how the helmsman made the second turn is still in question).

# Summary of Events (04/16/2014, 2/3)

- Listed 20 degrees into the water, causing cargo to fall to one side of the ferry.
- The ferry turned about 45 degrees to starboard and then, rotated 22 degrees on the spot for about 20 seconds.
- Water flow into the ferry through the bow and stern doors.
- At 08:50 am, listing 30 degrees to port.
- The Chief engineer stopped the engines.
- The Captain ordered the second mate to turn on the two anti-heeling pumps to return the ferry to its upright position, but the pumps were not working.
- At 09:16 am, the ferry was listing 45 degrees to port.
- At 10:31 am, the bow of the ferry was submerged.
- At 12:57 pm, the Sewol-Ho sank completely.

# Summary of Events (04/16/2014, 3/3)

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# Investigation Reports we reviewed

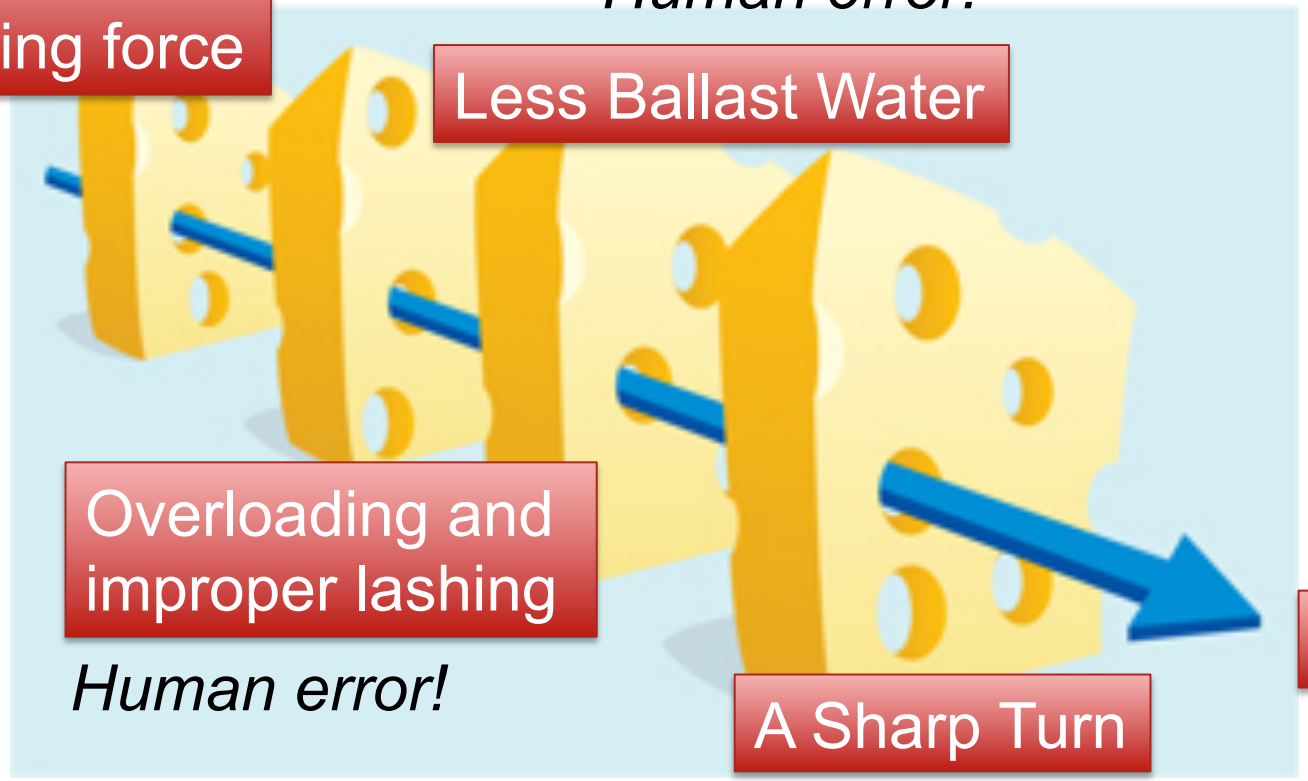
- KMST - Korea Maritime Safety Tribunal
  - Agency of Government of South Korea, which investigates maritime accidents
- BAI - Board of Audit and Inspection of Korea
  - For a special report to Special Committee of Korea National Assembly about the accident

# Root causes from Two investigation reports

Modification:
Lower Restoring force

*Human error!*

*Human error!*




*Human error!*

*Human error!*

There is comfort
These Chain of Events models are appealing because of the simplicity.
The simplicity allows for the model to be easily conveyed and comprehended.
However, the models are too simple to capture

Because the two investigation reports were completed
It could be much easier for them to simplify
Hindsight bias allows oversimplifying the causality,
If an outcome is good.

# Recommendations from Investigation reports

- Should provide training about proper methods of loading and lashing of cargo and vehicles to Crew of the ferry and Personnel of the loading and lashing service companies.
- Crew must follow the requirements of ballast water and cargo.
- Officers at KSA should have clear checklists, responsibilities, and roles.
- Install a weigh station on the quay to measure the total load.
- Include Ballast Water information in OMR.
- Reinforce the KR's safety inspection process including an update of the ship inspection checklist.
- Apply loading and lashing Codes required for far sea ferries or carrier to the near sea ferries or carriers.

# Problems with existing investigation reports

- Focus was on who or what to blame for the accident.
- Focused on eliminating failures and, therefore, provided obvious recommendations, but politically unaccepted ones were skipped.
- No systemic factors were considered.

During many months since the Sewol-Ho accident, mass media in South Korea had focused on finding people to blame for the accident. Due to the emphasis on the blame sought by Korean prosecutors, 399 people involved had been arrested, and 154 among them were put in jail at that time.

# CAST ANALYSIS

# Why Systems Theory needed for Safety?

- Safety is an emergent property.
- Systems with organized complexity (complex sociotechnical systems including the maritime transportation system) are too complex for complete analysis and too organized for statistics.
- However, ***General models*** of organized complex systems can be expressed in terms of ***a hierarchy of levels*** of an organization where each level imposes ***constraints*** on the activity of the level beneath it.

# STAMP
# (Systems-Theoretic Accident Model and Processes)

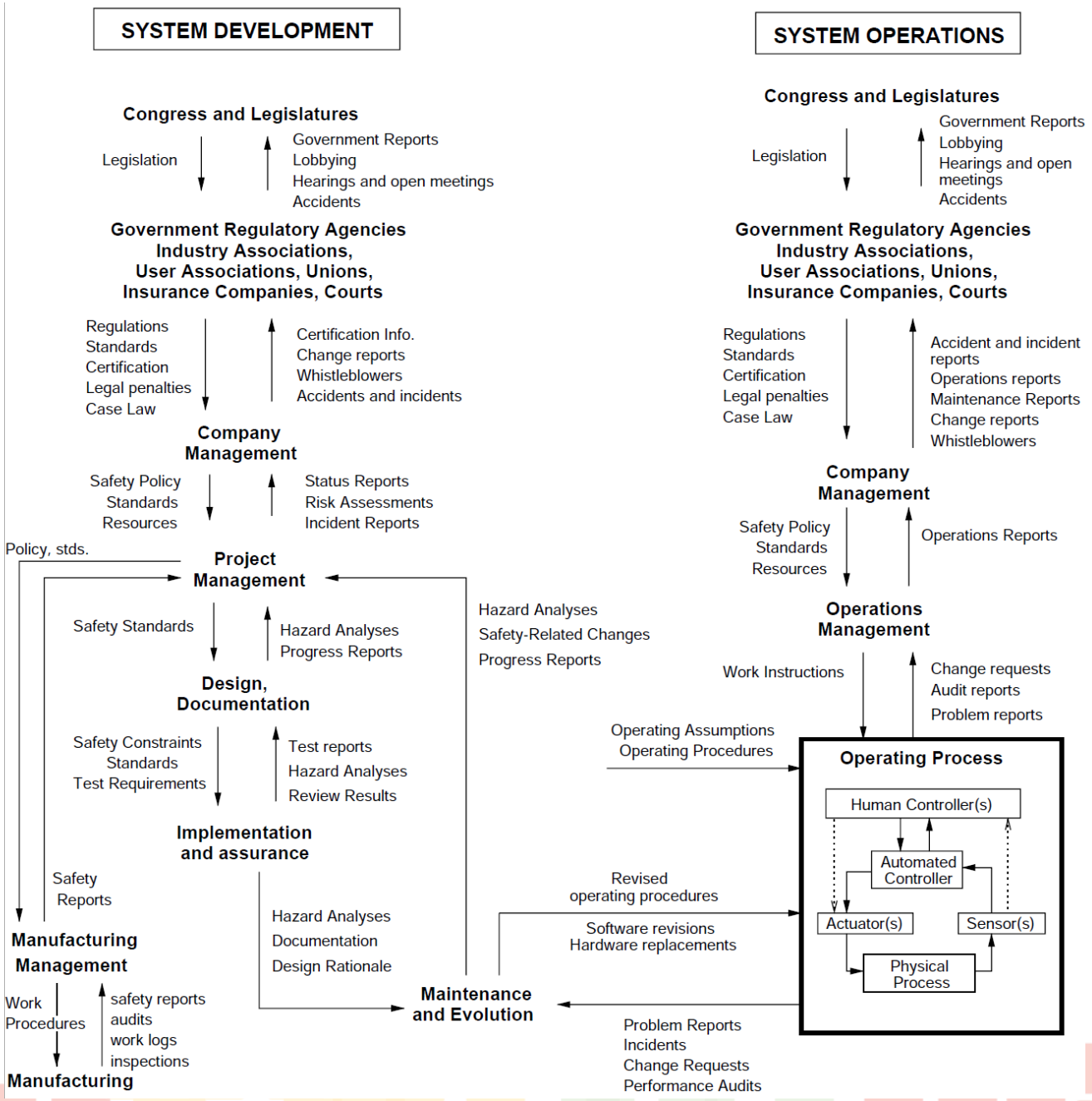
- An approach using systems theory and systems thinking
  - **Safety Constraints**
  - **Hierarchical Safety Control Structure**
  - **Process Models**
- A new causality model about how to prevent accidents of complex sociotechnical systems.
- Avoid hindsight bias by changing our emphasis in analyzing the role of humans in accidents from what they did wrong to why it made sense for them to act the way they did.
- Its focus is on eliminating or preventing hazards, not eliminating failures.

# STAMP

***The basis for a new foundation for safety engineering (Leveson, 2011)***

| Traditional Assumption | New Assumption |
|---|---|
| Accidents are caused by chains of directly related events. We can understand accidents and assess risk by looking at the chain of events leading to the loss. | Accidents are complex processes involving the entire sociotechnical system. Traditional event-chain models cannot describe this process adequately. |
| Most accidents are caused by operator error. Rewarding safe behavior and punishing unsafe behavior will eliminate or reduce accidents significantly. | Operator behavior is a product of the environment in which it occurs. To reduce operator "error" we must change the environment in which the operator works. |
| Major accidents occur from the chance simultaneous occurrence of random events. | Systems will tend to migrate toward states of higher risk. Such migration is predictable and can be prevented by appropriate system design or detected during operations using leading indicators of increasing risk. |
| Assigning blame is necessary to learn from and prevent accidents or incidents. | Blame is the enemy of safety. Focus should be on understanding how the system behavior as a whole contributed to the loss and not on who or what to blame for it. |

# STAMP




***Typical sociotechnical hierarchical safety control structure (Leveson, 2011)***

# CAST (Causal Analysis based on STAMP)

- Provide a framework or process to assist in understanding the entire accident process and identifying the most important systemic causal factors involved.
- Provide the ability to identify the symptoms and all the causal factors of the entire sociotechnical system design, including the weaknesses in the existing safety control structure and the systemic causes.

# CAST (Causal Analysis based on STAMP)

- Focus to why the accident occurred and how to prevent similar accidents in the future, understanding why people behaved the way they did, given the information they had at the time.
- Document dynamic process that led to the accident, by showing the sociotechnical safety control structure for the system involved and the safety constraints that were violated at each level of this control structure and why.

# Assumptions in CAST

- Sidney Dekker - Accident investigation should start with the assumption that most people (or professionals) have good intentions and do not on purpose cause accidents. Then, we can understand why people did not or could not act differently.
- Nancy G. Leveson - Blame is the enemy of safety. Blame is not an engineering concept but is a legal or moral one.

Most time, blame is assigned to the least politically powerful in the SCS or to those people who are physically and operationally closest to the accident.
The less we know about an accident, the most we will attribute to operator error.
Therefore, thorough investigation of serious accidents almost finds other factors.

# Nine steps of CAST (1)

1. Identify the system and hazard involved in the accident.
2. Identify the system safety constraints associated with that hazard.
3. Document the Safety Control Structure in place to control the hazard and enforce the safety constraints.
4. Determine the proximate events leading to the accident.
5. Analyze the accident at the physical system level.

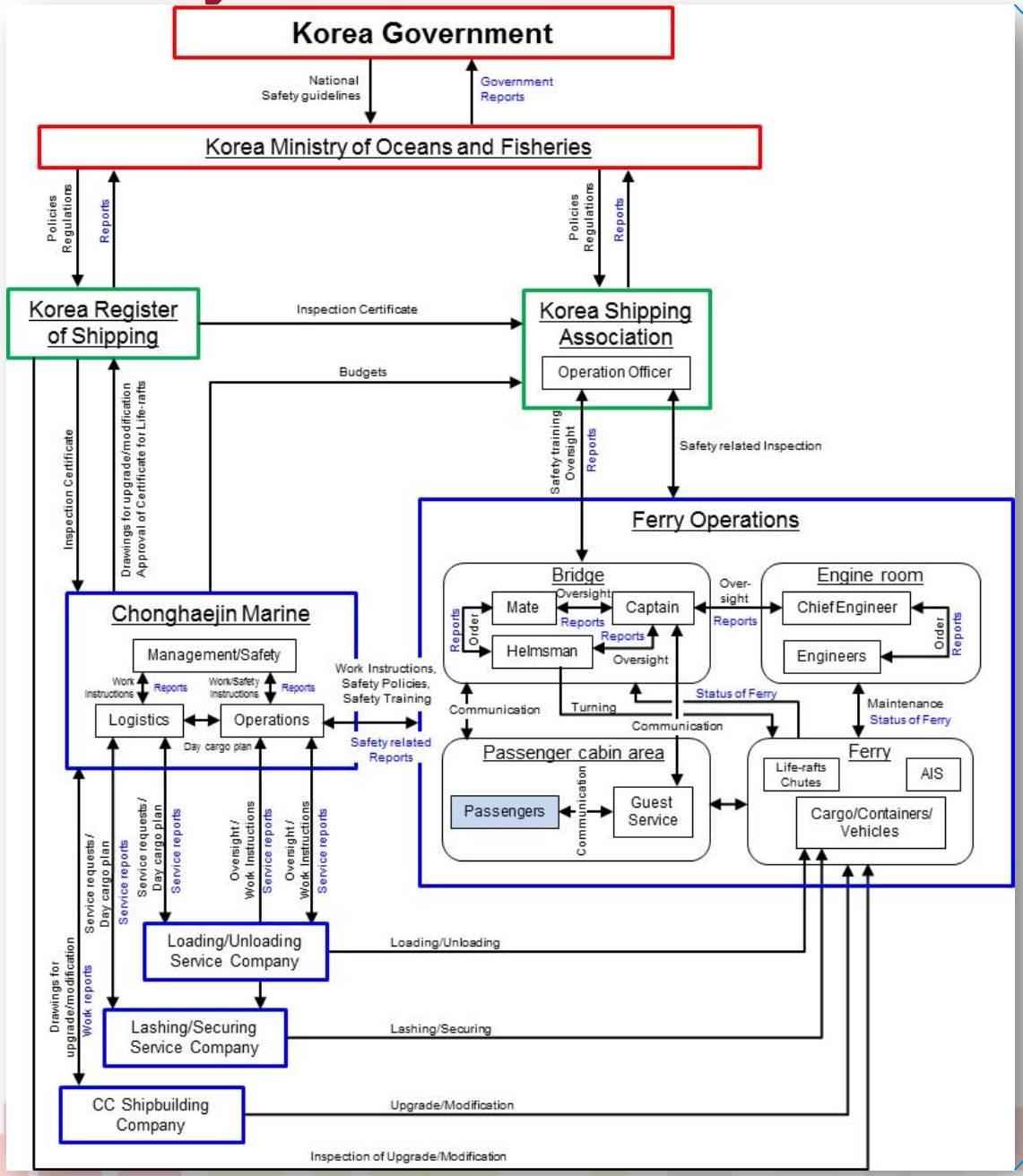
# Nine steps of CAST (2)

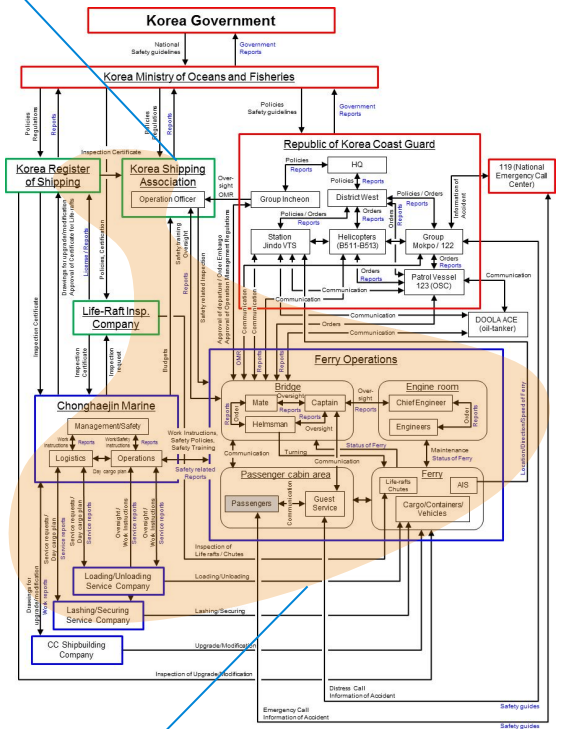
6. Moving up the levels of the SCS, determine how and why each successive higher level allowed or contributed to the inadequate control at the current level.
7. Examine overall communication and coordination contributors to the accident.
8. Determine the dynamics and changes in the system and the SCS relating to the accident and any weakening of the SCS over time.
9. Generate recommendations.

# Systems and Hazard Involved and System Safety Constraints

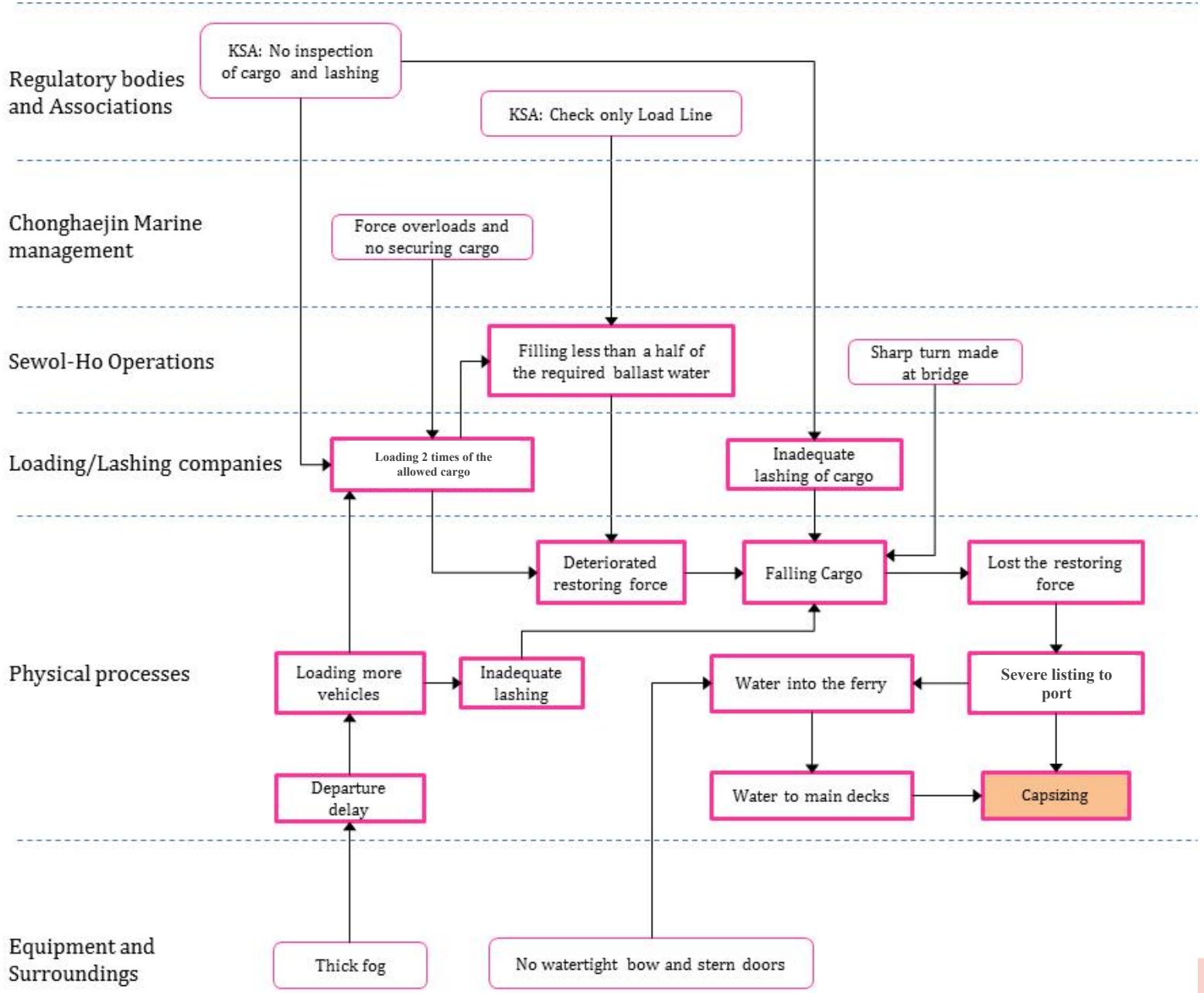
- System 1: Safe operations of the ferry
- System 2: Rescue operations of people on the distressed ferry
- Hazard: Capsizing of the ferry
- System Constraint: The ferry must not capsize

# Safety Control Structure



# Proximate events leading to the accident



# Physical System Level (1/4)

- Emergency and Safety Equipment involved: Partial list
  - Ballast: To maintain stability of the ferry
  - Lashing bands: Securing vehicles
  - Lashing bars, turnbuckles, twist locks and bridge fittings: Securing cargo containers
  - Watertight bow and stern doors
  - Anti-Heeling Pumps

# Physical System Level (2/4)

- Safety Requirements and Constraints violated
  - Load 987 tons or less
  - Load 10ft cargo only
  - Load ballast water at least 1,703 tons
  - Prevent water from flowing into the ferry
  - Secure vehicles lashed by using lashing bands.
  - Secure cargo lashed and fitted by using lashing bands and bars, turnbuckles, twist locks and bridge fittings.
  - Prevent the ferry from capsizing using anti-heeling pumps when the ferry is listed

# Physical System Level (3/4)

- Failures and Inadequate Controls
  - Inadequate quantitative methods or tools for assessing total weight of both cargo and vehicles and ballast water
  - Inadequate watertight bow and stern doors against water getting into the ferry
  - Inadequate emergency system: Anti-heeling pumps to return the ferry to its upright position didn’t work

# Physical System Level (4/4)

- Contextual Factors
  - Not enough lashing bands and bars, turnbuckles, twist locks and bridge fittings to carry out proper lashing
  - 8ft cargo needed to be loaded
  - New or foreign brand cars recently sold in South Korea had different types and locations of hooks
  - Practically unavailable lashing points on decks to secure cars
  - Cars arrived at the port 10 minutes before departure
  - Damaged rubber sealing parts of bow and stern doors
  - Load Line as the only quantitative indicator for assessing the total weight

# Moving up the levels – Captain (1/4)

- Safety Related Responsibilities
  - Check the following per the OMR:
    - Load total weight of max 987 tons and Ballast water min.1,703 tons
    - Cargo containers are all 10ft size ones
    - Cars are secured by four nylon lashing bands
    - Trucks are secured by ten nylon lashing bands
    - Minimum distance between vehicles is 2ft
    - Cargo containers are secured by lashing bars, turnbuckles, and corner fittings
    - Bow and stern doors closed and watertight

# Moving up the levels – Captain (2/4)

- Context in which Decisions made
  - Poor morale and Inadequate training
  - The captain was a part-time
  - The captain's safety-related reports and feedback had been ignored by the Logistics team and management.
  - Ballast water should be used to satisfy Load Line
  - No serious incidents before the accident

Morale at the company was low. "There was widespread belief among crew that the management had cut costs and attention to ensure safe operation of the ferry was absent."

Several months before the accident, several Mates left the company because the management ignored their reports about the overloading issue and they were concerned about the safety.

Overloads and less ballast water were routine occurrences and the concerns for them were seldom cared: Problems were either fixed without further examination or just ignored.

# Moving up the levels – Captain (3/4)

Due to the context, he had to do the following unsafe decisions allowing his members skip the safety procedures.

- Unsafe Decisions and Control Actions
  - Overlooked overload, less ballast and improper lashing
  - Overlooked ‘Ferry safety inspection chart: before-departure’ report process
  - Not report safety-related issues to safety team and management
  - Insufficient controls to correct the Logistics team on Overload and the loading/lashing companies on Improper lashing
  - Insufficient controls to correct 1st Mate on reduced ballast and 2nd Mate on no maintenance to fix water leak issue of bow and stern doors

# Moving up the levels – Captain (4/4)

- Process Model Flaws
  - Believed the big ferry was technically safe
  - Believed steering the ferry with small angle could prevent unsafe situations
  - Believed the management would not listen the feedback from part time captain

# Moving up the levels – Supervisor in Logistics (1/4)

- Safety Related Responsibilities
  - Provide ‘Day cargo plan’ to Operations, KSA and Loading and Lashing Service companies in advance for the safety review
  - Coordinate Loading and lashing members for safe operation
- Context in which Decisions made
  - Poor morale and Inadequate training
  - Due to the financial pressure, his manager directed to load as much as possible, no empty space available.

# Moving up the levels – Supervisor in Logistics (2/4)

- Unsafe Decisions and Control Actions
  - Not provide the day cargo plan to Operations, KSA and Service companies
  - Directed personnel from loading service company to do ‘overloads’
  - Directed personnel from loading service company to load 60 8ft cargo
  - Overlooked the improper lashing
- Process Model Flaws
  - Believed not much overloaded
  - Believed the ferry could carry the cargo-before-the-modification
  - Believed loading cargo evenly did not deteriorate the restoring force
  - Instead, adding more loads helped the ferry be more stable

# Moving up the levels – President (1/4)

- Safety Related Responsibilities
  - Provide and maintain the organizational safety culture
  - Establish the organizational safety policy

- Context in which Decisions made
  - Under financial pressures (too much spent on the modifications)
  - High personnel turnover (too much spent on the modifications)
  - No managers told about the safety issues after the modifications
  - No managers reported overload-related issues
  - No serious incidents before the accident

# Moving up the levels – President (2/4)

- Unsafe Decisions and Control Actions
  - Did not maintain the safety culture
  - Inadequate capability to detect overloading related issues
  - Insufficient controls to correct 'overloads,' and 'overlook'
  - Not provide any ways to stop overloading and poor lashing
  - Insufficient controls to collect ‘feedback’
- Process Model Flaws
  - Believed the big ferry was technically safe
  - Believed the ferry could carry the cargo capacity and the ballast required before the modifications
  - Believed loading cargo evenly helps the ferry be more stable

# Moving up the levels – KSA's Operation officer (1/4)

- Safety Related Responsibilities
  - Review 'Ferry safety inspection chart: before-departure' submitted by the ferry's captain before departure
  - Check and inspect safety-related equipment and watertight bow and stern doors before departure
  - Check the number of passengers and total weight of both cargo and vehicles before departure
  - Check and examine how well cargo and vehicles are secured before departure
  - Check Load Line before departure

# Moving up the levels – KSA's Operation officer (2/4)

- Context in which Decisions made
  - Relied on the operations' voluntary compliance with guidelines
  - Crew and passengers complained about departure delay
  - KSA as an association of maritime transportation companies
  - Not provided quantitative methods for assessing total weight
  - No ballast water information given by KR
  - Not provided appropriate time for checking all cargo and vehicles and the securing conditions
  - 'Ferry safety inspection chart: before-departure' process overlooked by his supervisor.
  - Inadequate training

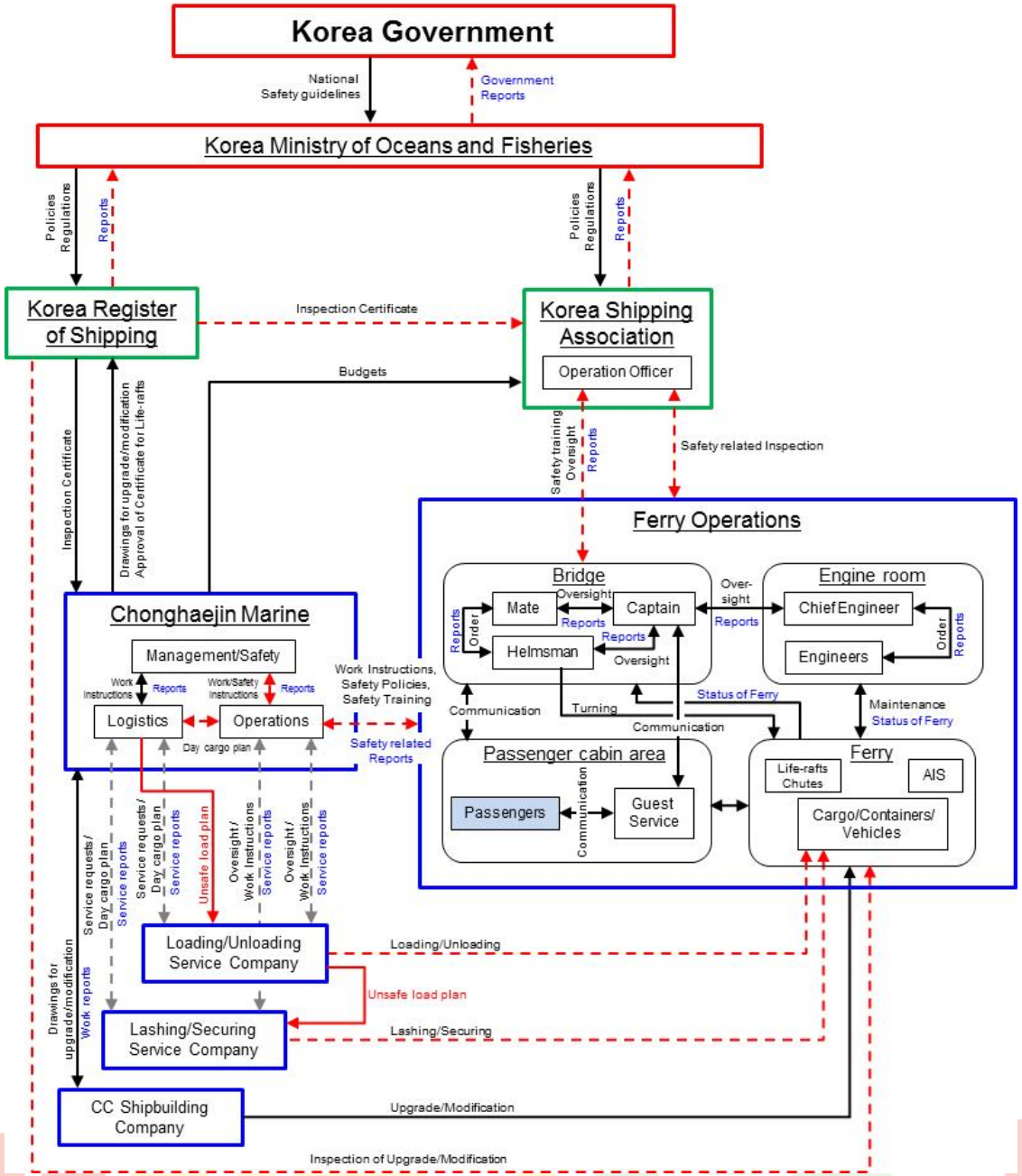
# Moving up the levels – KSA's Operation officer (3/4)

- Unsafe Decisions and Control Actions
  - Inadequate capability to detect overloading related issues
  - Inadequate capability in understanding restoring force, ballast water, load limit and load line
  - Insufficient controls to correct 'overloads'
  - Not report the safety-related issues to manager whenever needed
  - Not detect 8ft cargo containers loaded
  - Not inspect if cars secured by four lashing bands, trucks secured by ten nylon lashing bands, and cargo secured by lashing bars, turnbuckles, corner fittings
  - Not inspect minimum distance between vehicles
  - Not provide direction to stop overloading and poor lashing
  - Overlook submitting inspection chart without data after the departure

# Moving up the levels – KSA's Operation officer (4/4)

- Process Model Flaws
  - Believed the load line is the only critical factor to guarantee the ferry's safe operation
  - Believed ballast water is filled as much as required

# Communication and coordination Contributors



# Communication and coordination Contributors

- Day-cargo-plan made by Chonghaejin Marine had never been shared with Lashing service company
- Logistics neither communicated nor coordinated with Lashing service company
- Instead, Loading service company had communicated with Lashing service company

# Communication and coordination Contributors

- Overlap problems in communications
  - Operations had no communications with personnel of the Lashing service company because Captain and 1st Mate thought Logistics commanded them but no parties at Chonghaejin Marine communicated with them about safety issues
    - Only Foreman who was an on-site manager of Loading service company did so
  - Lashing service company could not report any safety issues to Chonghaejin Marine directly but only to Foreman of Loading service company. Foreman filtered out the issues on his own judgment and provided no feedback to Chonghaejin Marine

# Dynamics and changes

- Financial problem led management to cut safety margins:
  - Overloaded cargo and vehicles, improperly secured cargo containers and vehicles and then, filled less ballast water
  - Maintained their mental model about cargo weight and ballast with the ‘before-modification ones,’ causing management to force Captain and the crew to operate the ferry in the state of risk
- New types of hooks of new Korean and European vehicles
- KR contributed to the accident through the erosion of the safety controls:
  - Without having any history of severe accidents, the inspector allowed CM to modify the ferry by reducing load weight and increasing ballast water, believing CM follows the requirements

# Recommendations

- Government to implement programs to monitor the effect of privatization on the notification procedures followed
  - Korea Ministry of Oceans and Fisheries needs to involve in it under the anti-regulatory culture in Korea, although KSA is an association of marine transportation business companies.
  - Safety Cultural Changes in organizations require high-level leadership by management including Korea government.
  - KMOF should have stepped in to achieve the overall safety goals, instead of fully relying on voluntary compliance with regulations, policies and guidelines.

# Recommendations

- Review and enhance processes for approving inspection certificate at KR
  - Enforce a physical inspection process for lashing of various vehicles including new Korean and European vehicles
  - Enforce a review process for inspecting drawings with actual structures
  - Consider introducing safety leading indicators to identify leading indicators of migration toward states of higher risk per cargo load and ballast water

# Recommendations

- Establish and reinforce organizational safety policy and culture at Chonghaejin Marine
  - Improve morale in the company; Maintain leadership and commitment to safety as the highest priority; Enforce safety integrated into the organizational culture
- Create and provide safety information training to the management and Logistics team
  - Provide a complete understanding of restoring force, ballast water, maximum load limit and load line; Update and reinforce safety information training policy for a part-time captain to provide safety training to his or her crew

# Recommendations

- Regularize and improve safety communication (information and feedback) channels
  - Review and enforce effective communication channels for disseminating safety information
  - Improve feedback loops between Operations and Management and between Operations and Loading and Lashing services companies

# Conclusions

- Behaviors of Captain and the crew and KSA's officer made sense in context, and could be very good if they did "heroic actions"
- The more we know about the accident process using CAST, the more difficult we find persons to blame
- We can easily find effective ways to prevent similar accidents in the future
- Holistic approach of STAMP and CAST, based on control and enforcing safety constraints in the entire sociotechnical system is needed to ensure the safety

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