Design for Safety: Risk-Based Design

Life-Cycle Risk Management

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In Partnership with
Safety at Sea Ltd / Brookes Bell Group

Presentation Outline

- Background
- Prevailing Safety System
- Emerging Safety System
- Design for Safety: Risk-Based Design
- Life-Cycle Risk Management
- Risk-Based Design Implementation Example
- Concluding Remarks

Risk is an Inherent Feature in the Maritime Industry!

Containing Risk Today (Human Life)

SOLAS

⇩

Consensus-based, **minimum** standards of safety

Targeting to reduce consequences

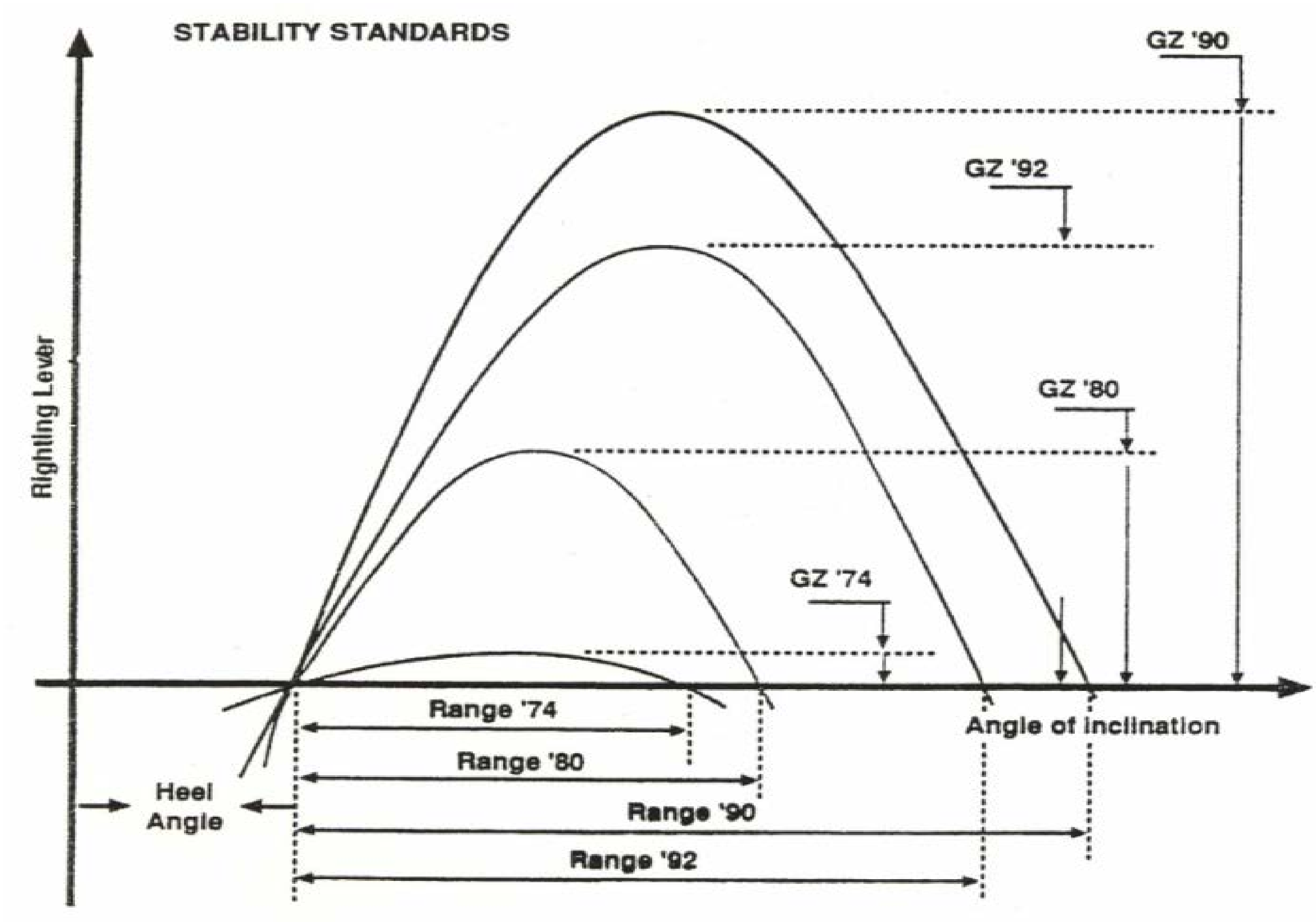
Historical risk, reflecting specific data sets

⇩

Compliance with Rules/Regulations

Prevailing Safety System

Amendments



Prevailing Safety System

Accident Driven

Year	Ferry Accidents
1953	Princess Victoria: **vehicle deck** and starboard engine room **flooding** (134 dead).
1974	Straitsman: **vehicle deck flooding** (2 dead)
1987	Herald of Free Enterprise: **flooding of the vehicle deck** (193 dead).
1987	Santa Margarita Dos: **flooding of the vehicle deck** (5 dead).
1994	Estonia: **flooding of the vehicle deck** (852 dead).
2006	Al Salam Boccaccio '98: **flooding of the vehicle deck**, following fire (1,002 dead).

Design Today: Rules-Based Design

Logistics

Business

“Perceived” Risk

Owner

Requirements

Needed functions, basic
servi… earning …
low… gh spe…
manoeuvrability, etc.

Performance

Functionality

Safety Rules

Expected safety level for
all accident …
…gu…
double h…
protection, etc.

Yard

Concept Design Studies

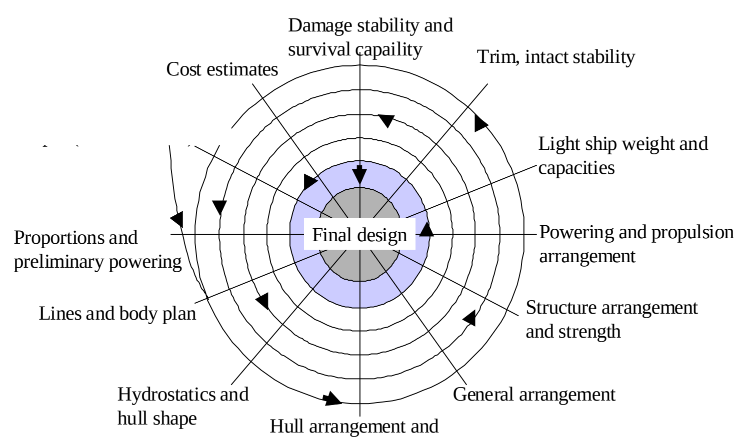
Final Concept Design Solution

Time

Contract

Experience, Talent!

Available Knowledge
Design Tools
& methods

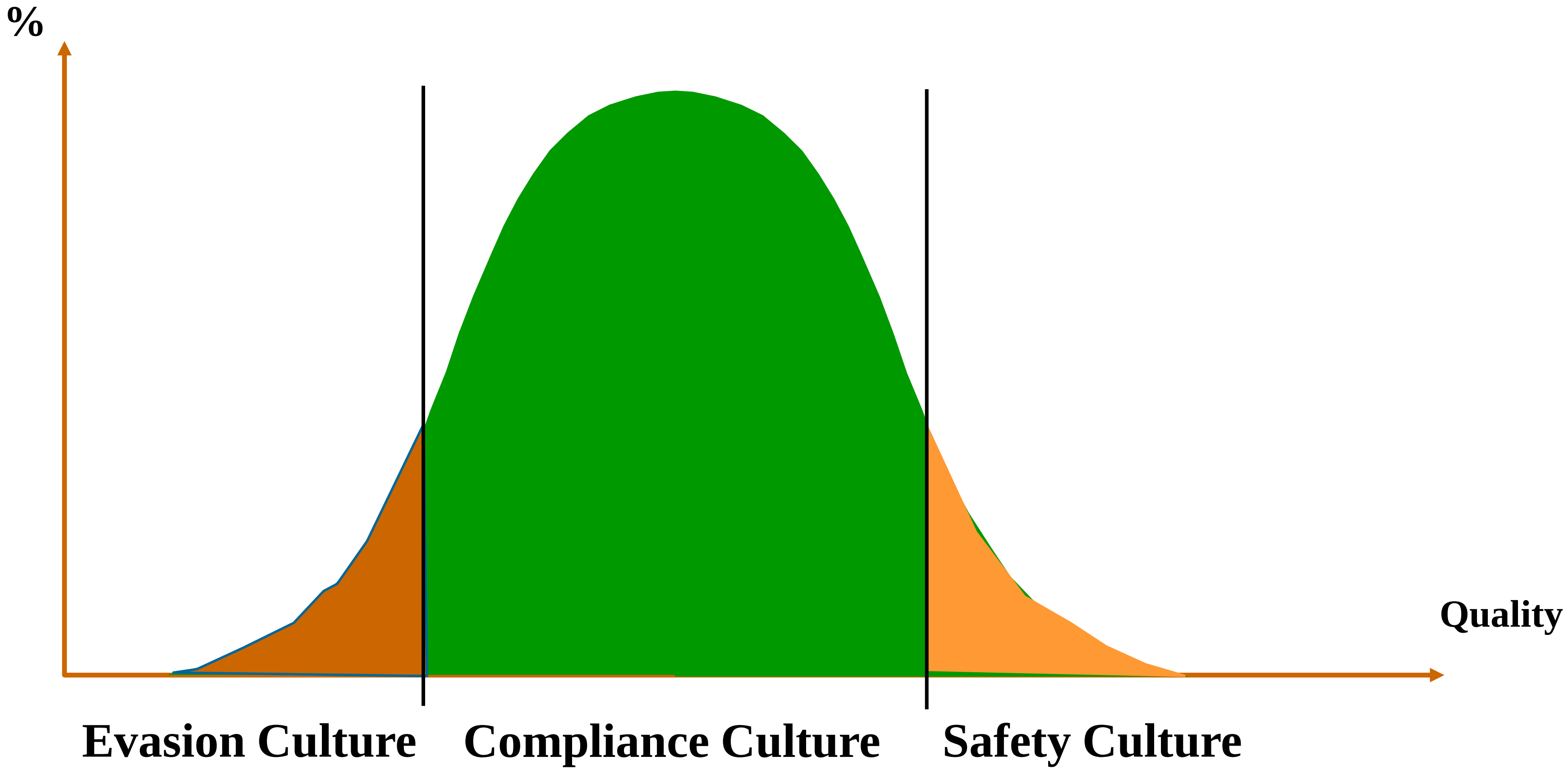


Dillon, 1969 and Erichsen 1989

Design Today: Rules-Based Design

Safety is treated as Rule Compliance

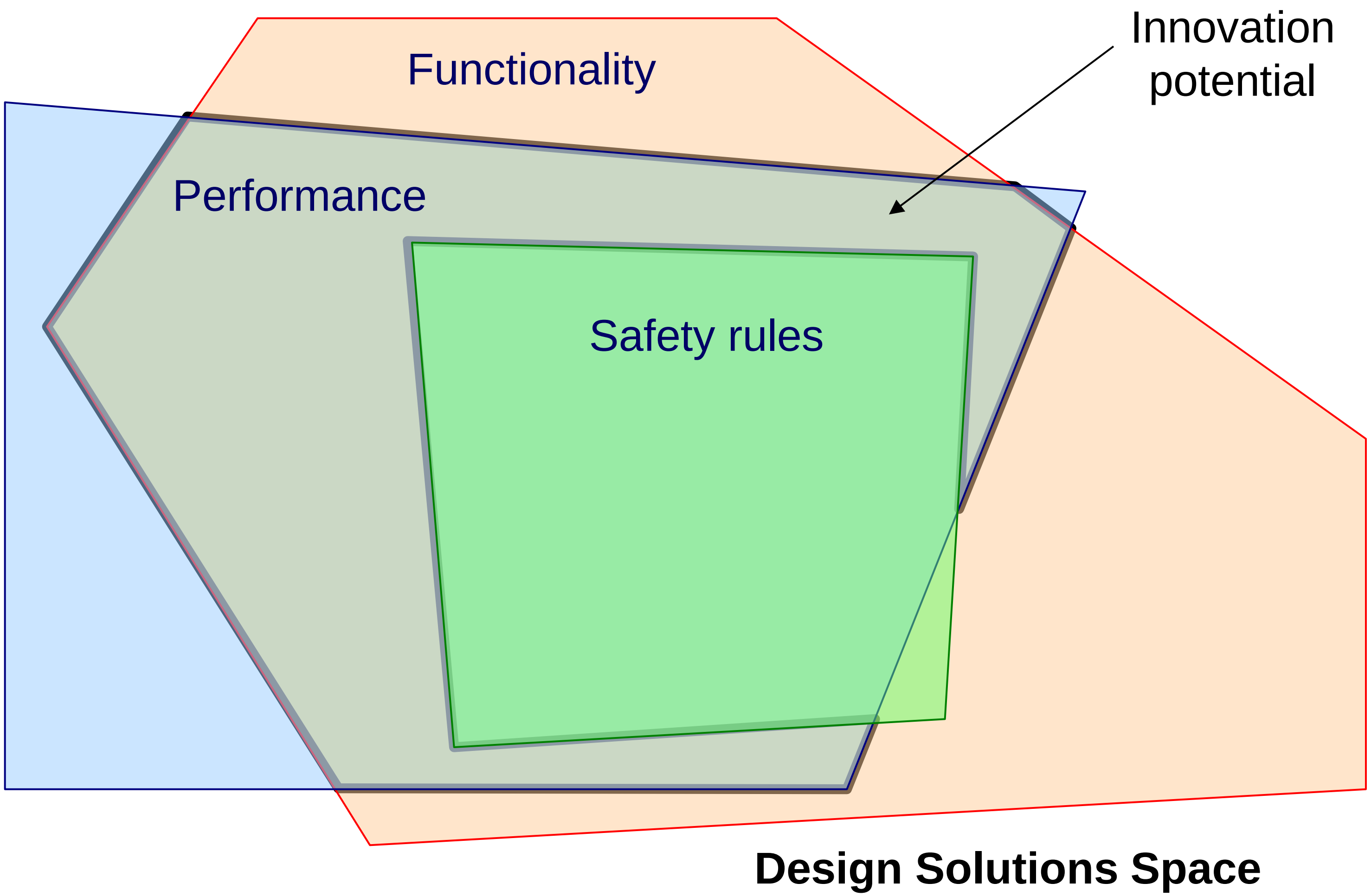
→ This can not nurture a safety culture!



Design Today: Rules-Based Design

Safety is treated as Constraint

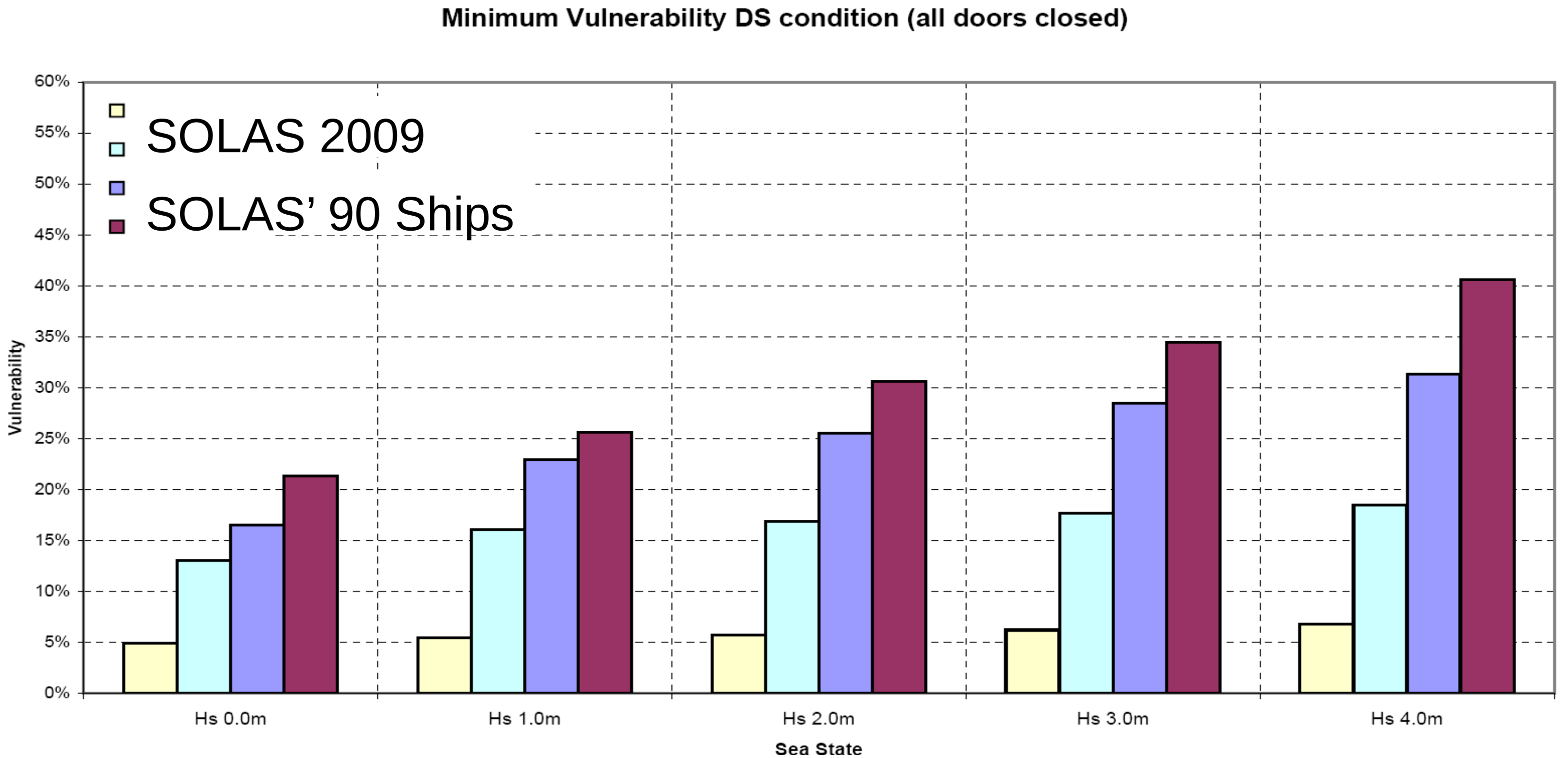
→ Safety eats on innovation potential



Design Today: Rules-Based Design

Safety Level of a Design is unknown

SOLAS 90 and SOLAS 2009 are meant to provide the same safety level for damage stability of passenger ships → they do not!



Design Today: Rules-Based Design

Meeting Safety Expectations is left to Chance

- Incompatibility of design and performance evaluation tools, time limitations, lack of an integrated design environment; all **hinder design optimisation** in the design process.
- Lack of a formal optimisation process also implies that **life-cycle issues** (future costs / earning potential) **are not being taken "explicitly" into account** in design decision-making.

→ optimal design solutions are not possible!

The Changing Face of Ship Safety

Safety Drivers

Shipping → **Safety** Need for change ← Society

Shipping

- escalation in size
- specialisation
- higher speed
- construction materials
- over-capacity
- greater complexity
- more information
- less time
- competition
- manning
- ageing fleet

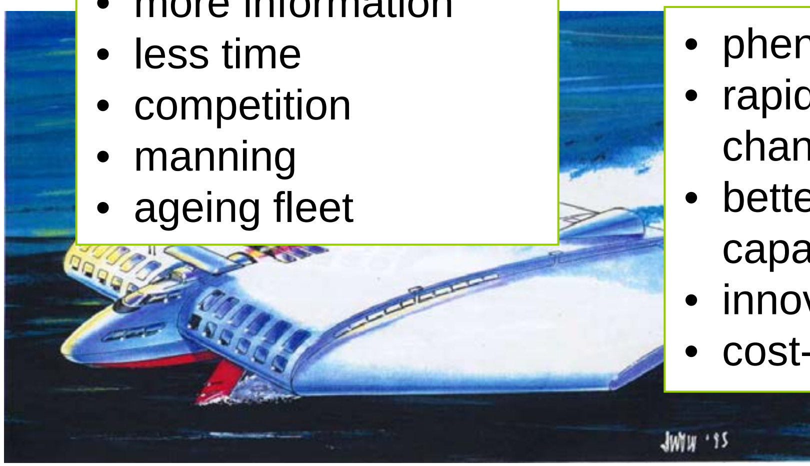
Safety
Need for change

Society

- public expectation for higher safety
- Increased public regard for human life and environment
- media coverage
- political pressures

Science & Technology

- phenomenal progress
- rapid technological change
- better technical capabilities
- innovation potential
- cost-effective safety



The Changing Face of Ship Safety

Need for Change

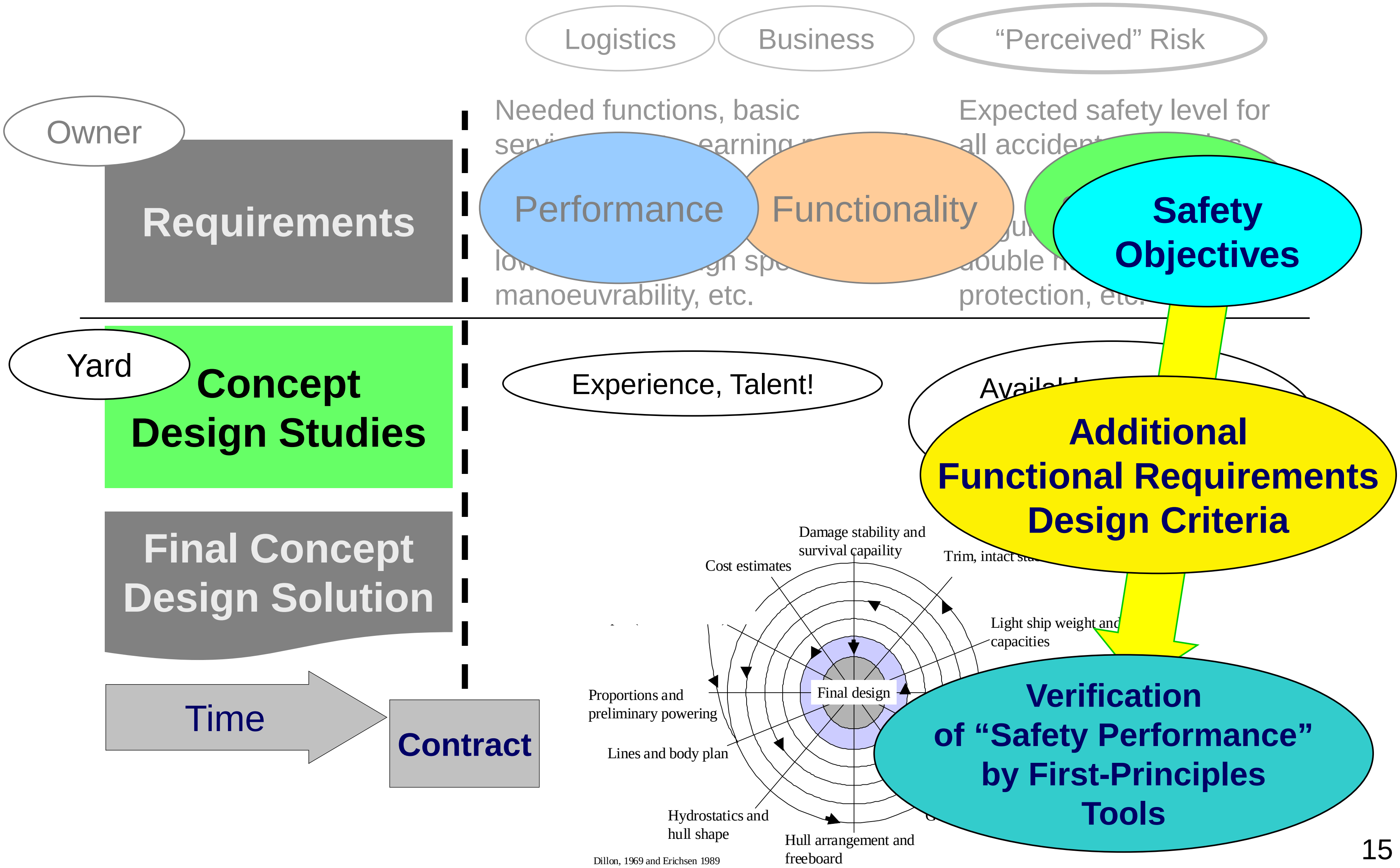
Traditional approaches to safety (rules-based) are experiential and with **change happening faster than experience is gained**, the "safety system" is unsustainable.

Need for a New Safety System

"Design for Safety"

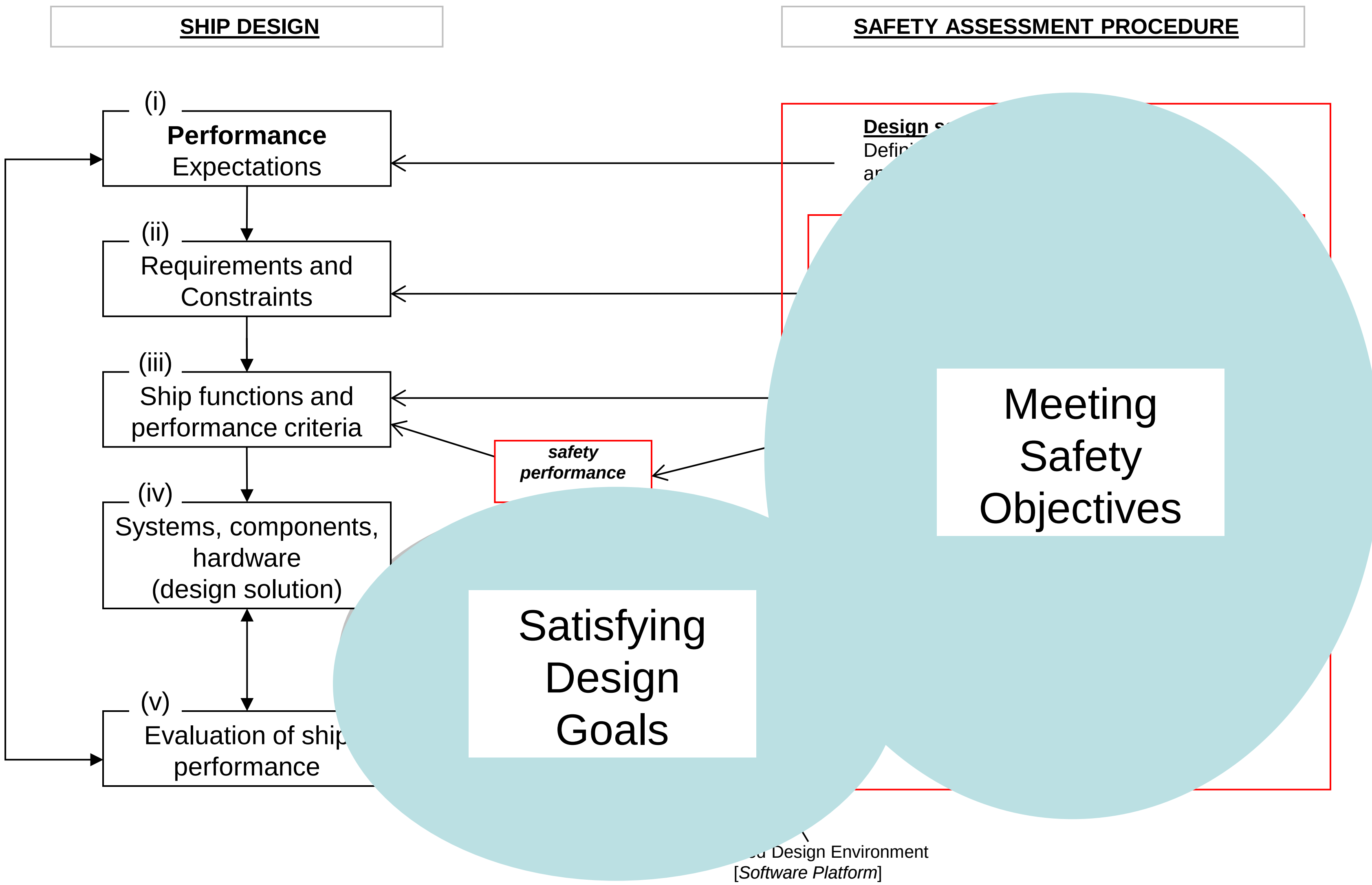
Risk-Based Design

Safety is an Objective



RBD High-Level Framework

RBD → Design with known safety level



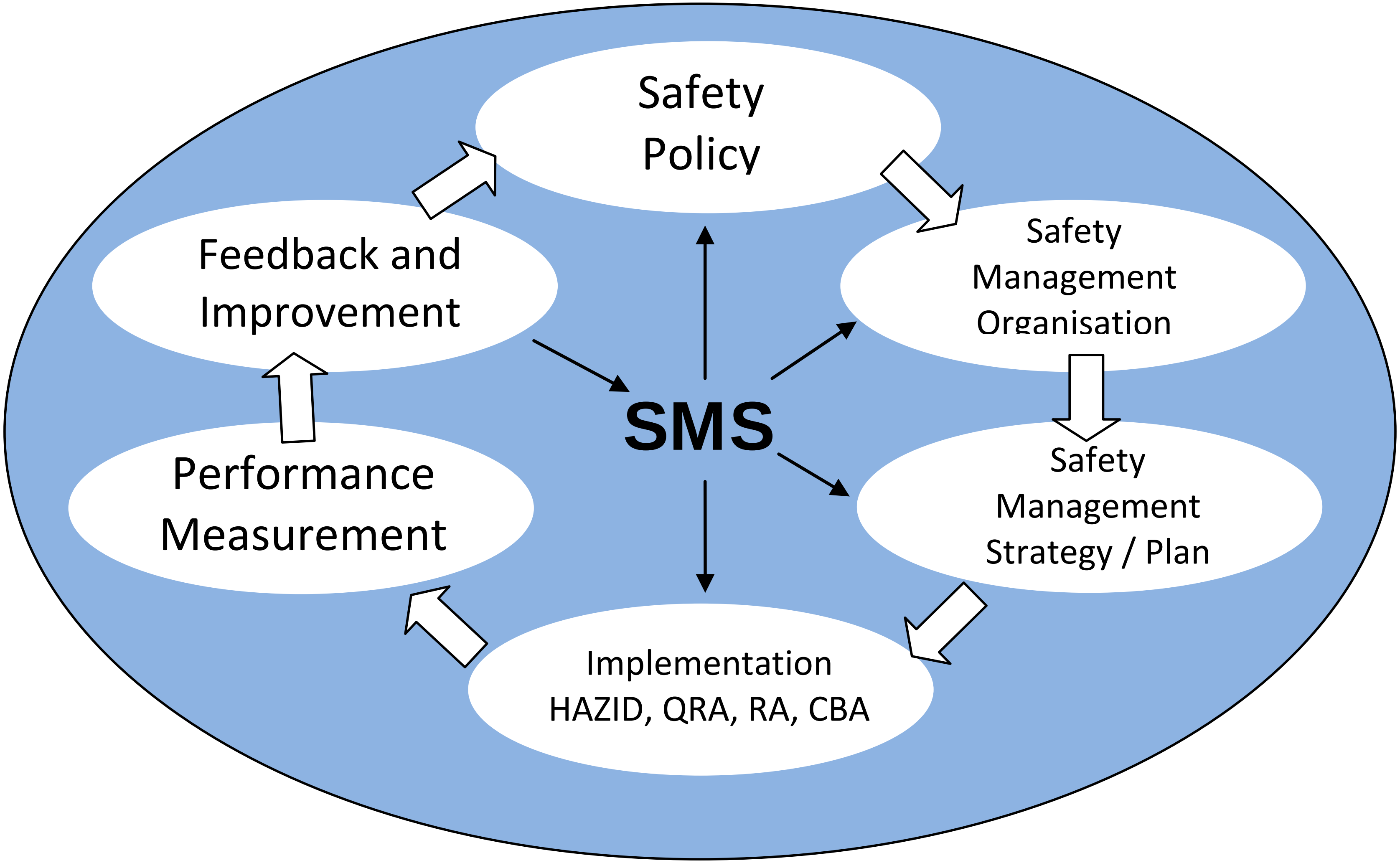
Life-Cycle Risk Management

Sustainable System for Coninuous Improvement

- A formal process to address risk at the **design** stage (risk reduction / mitigation), in **operation** (managing residual risk) and ultimately in **accidents** (crisis management), ensuring in all cases an **acceptable level of risk** (safety assurance).
- A formal process facilitates **measurement of safety performance**, which constitutes the basis for continuous improvement (**Virtuous Cycle**).

Life-Cycle Risk Management

Design, Construction (SLE), Operation (MRR)



RBD Impimplementation

Motivation

Alternative Design and Arrangements

→ local level

- ✓SOLAS Ch. I, Regulation 5 (certain systems - excemptions)
- ✓SOLAS Ch. II, Regulation 17 (Fire Safety)
- ✓SOLAS Ch. III, Regulation 38 (LSA Code)
- ✓SOLAS Ch. I, Regulation 4 (Damage Stability – equivalence)

(RBD) Design Optimisation

→ ship/platform level

- ✓HSC Code / SRtP / SPS Code / Polar Code
- ✓Safety level
- ✓Goal-Based Standards

RBD Impimplementation – AD&A

IMO Guidelines – Overview

- Establishing a Design team
- Preliminary (qualitative) analysis
  - Definition of **scope**
  - Development of **casualty scenarios**
  - Development of trial **alternative designs**

Preliminary Approval

- Quantitative analysis
  - Quantification of design scenarios
  - Development of Performance criteria
  - Evaluation of trial alternative designs

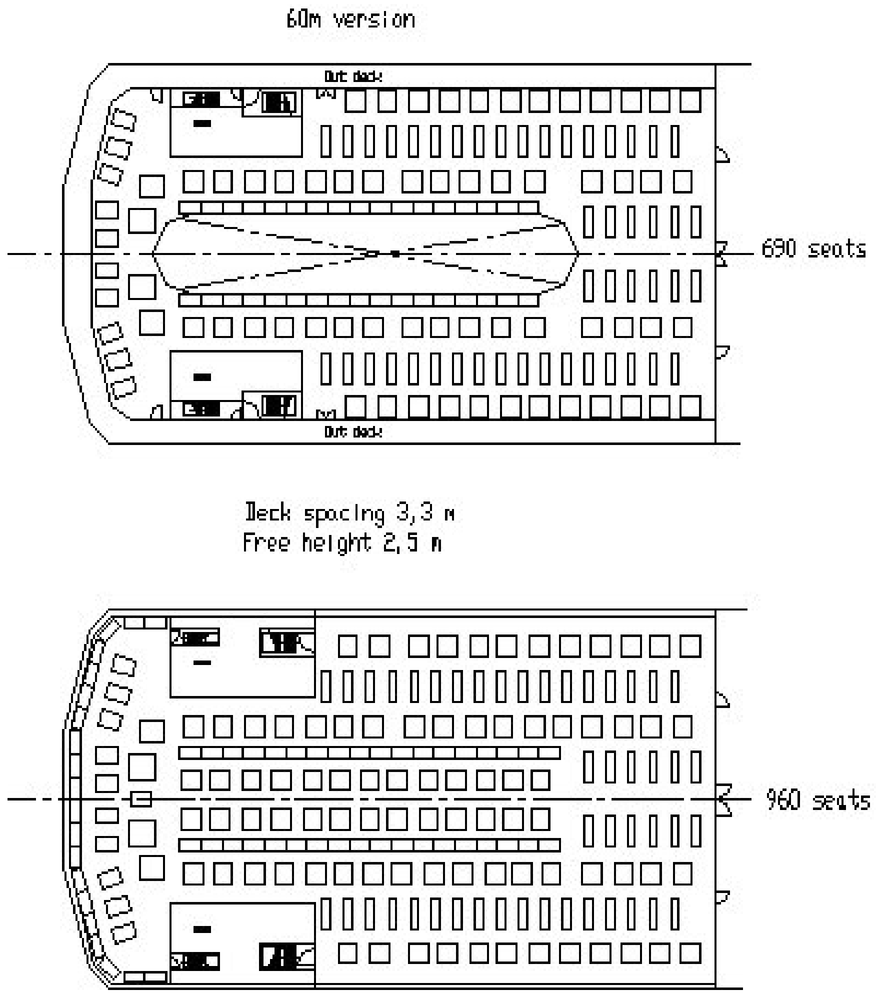
Final Approval

- Documentation

RBD Impimplementation – AD&A

Fire Safety – Alternative Design (Large Restaurant)

Two decks high 60 m long restaurant



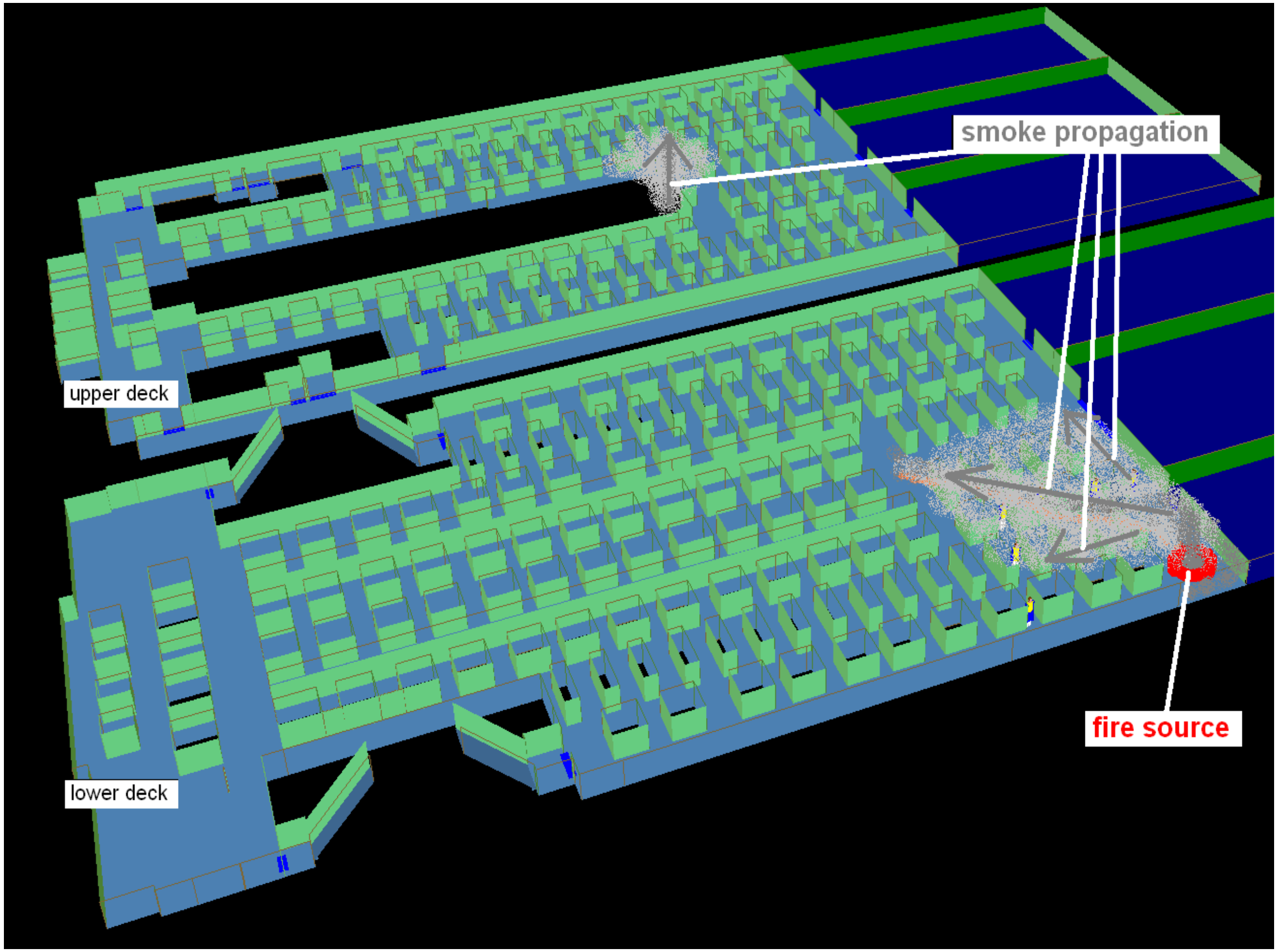
RBD Impimplementation – AD&A

Fire Safety – Alternative Design (Large Restaurant)

Restaurant Design		Alternative	
Length		60 m	> 48m
Capacity	(lower deck)	960 pax	
	(upper deck)	690 pax	
	(total)	1,650 pax	
Total exits width	(lower deck)	11.4 m	
	(upper deck)	10.8 m	
Floor area	(lower deck)	1,872 m^2	>1,600 m^2
	(upper deck)	1,748 m^2	>1,600 m^2

RBD Impimplementation – AD&A

Fire Safety – Alternative Design (Large Restaurant)

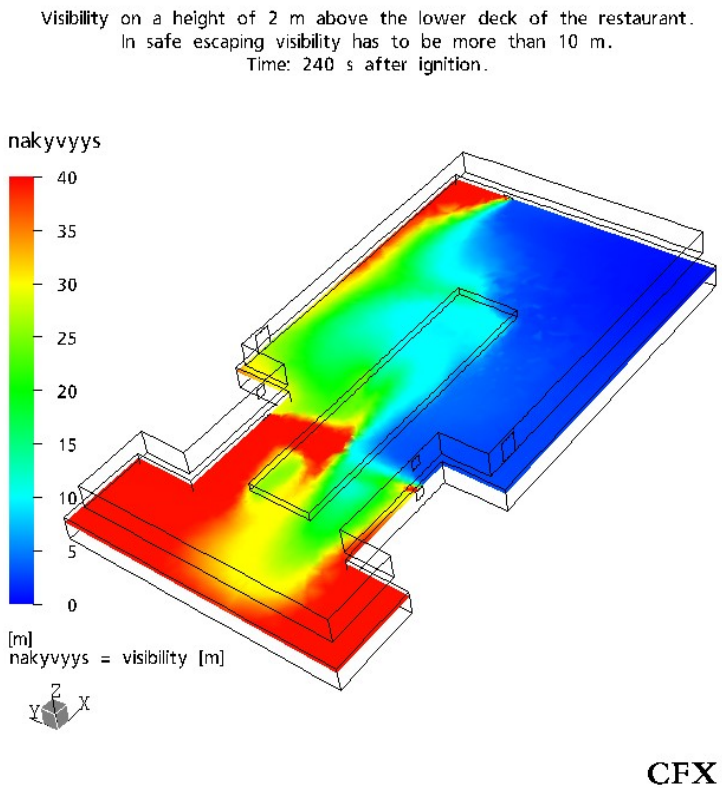


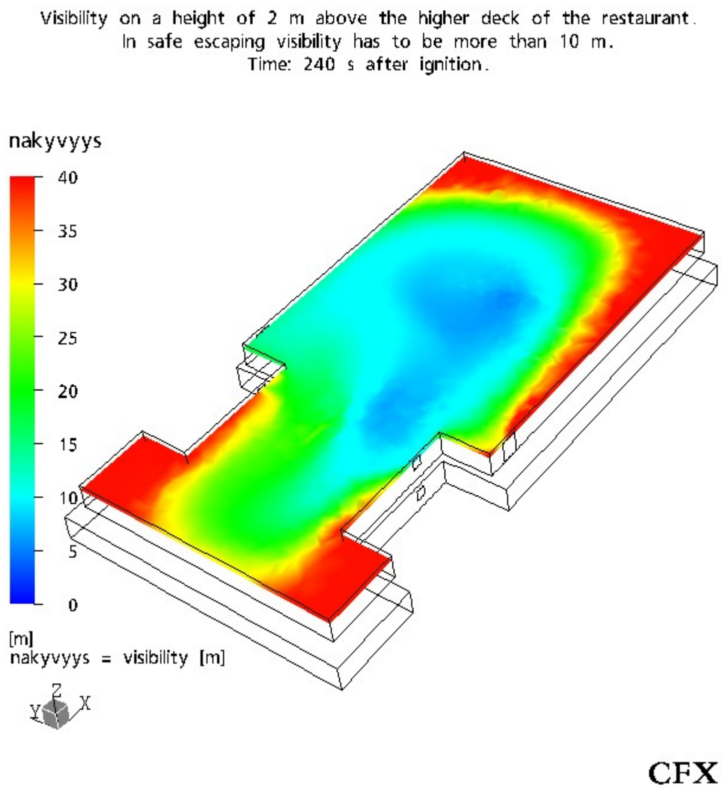
Worst/most critical fire scenario blocking one of the main escape ways

RBD Impimplementation – AD&A

Fire Safety – Alternative Design (Large Restaurant)

Fire Design Scenario (fire FIELD model results, t=240s)





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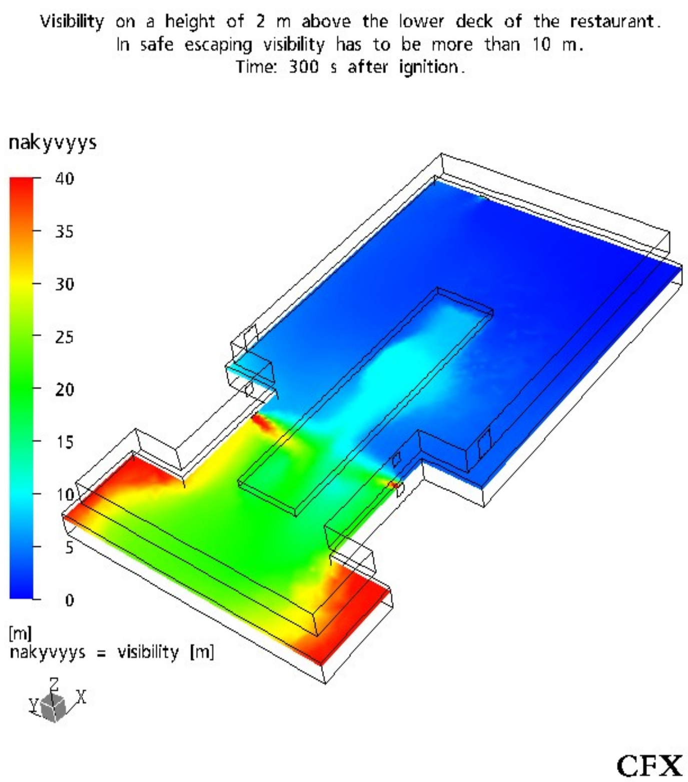
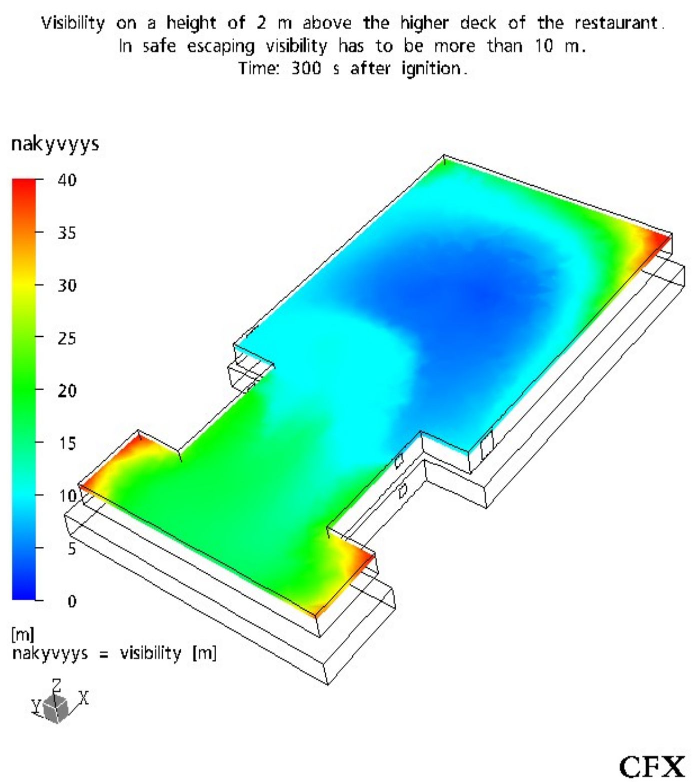
Fire Safety – Alternative Design (Large Restaurant)

Fire Design Scenario (fire FIELD model results t=300s)





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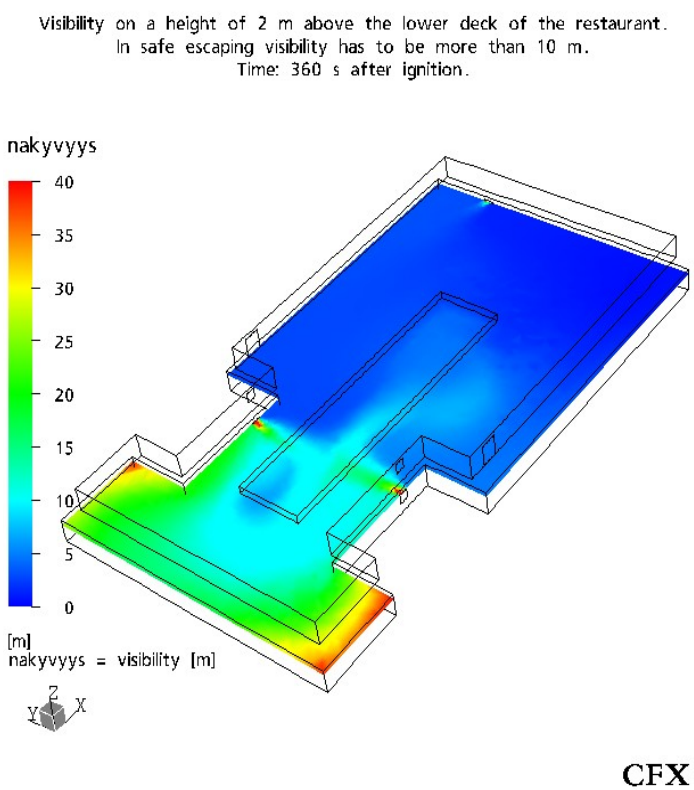
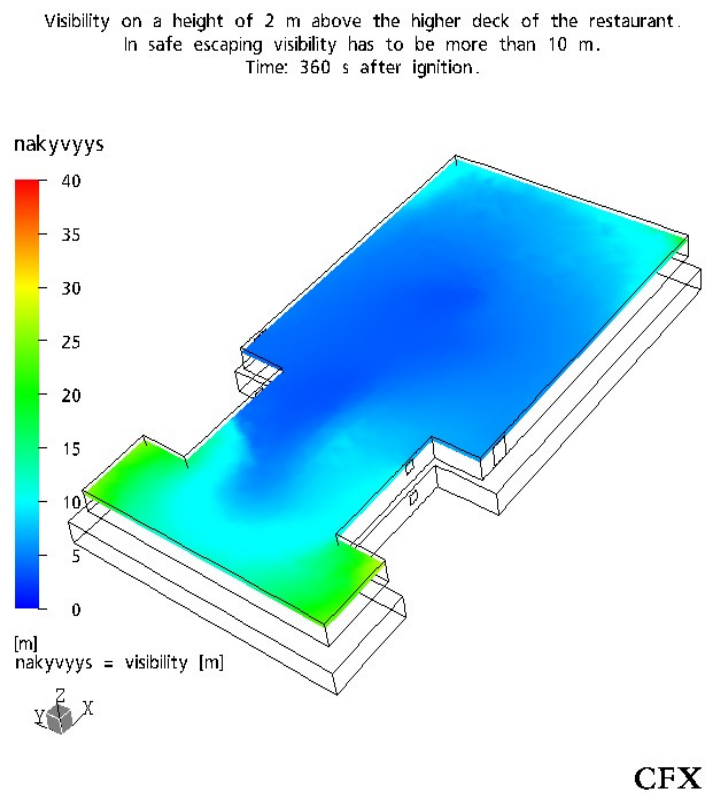
Fire Safety – Alternative Design (Large Restaurant)

Fire Design Scenario (fire FIELD model results t=360s)





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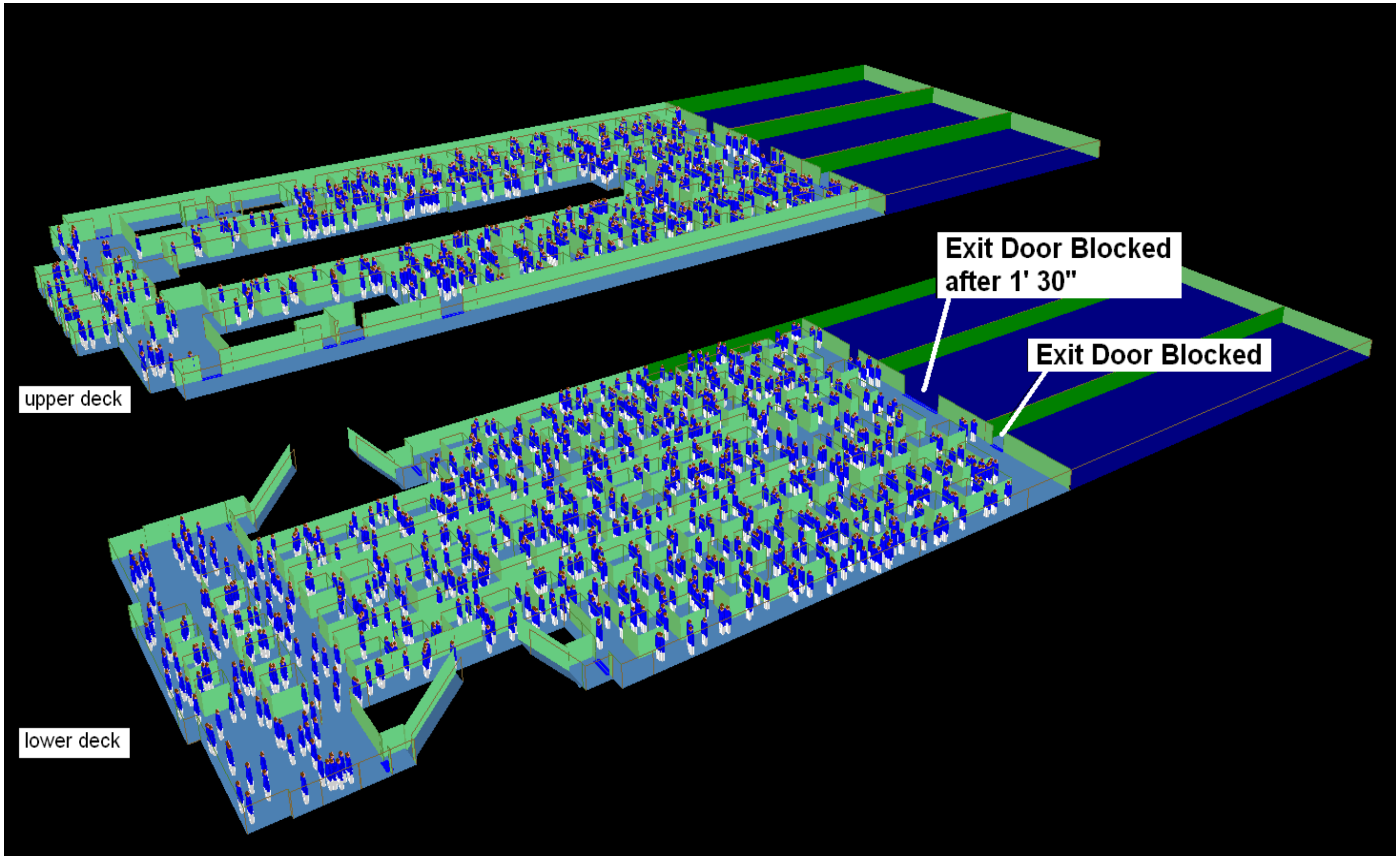
Fire Safety – Alternative Design (Large Restaurant)

Evacuation Model



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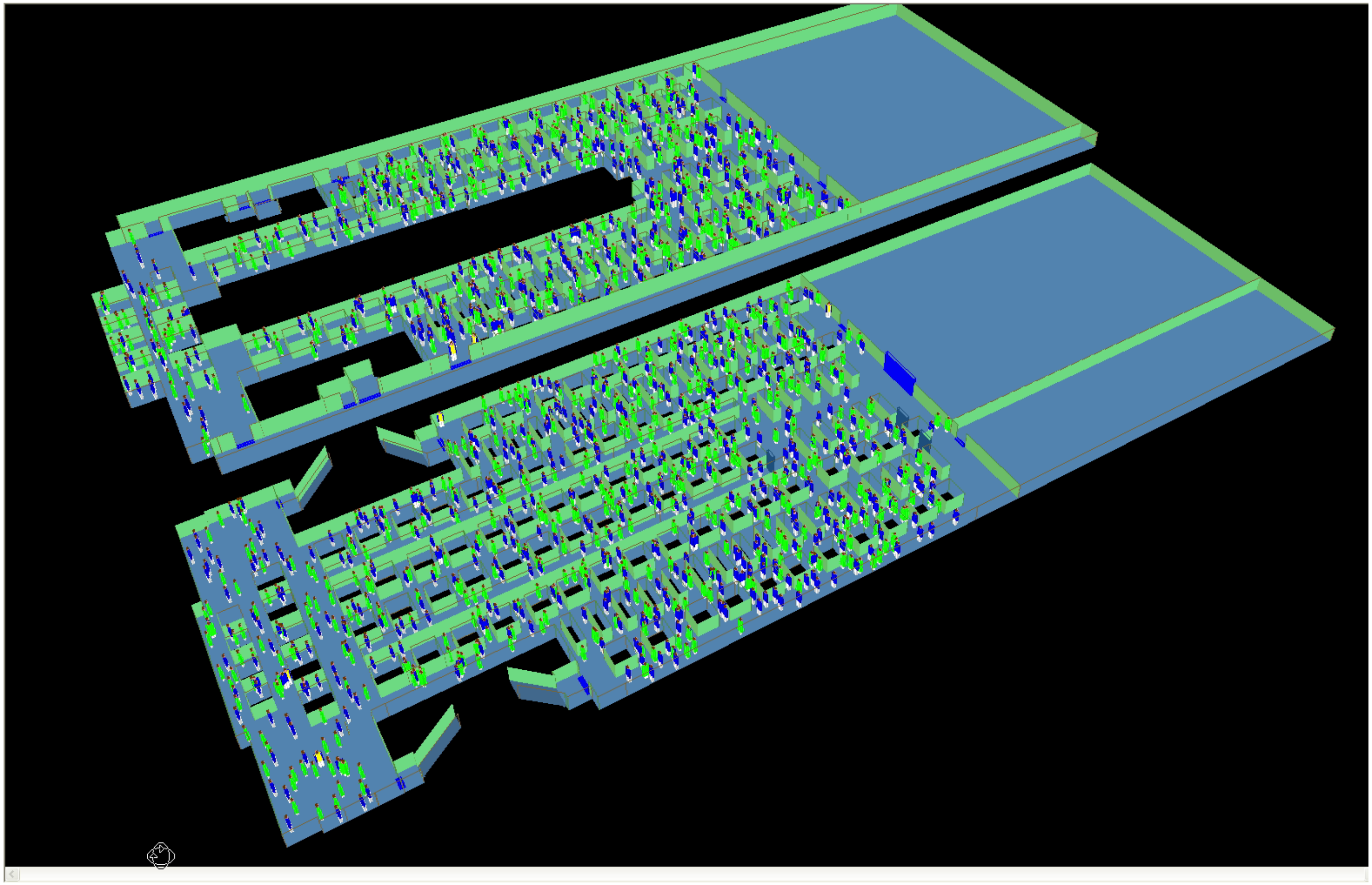
Fire Safety – Alternative Design (Large Restaurant)

Evacuation simulation – integrated fire/smoke propagation information



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Fire Safety – Alternative Design (Large Restaurant)

Fire Design Scenario – Version 0

Spaces affected	Egress Time	Time to UC	No.Pax
upper deck	7 – 8 min	4 – 5 min	28 (~4%)
lower deck	8 – 9 min	4 – 5 min	50 (~5%)

(consequences unacceptable).

Cost-Effective RCOs include the following:

- Increasing the number of smoke extraction fans from 2 to 4
- Increasing the number of inlet air fans from 2 to 4
- Wider escape ways

RBD Impimplementation – AD&A

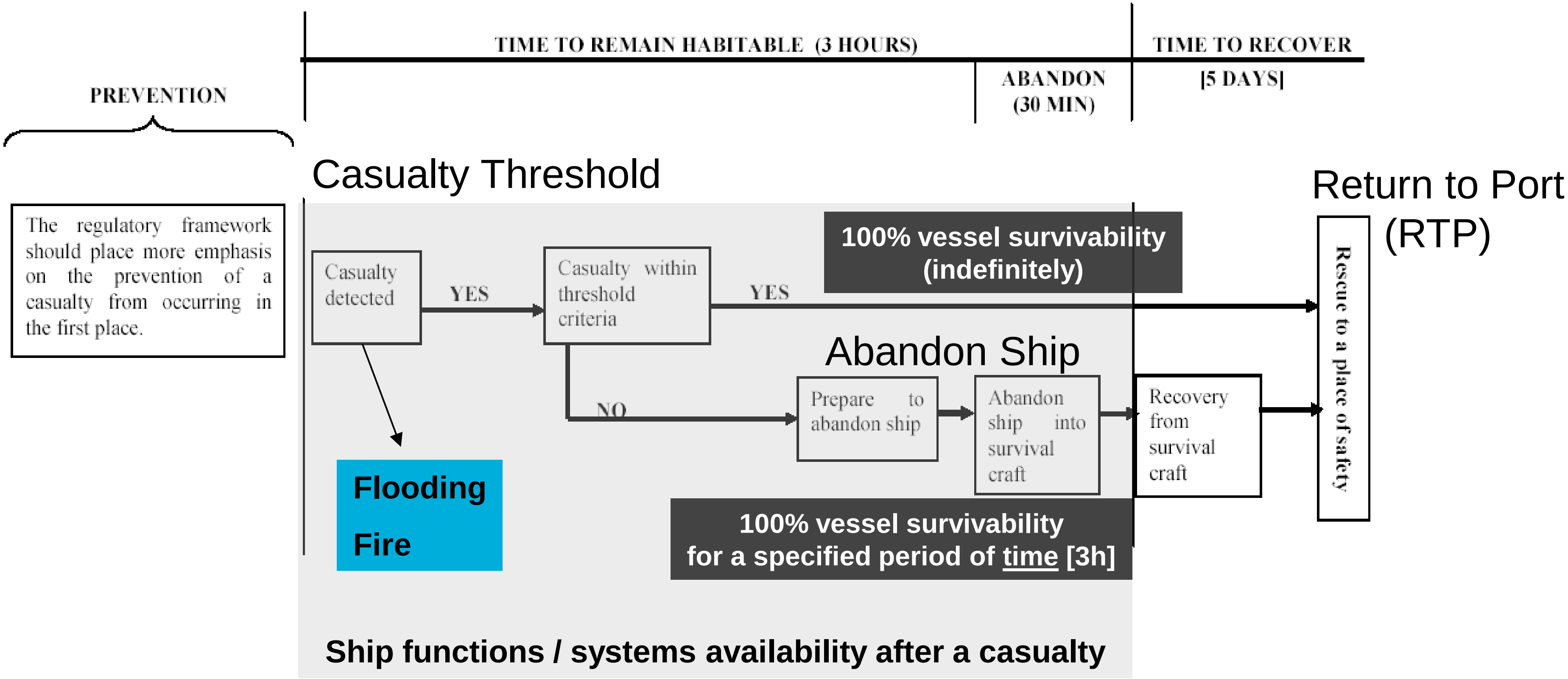
Fire Safety – Alternative Design (Large Restaurant)

Evaluated Fire Design Scenario – Version 1

Spaces	Egress Time	Time to UC	No. Pax affected
upper deck	6 – 7 min	8 – 9 min	0
lower deck	6 – 7 min	8 – 9 min	0

(consequences acceptable).

IMO (SLF 47/48) *Passenger Ship Safety*



RBD Impimplementation – PSS

IMO Framework for Passenger Ship Safety

Casualty Threshold /Safe Return to Port

Accident Causality Analysis		Consequence Analysis	Mitigation Analysis
Collision	Scenarios	Flooding survivability analysis	Systems Availability Evacuation & Rescue
Grounding/ Stranding	Scenarios	Flooding survivability analysis	Systems Availability Evacuation & Rescue
Fire	Scenarios	Fire safety analysis	Systems Availability Evacuation & Rescue

Safety Level (Total Risk)

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Safety Level (Total Risk)

- Risk is a chance of loss of life
- The chance is measured by statistics

loss scenarios:

flooding
fire
~90% of the risk
intact stability loss
other

loss of **life**

(expected number of fatalities per year)

Example Loss Scenario

Flooding | Collision

prevention

Navigation failure

Water ingress (hull breach)

mitigation

Loss of stability

Abandonment

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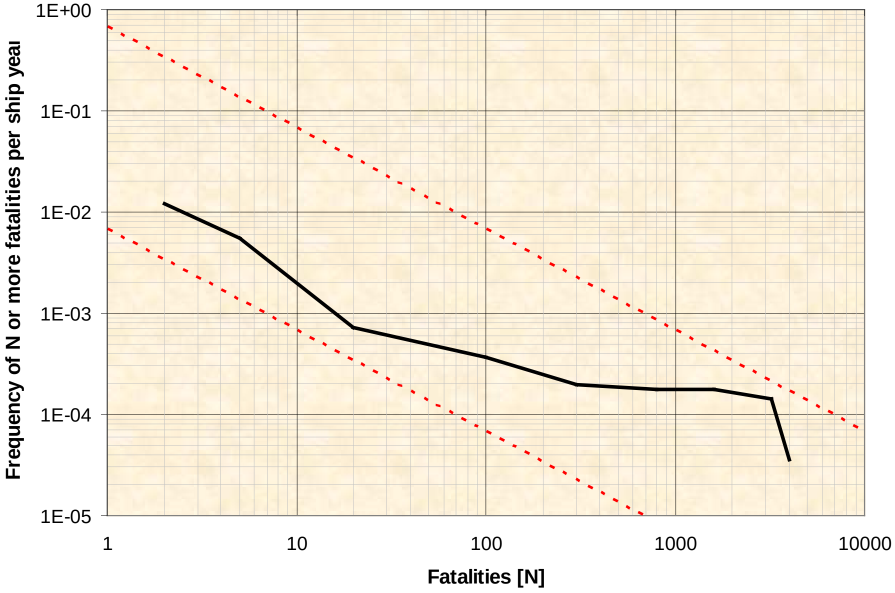
Risk Model

$$Risk_{PLL} \equiv E(N) \equiv \sum_{i=1}^{N_{\max}} F_N(i)$$

$$F_N(N) = \sum_{i=N}^{N_{\max}} fr_N(i)$$



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Risk Model

$$fr_N(N) = \sum_{j=1}^{n_{hz}} fr_{hz}(hz_j) \cdot pr_N(N|hz_j)$$

j	Principal hazards, hz_j
1	Collision and flooding
2	Fire
3	Intact Stability Loss
4	Systems Failure
	… etc

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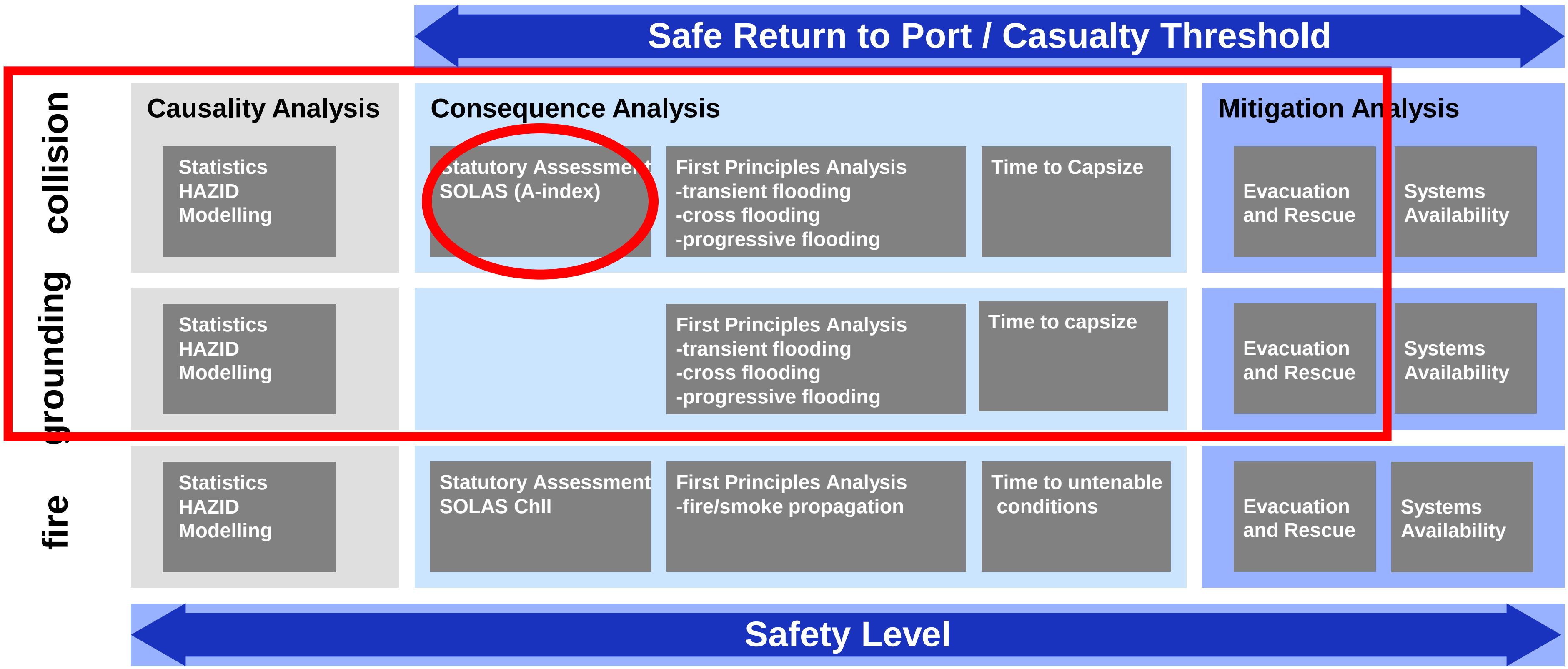
Flooding Risk Analysis



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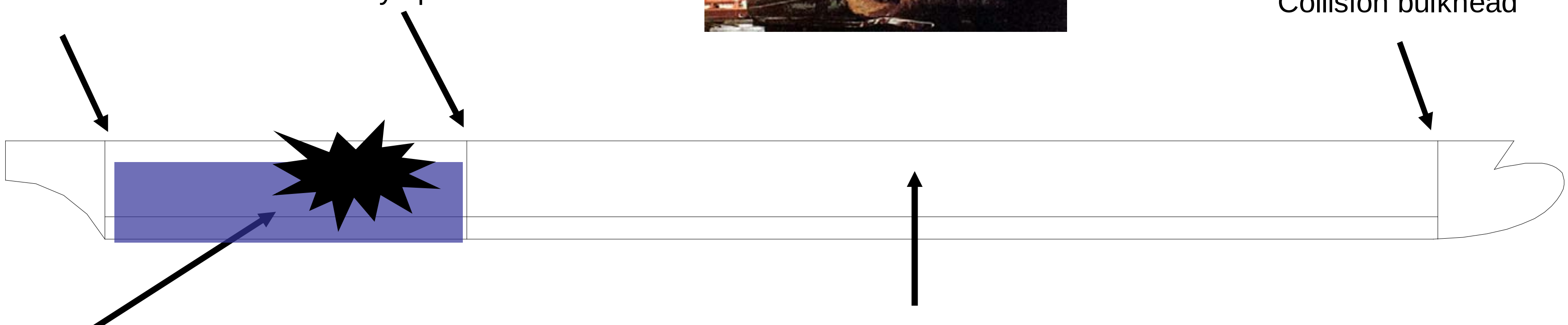
Statutory Assessment – SOLAS 2009



$$\sum_{i=1}^{n} (pi \times si) = A > R$$

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Platform Optimisation – SOLAS 2009

Optimisation of the internal subdivision arrangement:

- Design database → KPIs → KIMs → Parametric model
- MDO: safety (Index-A + other performance and functional requirements:
  - Weight, capacity, service flows, escape routes
  - Layout constrains (e.g. machinery, MFBs)
  - Tank arrangement
  - Systems location for SRtP
- Systematic exploration of design space

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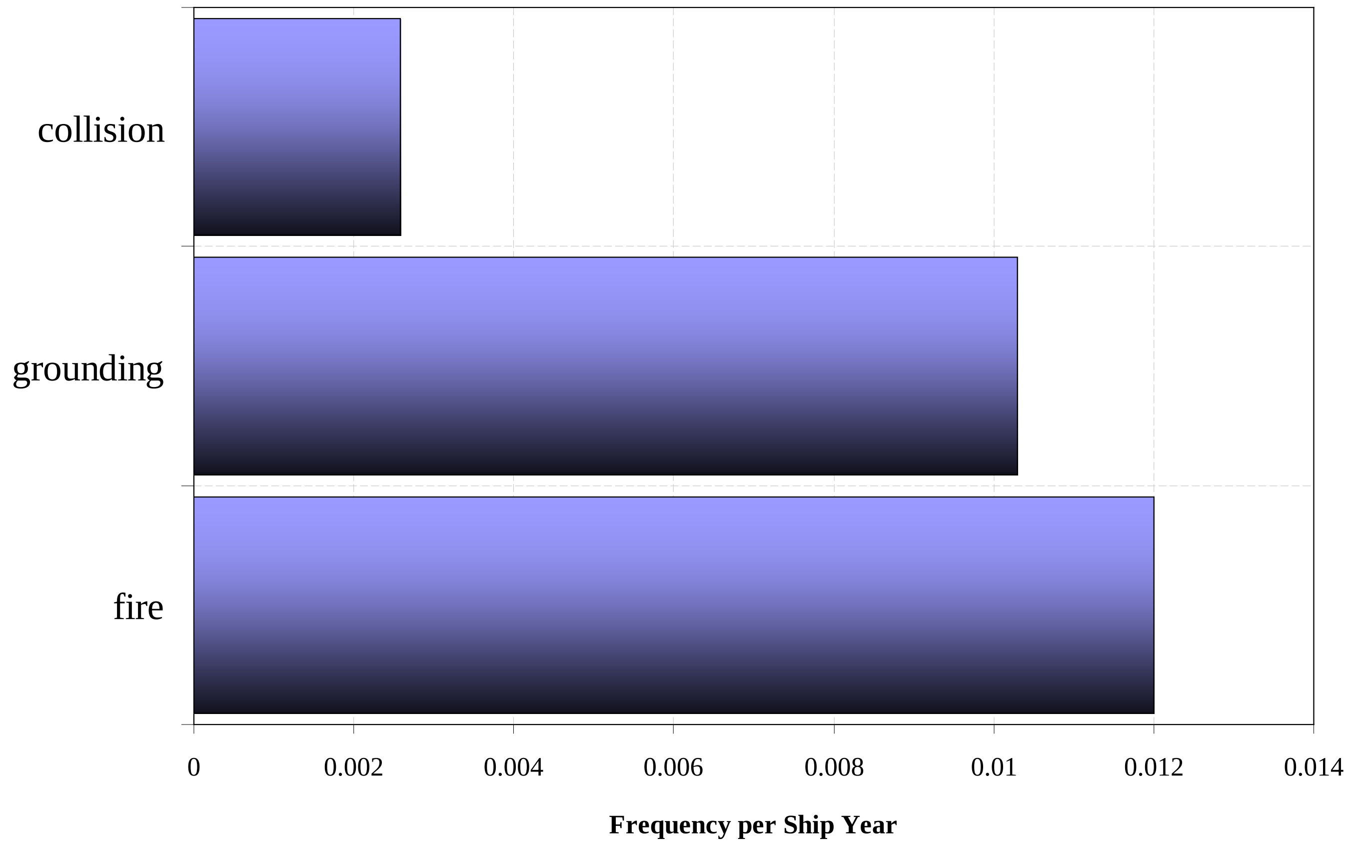
Flooding Risk Analysis – Frequency (Historical Data)

$$fr_{hz}\left(hz_1\right)$$

Source: DNV

1.148 E-3 1/sy

FSA Cruise Ships (SAFEDOR, FSA, 2007): 1 event every 871 ship years



Frequency of event occurrence

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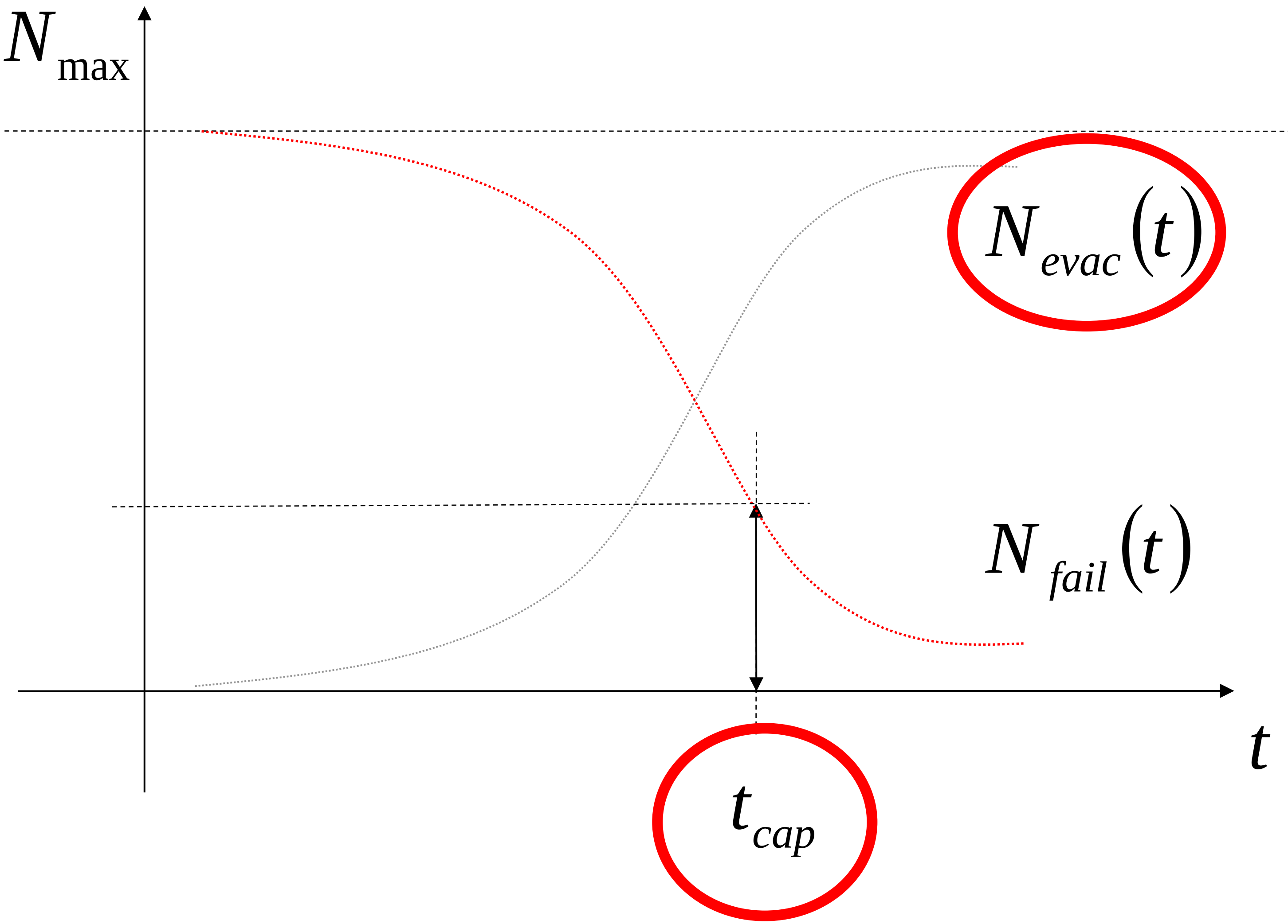
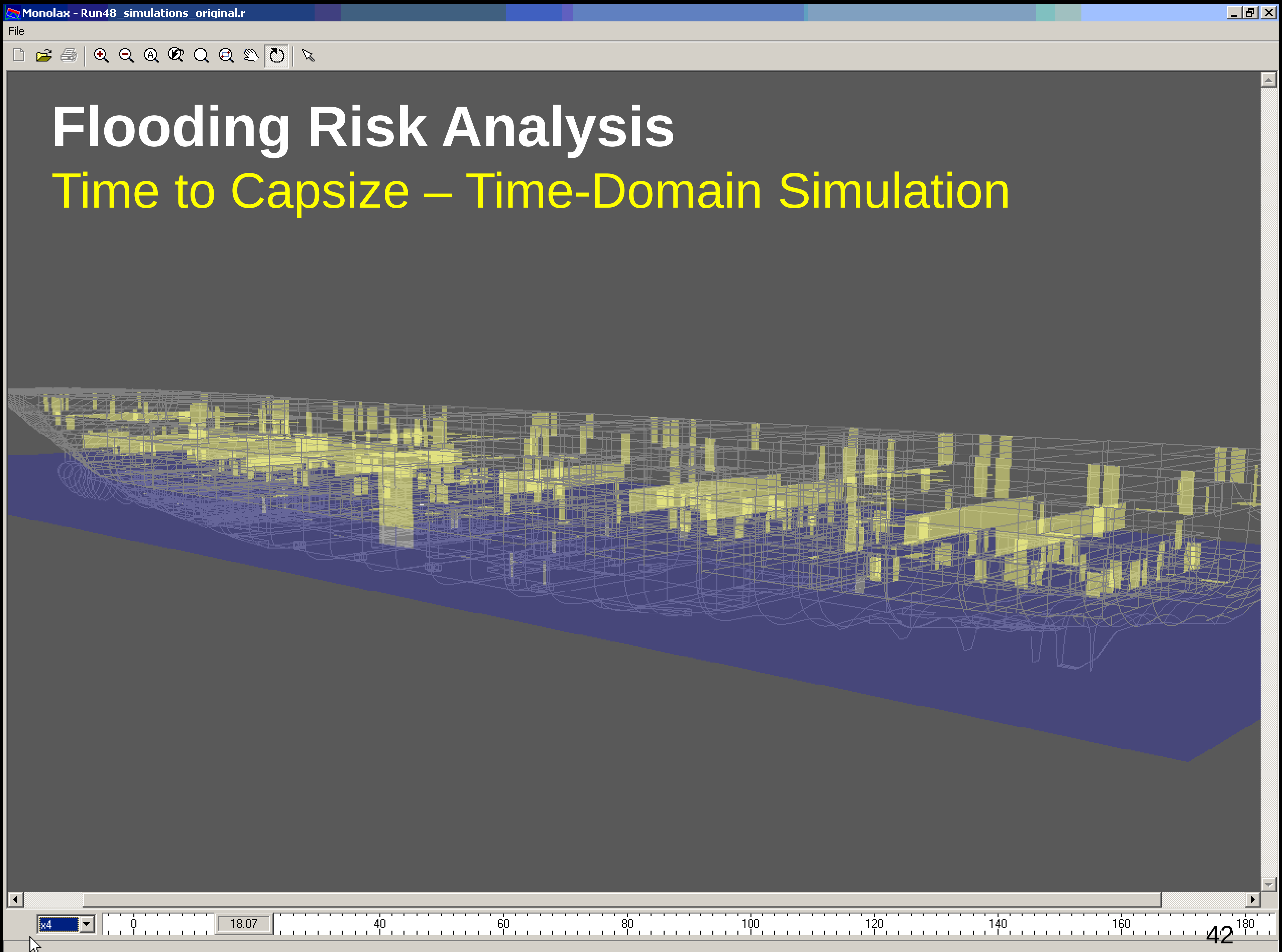
Flooding Risk Analysis – Consequences (Human Lives)



Flooding Risk Analysis

Time to Capsize – Time-Domain Simulation



RBD Impimplementation – PSS

Flooding Risk Analysis – Time to Capsize

Random Variables (MC sampling)

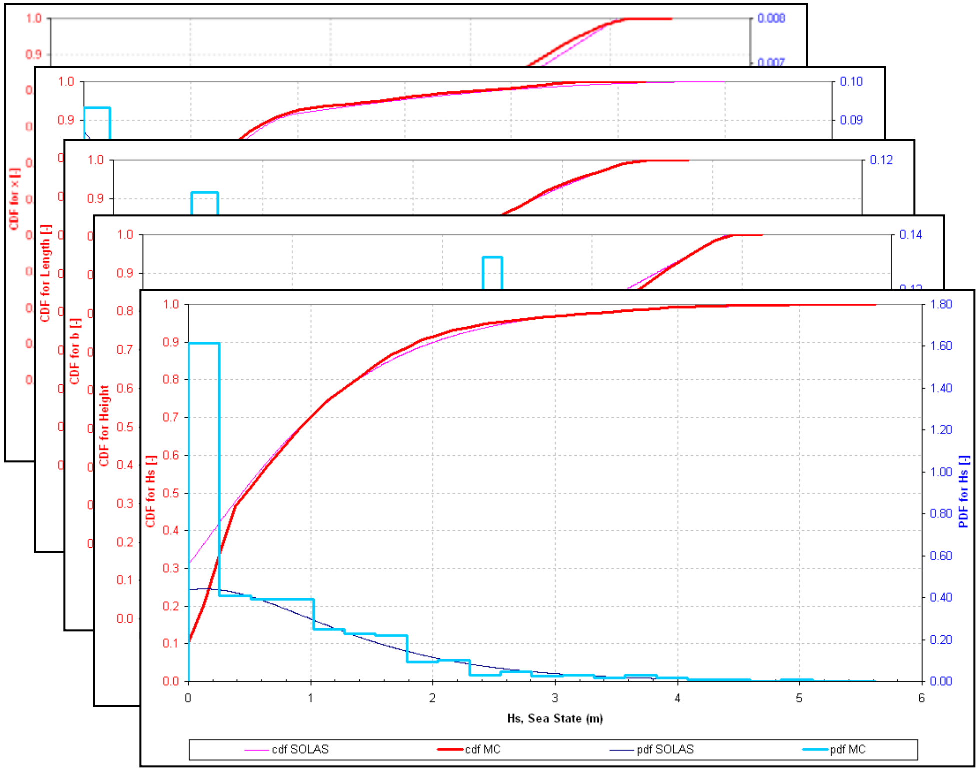
Damage characteristics:

- Location
- Length
- Penetration
- Height

  width → grounding

Environment (Hs, T_P)

Loading condition



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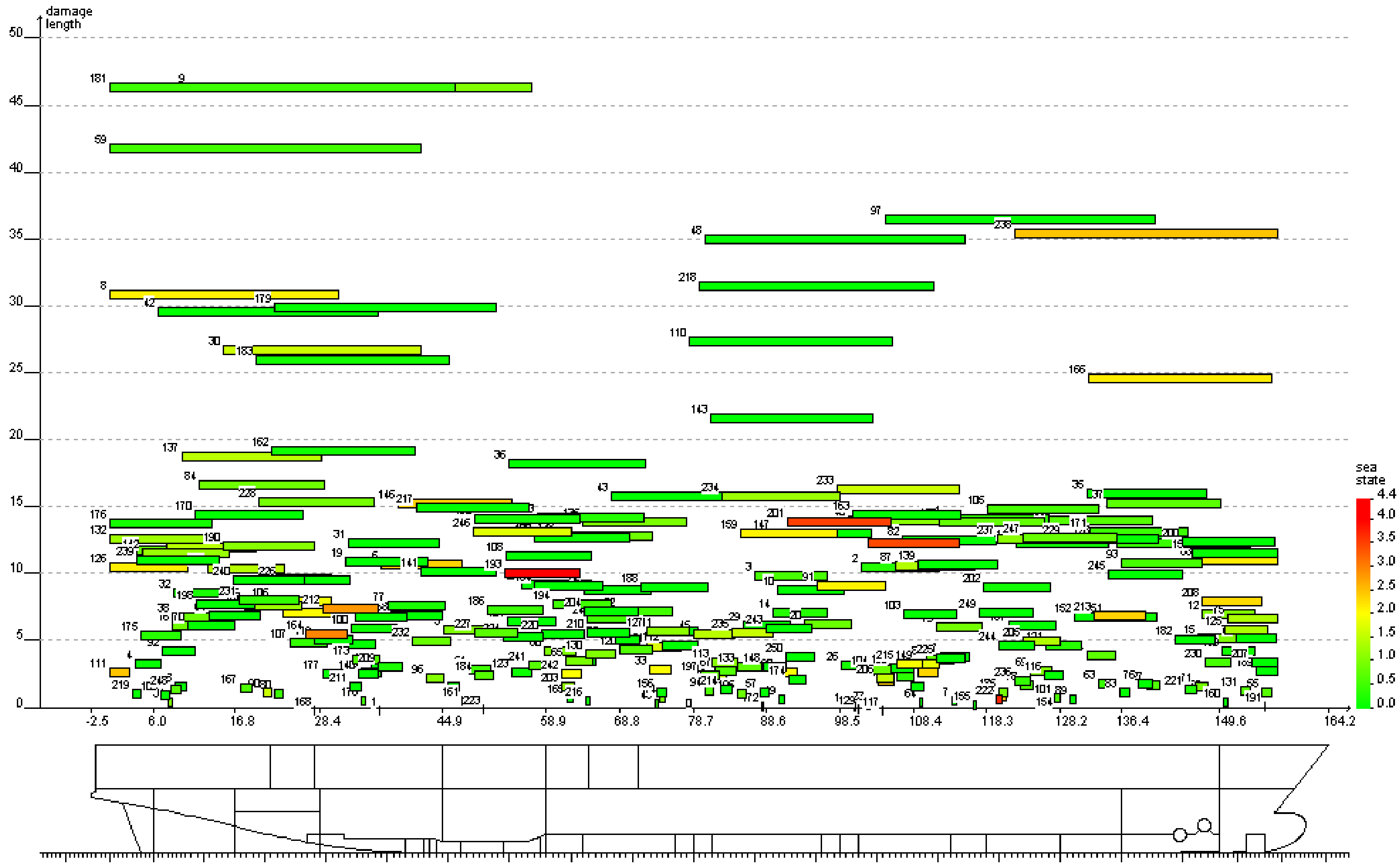
Flooding Risk Analysis – Time to Capsize (Collision)

380 scenarios set-up



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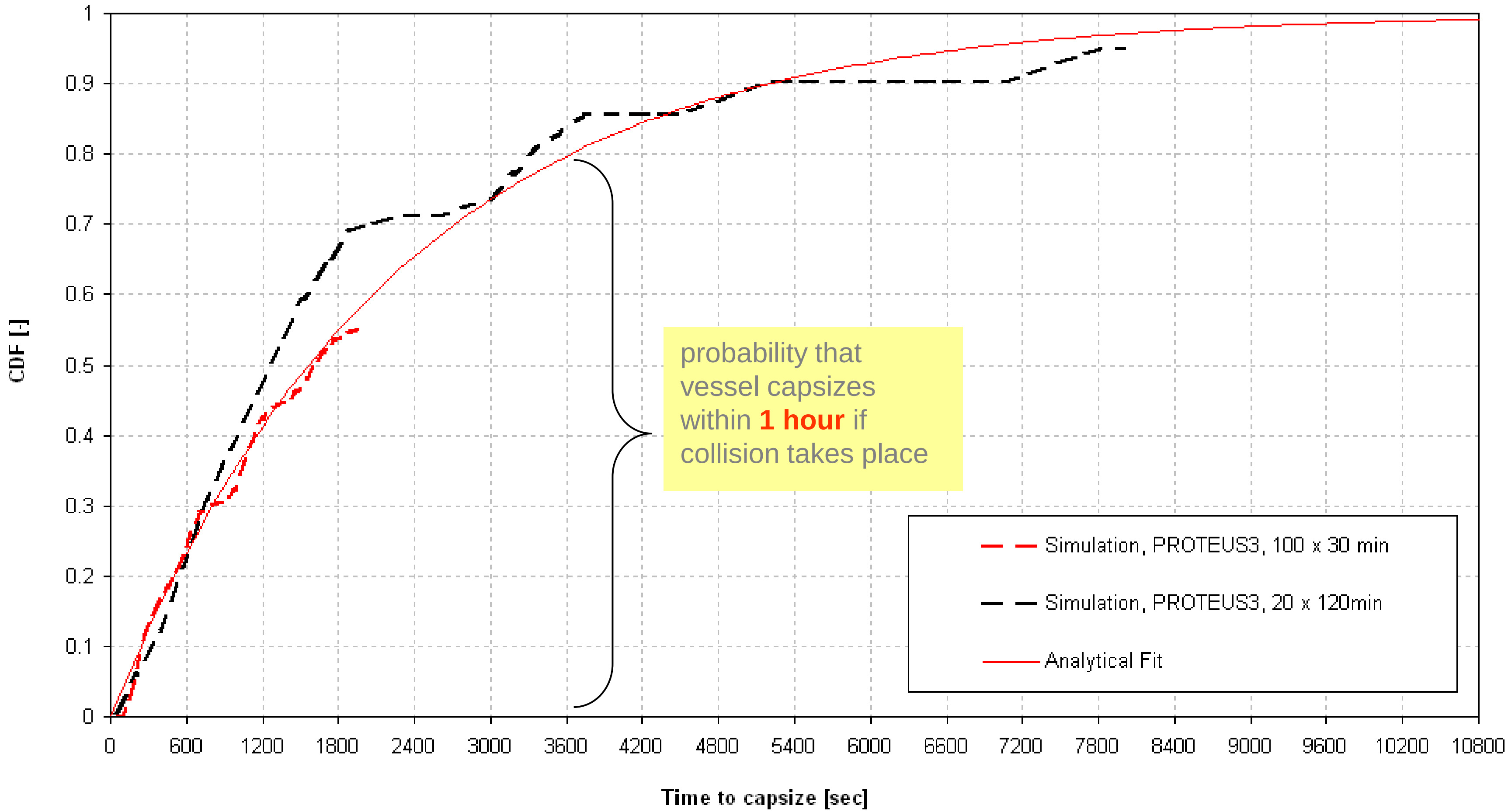
Flooding Risk Analysis – Time to Capsize (Collision)

Scenario={displ, KG, damage, Hs}



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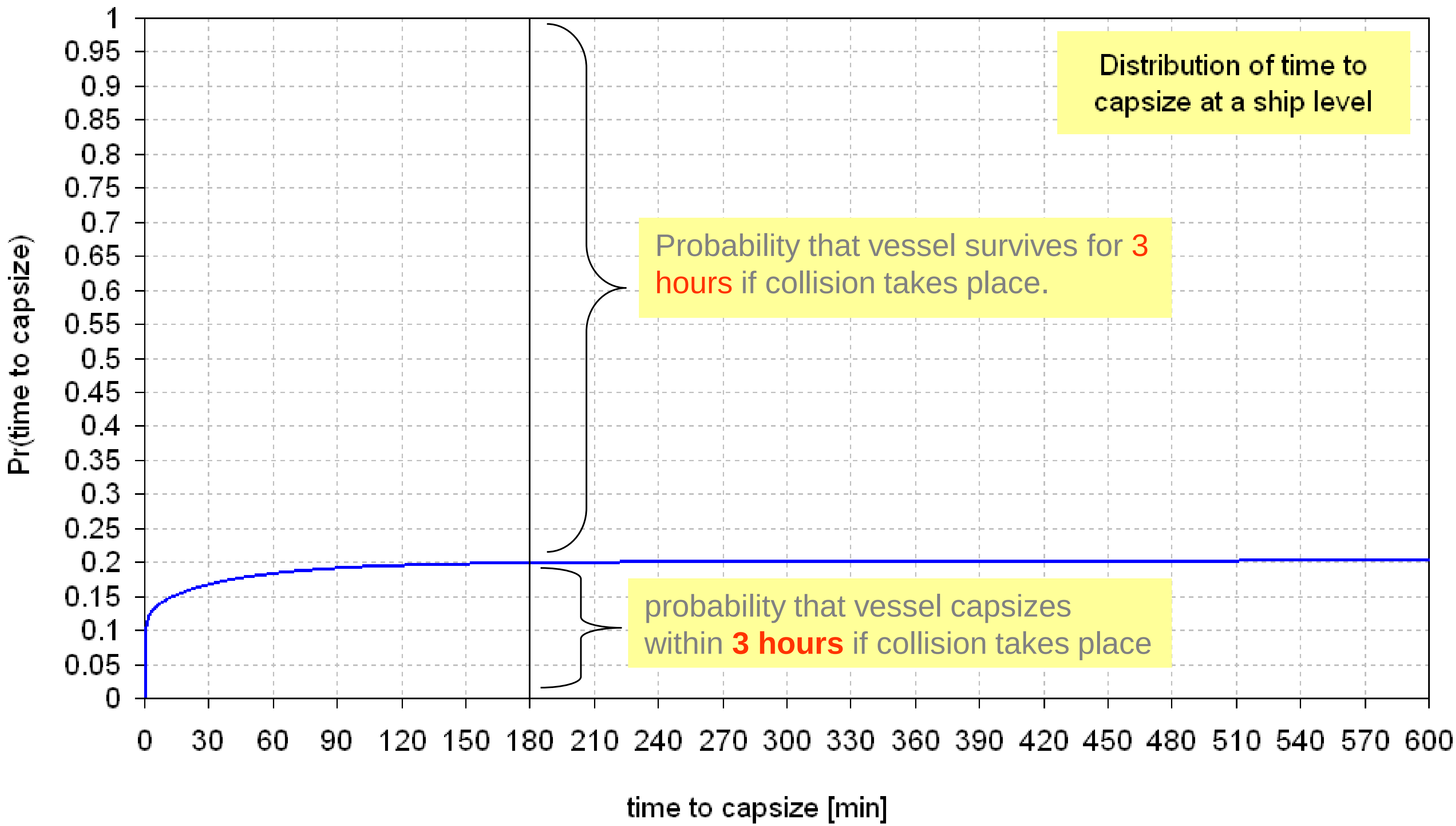
Flooding Risk Analysis – Time to Capsize (Collision)

40,000 scenarios



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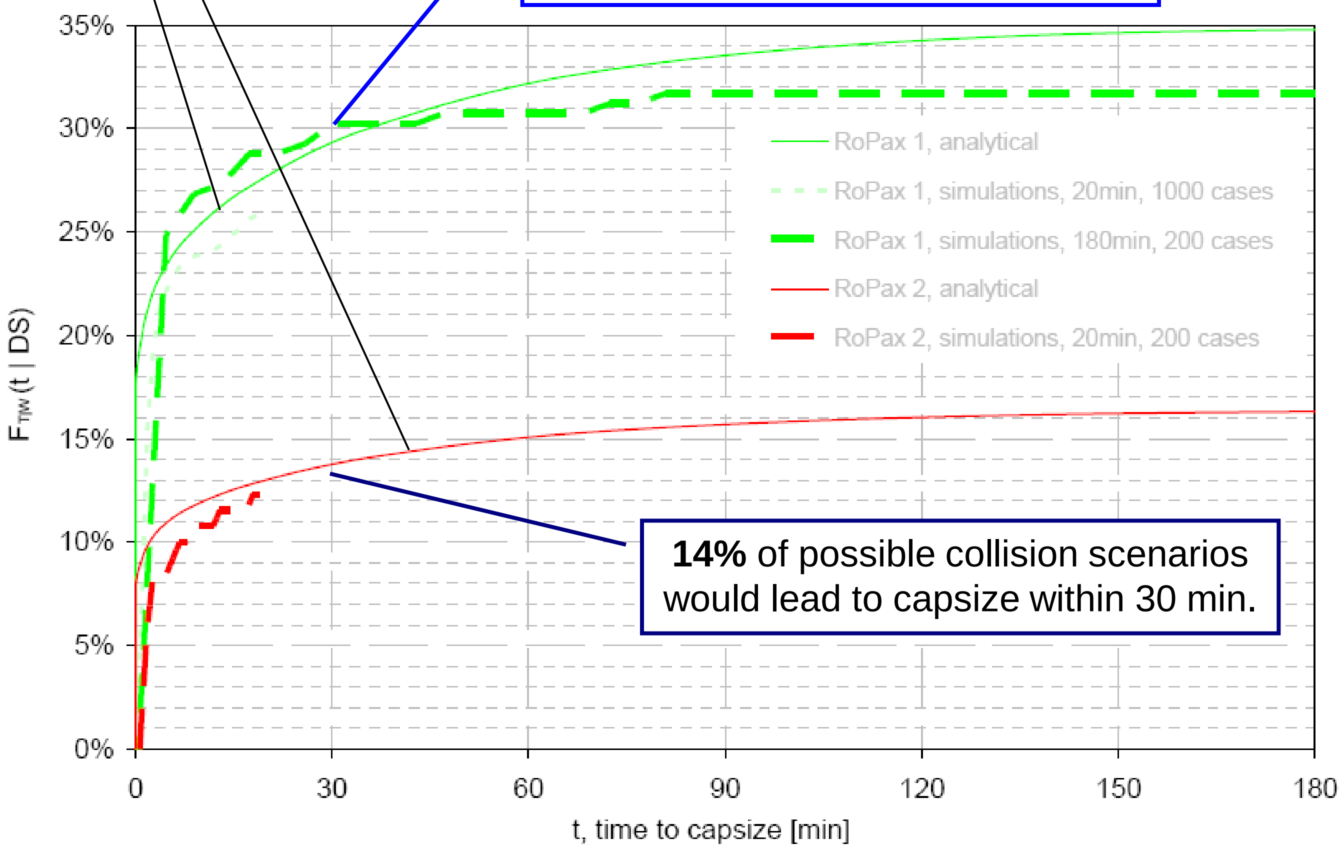
Flooding Risk Analysis – Time to Capsize (Collision-RoPax)

Analytical estimates of time to capsize based on SOLAS 2009 s-factor agree reasonably well with results from numerical simulations

30% of possible collision scenarios would lead to capsize within 30 min.



14% of possible collision scenarios would lead to capsize within 30 min.

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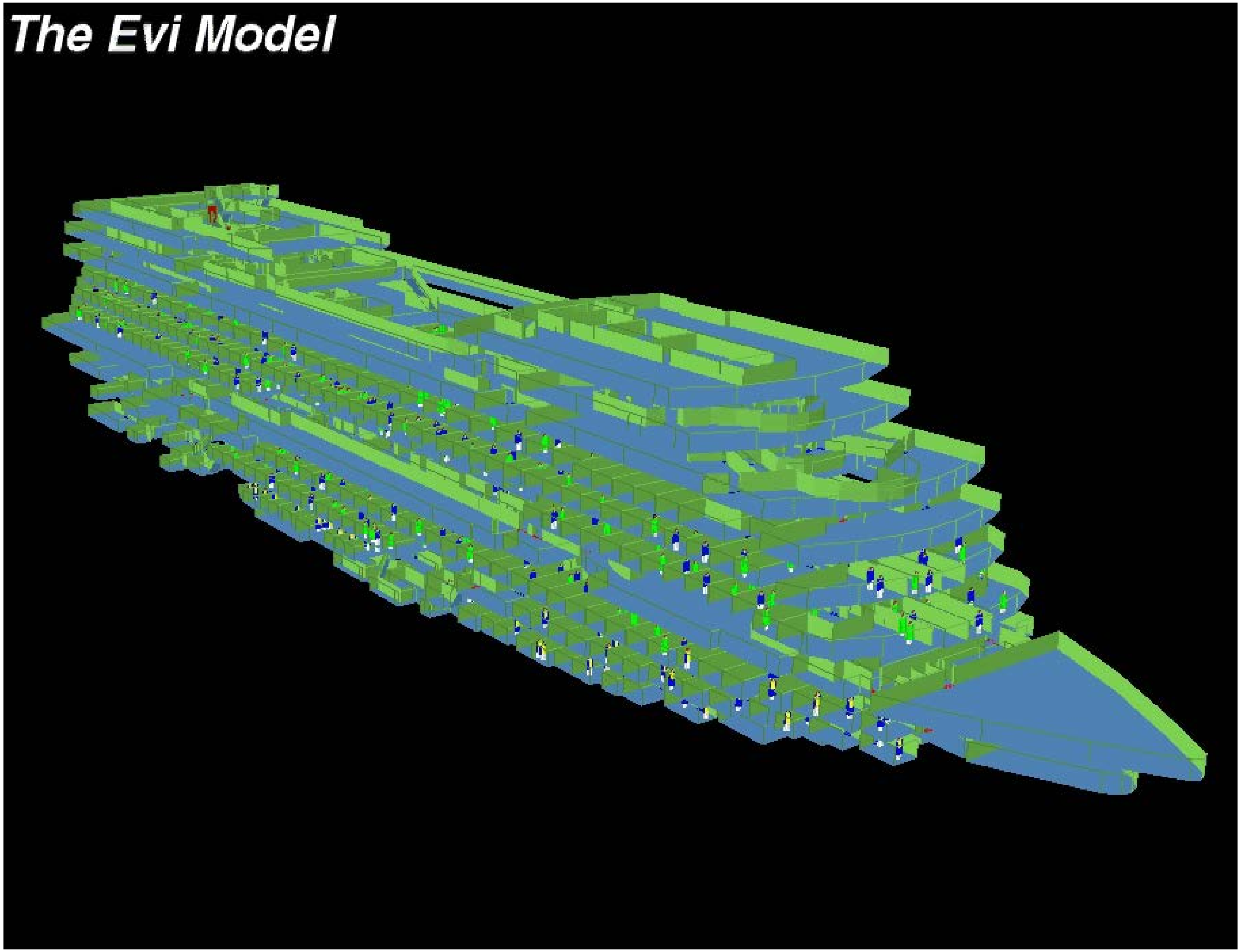
Time to Evacuate – Advanced Evacuation Simulation



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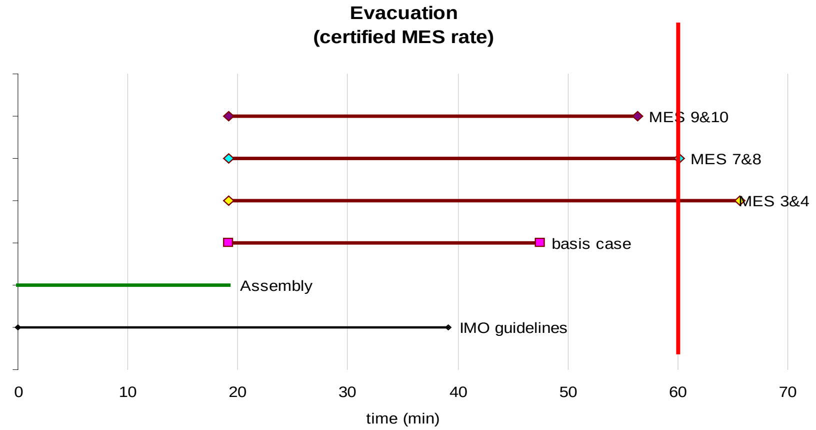
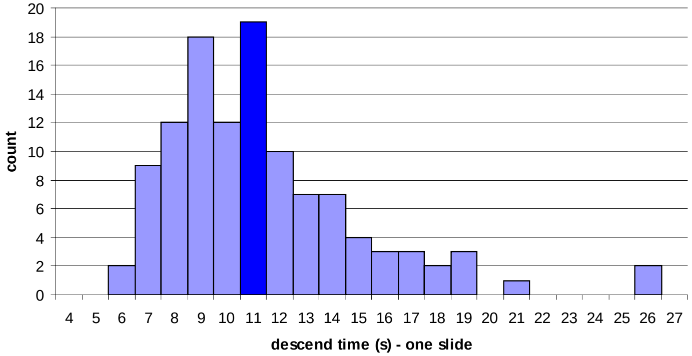
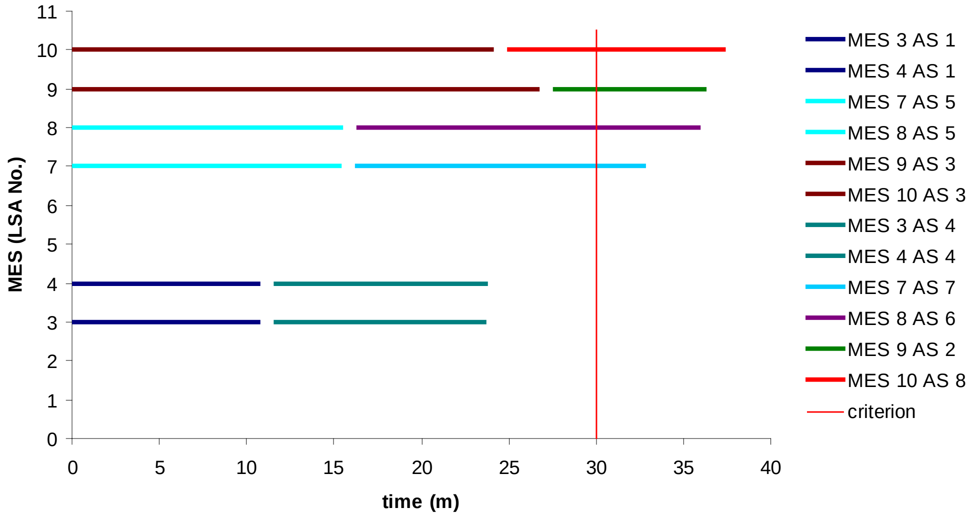
Evacuation and Rescue – Abandonment Studies

P&O Ferries







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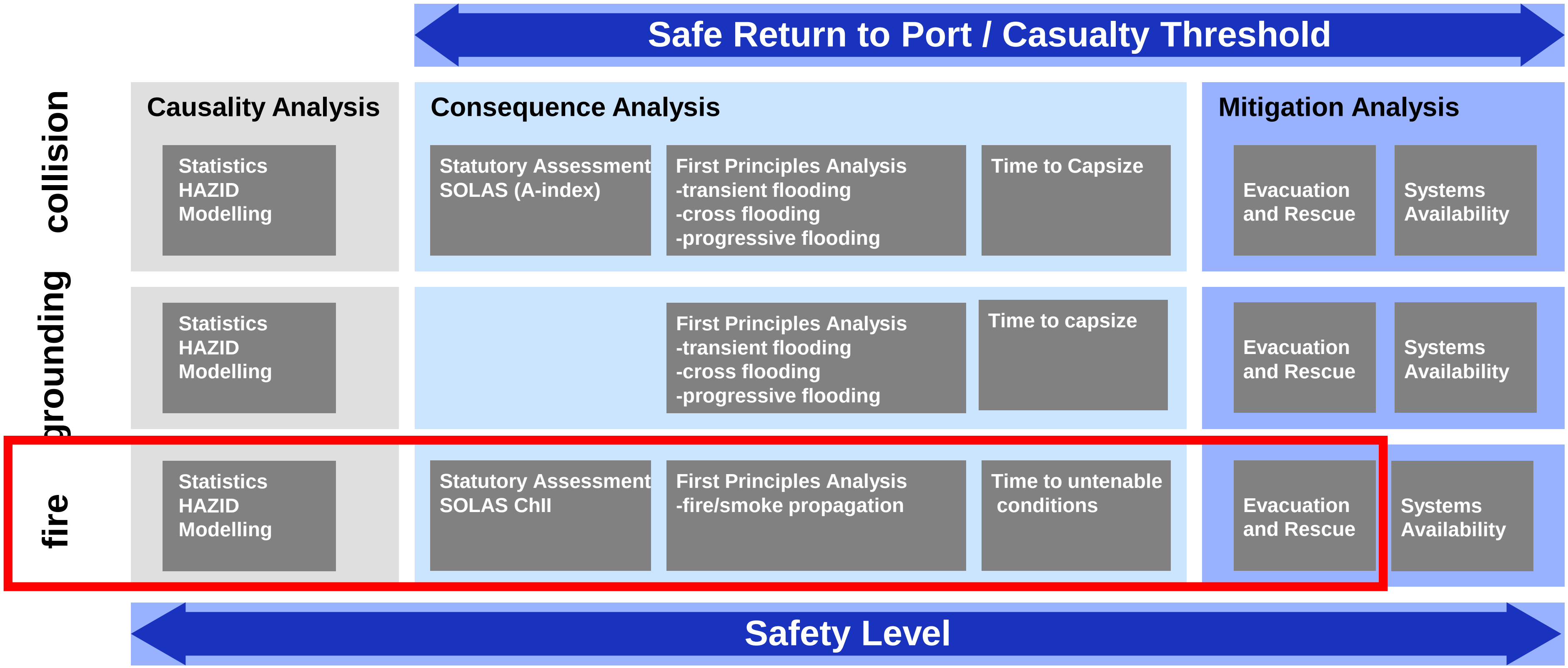
Fire Safety Analysis



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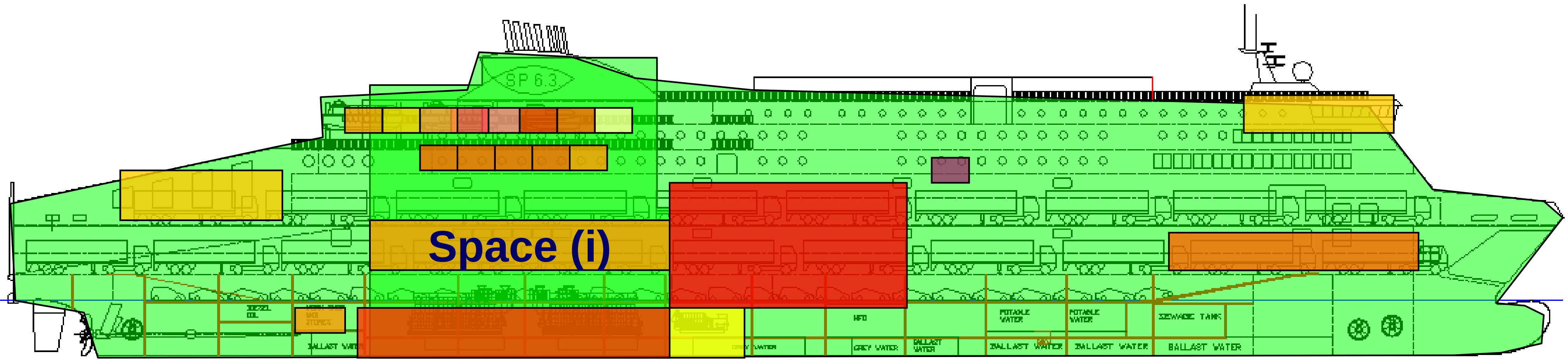
Fire Safety Analysis – Fire Risk Model



Frequency of
fire ignition event
in space *i*

fire escalation
from space of fire origin

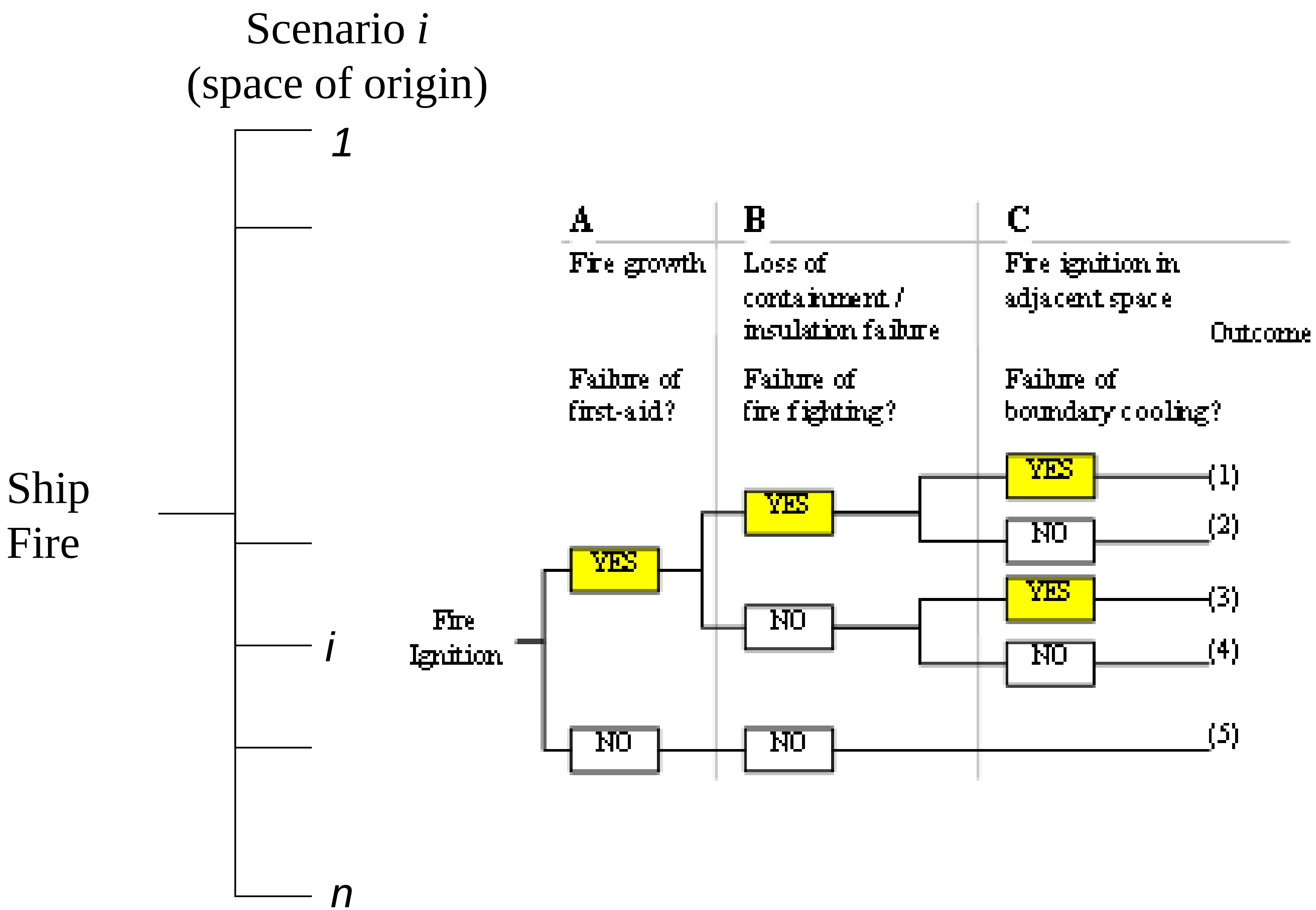
Loss of human life
injuries/fatalities

f(i) Pi(E|f) $pdf(N)$

$$R_F = \sum_{i=1}^{n} dR_i \Leftarrow \Delta Risk\text{i} \Rightarrow dR_i = f_i \times \sum_k \left(P(E)_{i,k} \; N_{i,k} \right)$$

RBD Impimplementation – PSS

Fire Safety Analysis – Fire Risk Model



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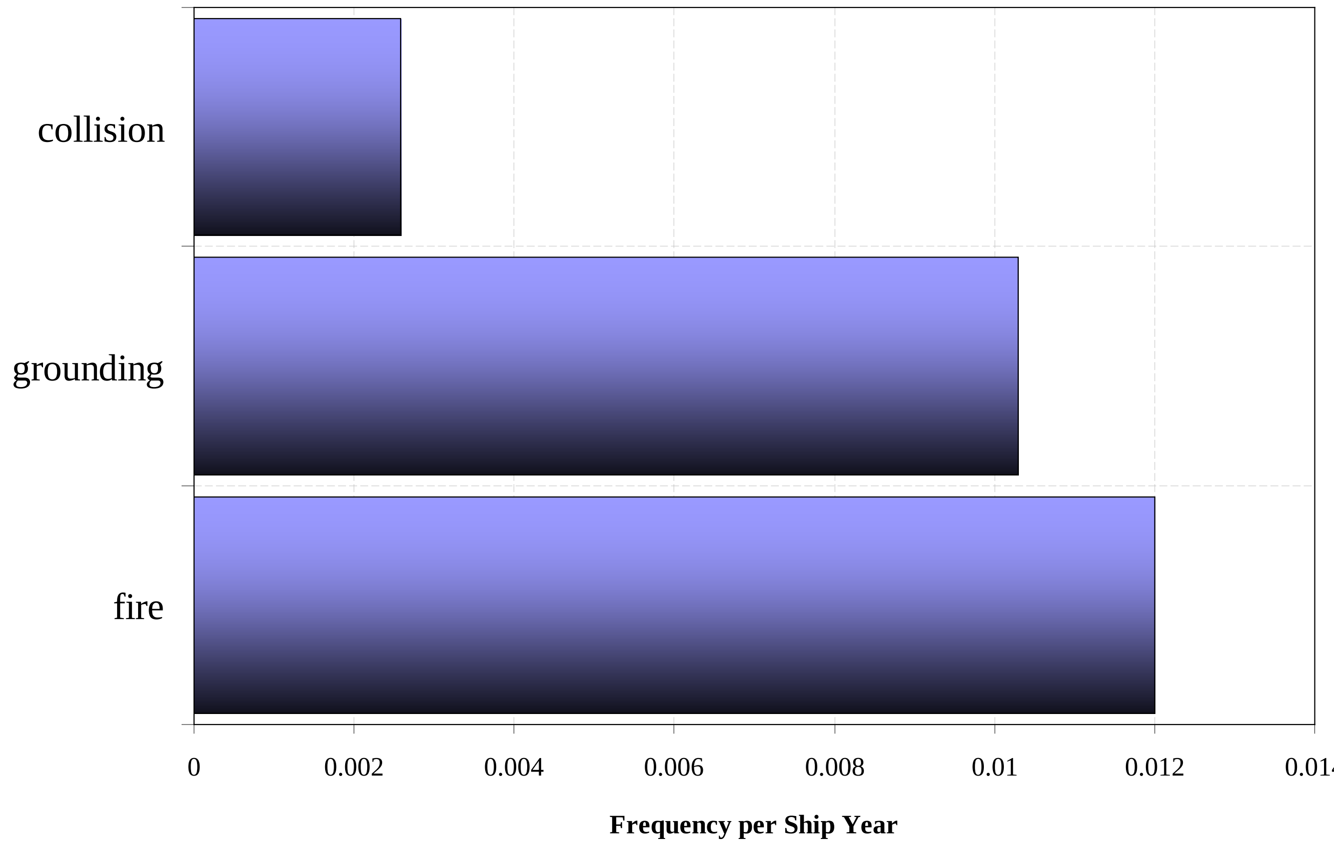
Fire Risk Analysis – Frequency (Historical Data)

Source: DNV

$$fr_{hz}\left(hz_2\right)$$

0.92 E-2 1/sy

FSA Cruise Ships (SAFEDOR, FSA, 2007): 1 event every 109 ship years



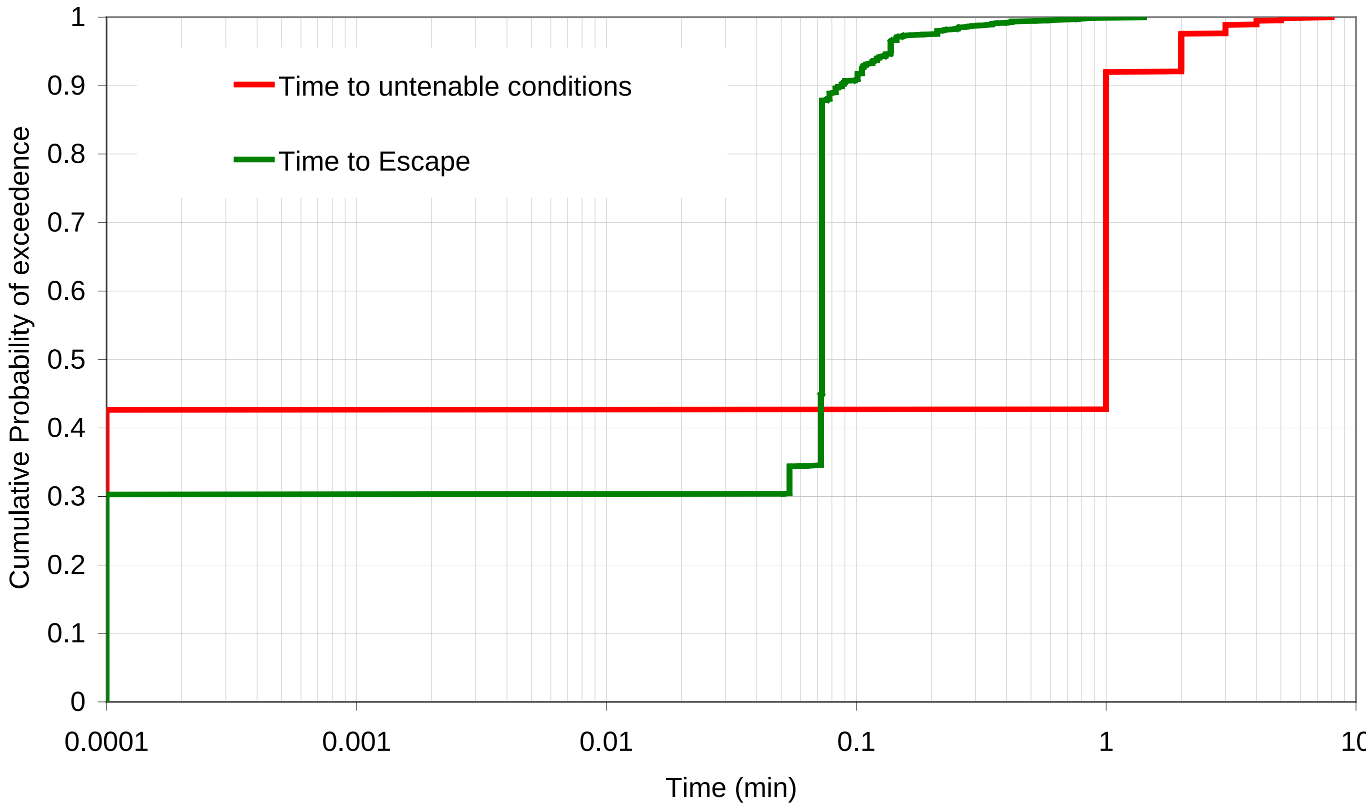
Frequency of event occurrence

RBD Impimplementation – PSS

Fire Risk Analysis – Consequences (Human Lives)

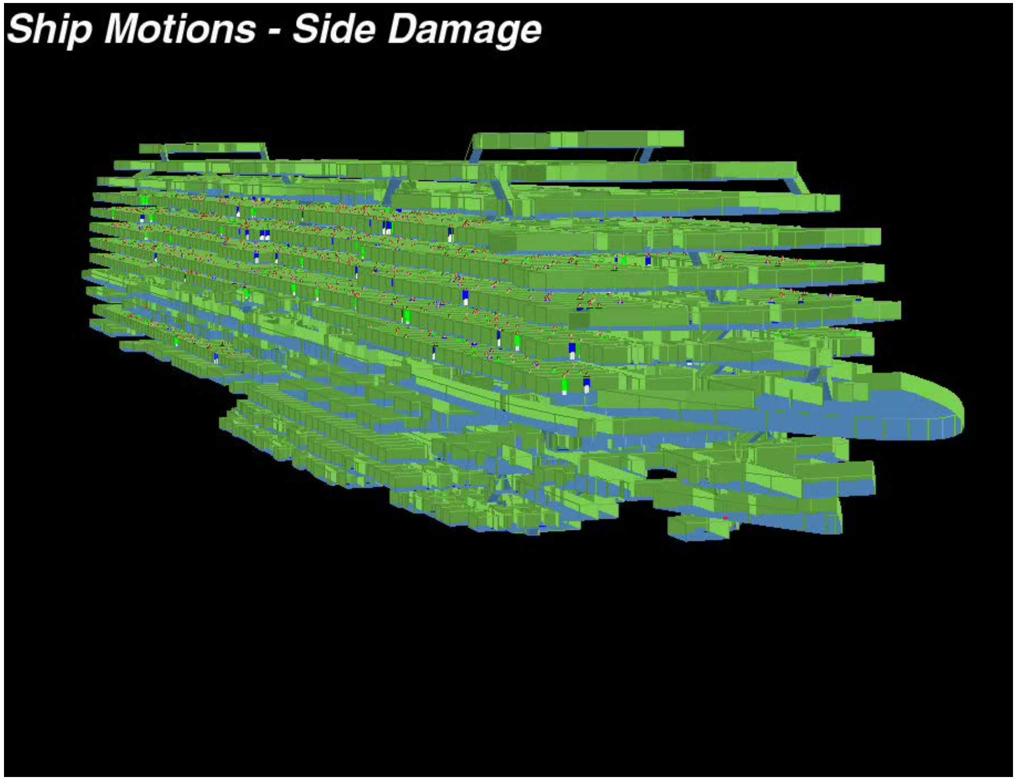
RSET > ASET

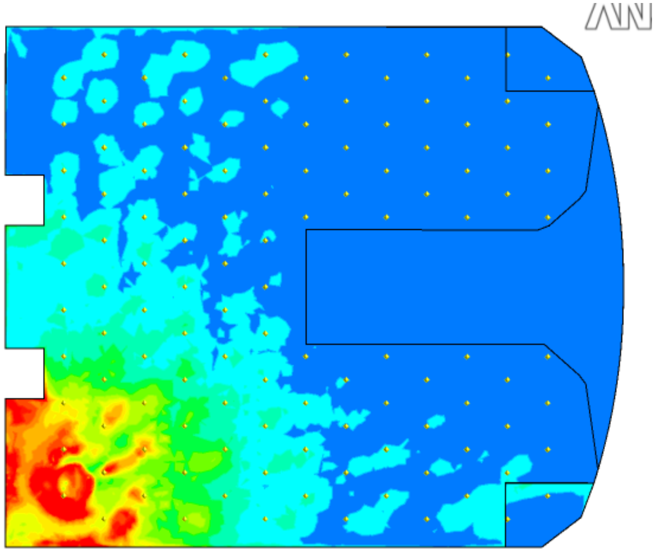
- *RSET* → time required for escape (escape analysis)
- *ASET* → time available before conditions become untenable (toxicity, heat, and visibility)

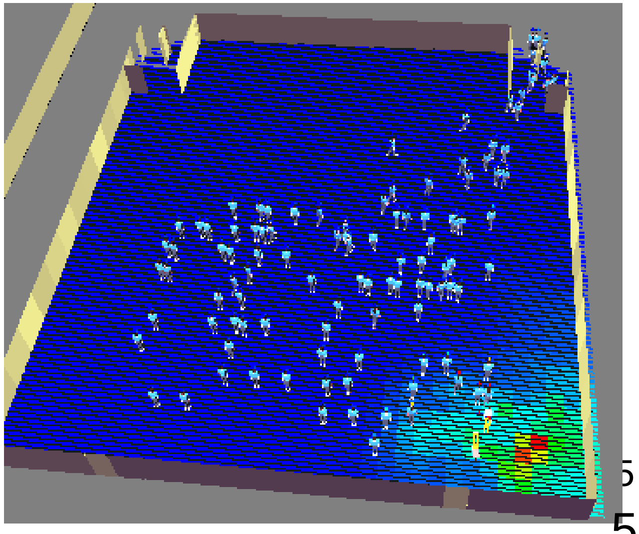


RBD Impimplementation – PSS

Time to Evacuate – Advanced Evacuation Simulation

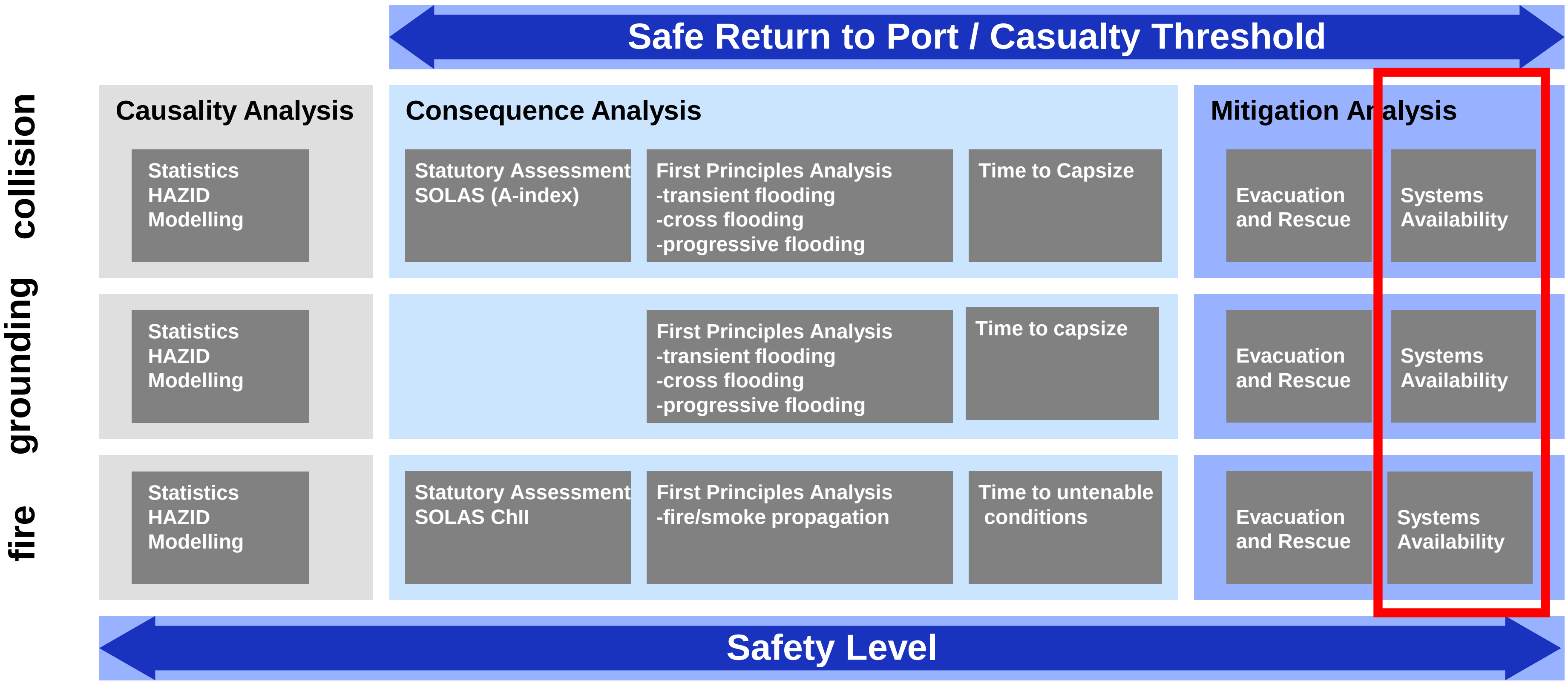






RBD Impimplementation – PSS

Systems Availability Analysis



RBD Impimplementation – PSS

Systems Availability Analysis – SRtP Casualty Scenarios

SAFE RETURN TO PORT

- Flooding to SWT Compartment (Reg. 8-1)
- Fire within casualty threshold (Reg. 21)

- Loss of a MVZ (Reg. 22)

EVACUATION AND ABANDONMENT

SWT = Single Watertight Compartment

MVZ = Main Vertical (Fire) Zone

RBD Impimplementation – PSS

Systems Availability Analysis – SRtP Essential Systems

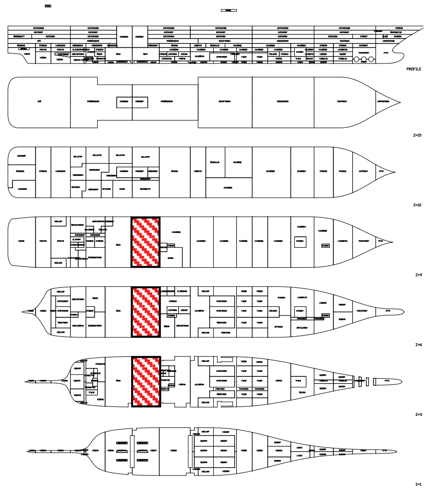
List of essential systems as defined in SOLAS II-2 Regulation 21-4 and 22-3

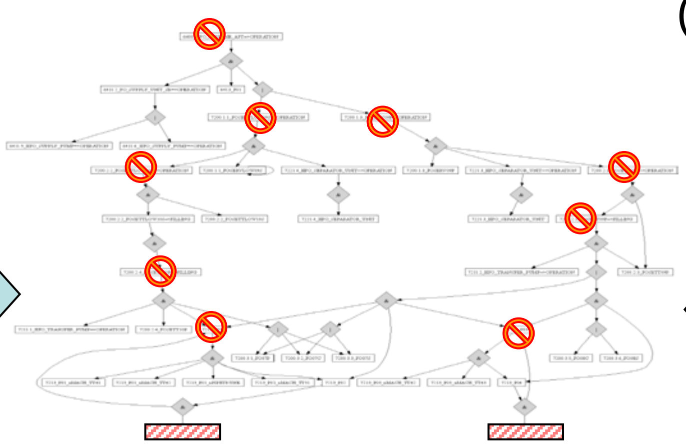
ID	System	SRTP Reg. 21-4	EAA Reg. 22-3
1	Propulsion and necessary auxiliary systems	X	
2	Steering systems and steering-control systems	X	
3	Navigation systems	X	
4	Systems for fill, transfer and service of fuel oil	X	
5	Internal communications system	X	X
6	External communications	X	X
7	Fire main system	X	X
8	Fixed fire-extinguishing systems (gaseous and water)	X	
9	Fire and smoke detection systems	X	
10	Bilge and ballast systems	X	X
11	Power operated watertight and semi-watertight doors	X	
12	Systems intended to support “safe areas”	X	
13	Flooding detection systems	X	
14	Other systems vital to damage control efforts	X	
15	Lighting along escape routes, at assembly stations and at embarkation stations of lifer-saving appliances		X
16	Guidance systems for evacuation		X

RBD Impimplementation – PSS

SRtP – Residual Functionality Post-Casualty (iSys)

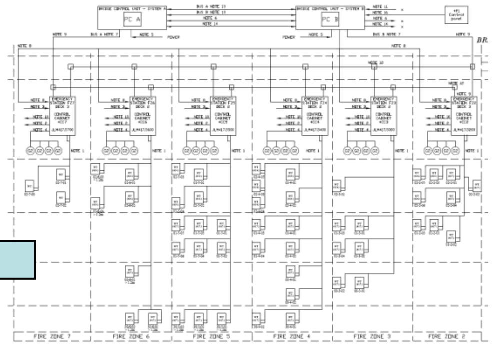
Watertight subdivision





“BDD”

Systems’ diagrams
(systems’ design principles)

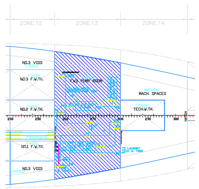


Casualty scenario

Essential System	# 1	Room	PUMP13
Scenario	FLOODING	Location	MVZ 3 Deck 01

Observations

ES not operable due to failure of the Power Supply System.(# X03)
Power System fails due to Diesel Generators failure.
Diesel Generators fail due to LO system (# 651) failure.
LO system fails due to failure of lubrication function for the No1-6 Main Generator.
The lubrication functions fail due to failure of LO purification system.
LO purification system fails due to failure of technical water.

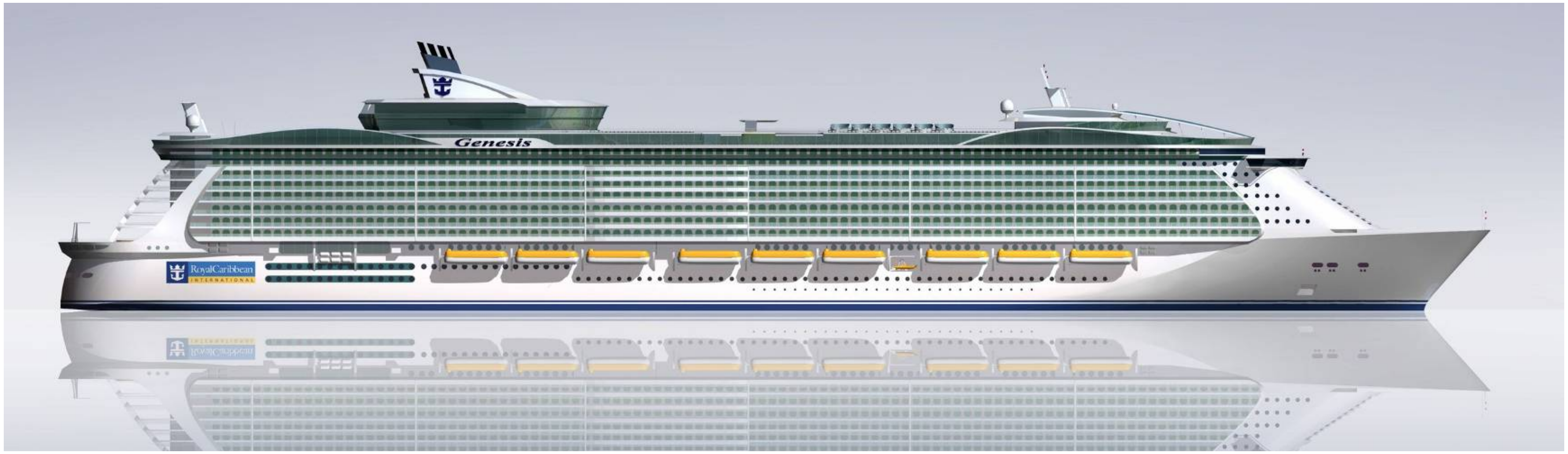


Details of damage

Ship system	Component ID	Level
TECHNICAL WATER SYSTEM	515_E_FwdWtrMistFeedPump	E
TECHNICAL WATER SYSTEM	515_E_No1_2TechWPump	E
TECHNICAL WATER SYSTEM	515_P1_nPUMP13	P
TECHNICAL WATER SYSTEM	515_P2_nPUMP13	P
TECHNICAL WATER SYSTEM	515_P3_nPUMP13	P
TECHNICAL WATER SYSTEM	515_P4_nPUMP13	P
TECHNICAL WATER SYSTEM	515_P5_nPUMP13	P
662 GENERAL FW COOLING SYSTEM	662_P01_nPUMP13	P
671 FEED WATER SYSTEM	671_P01_nPUMP13	P
671 CONDENSATE SYSTEM	671_P03_nPUMP13	P
712 WORKING AIR	712_P01_nPUMP13	P

RBD Impimplementation Example

Oasis of the Seas – General particulars

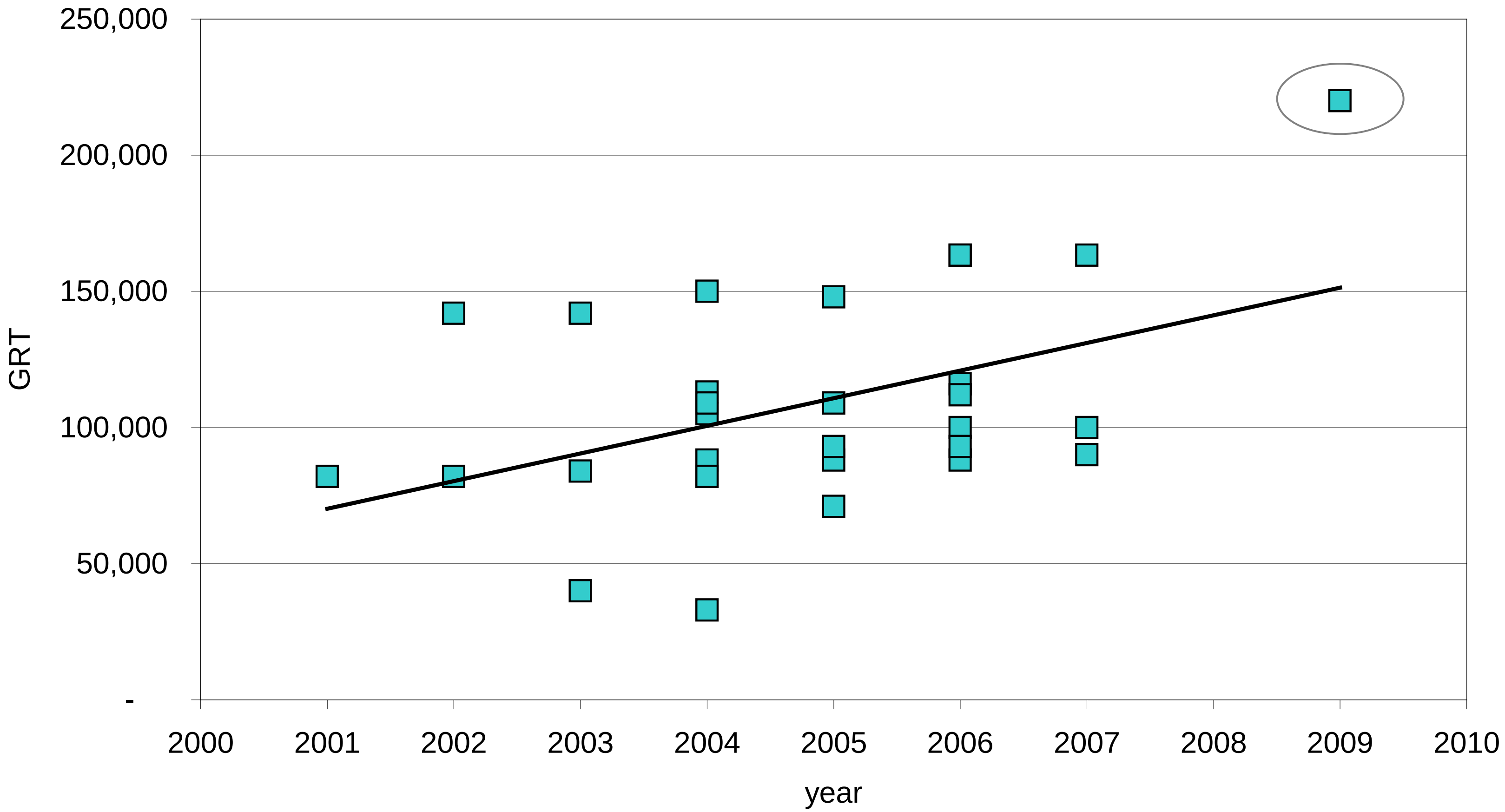


- Gross Tonnage 225 000
- Delivery November 2009
- DNV ✠ 1A1, Passenger Ship: EC0, RPS, F-M, LCS(DIS), BIS,
- TMON, CLEAN, COMF(V)1, FUEL
- Design basis: E0, DP notation AUTR, NAUT-AW

- Length 361 m
- Breadth 47 m
- Draught 9,15 m
- Air Draught 72 - 65 m
- Number of Guests 5400
- Number of Crew 2166
- LSA Capacity 8460

RBD Impimplementation Example

Oasis of the Seas – Building Bigger Ships



RBD Impimplementation Example

Oasis of the Seas – Flooding Risk Analysis $fr_{hz}(hz_1)$

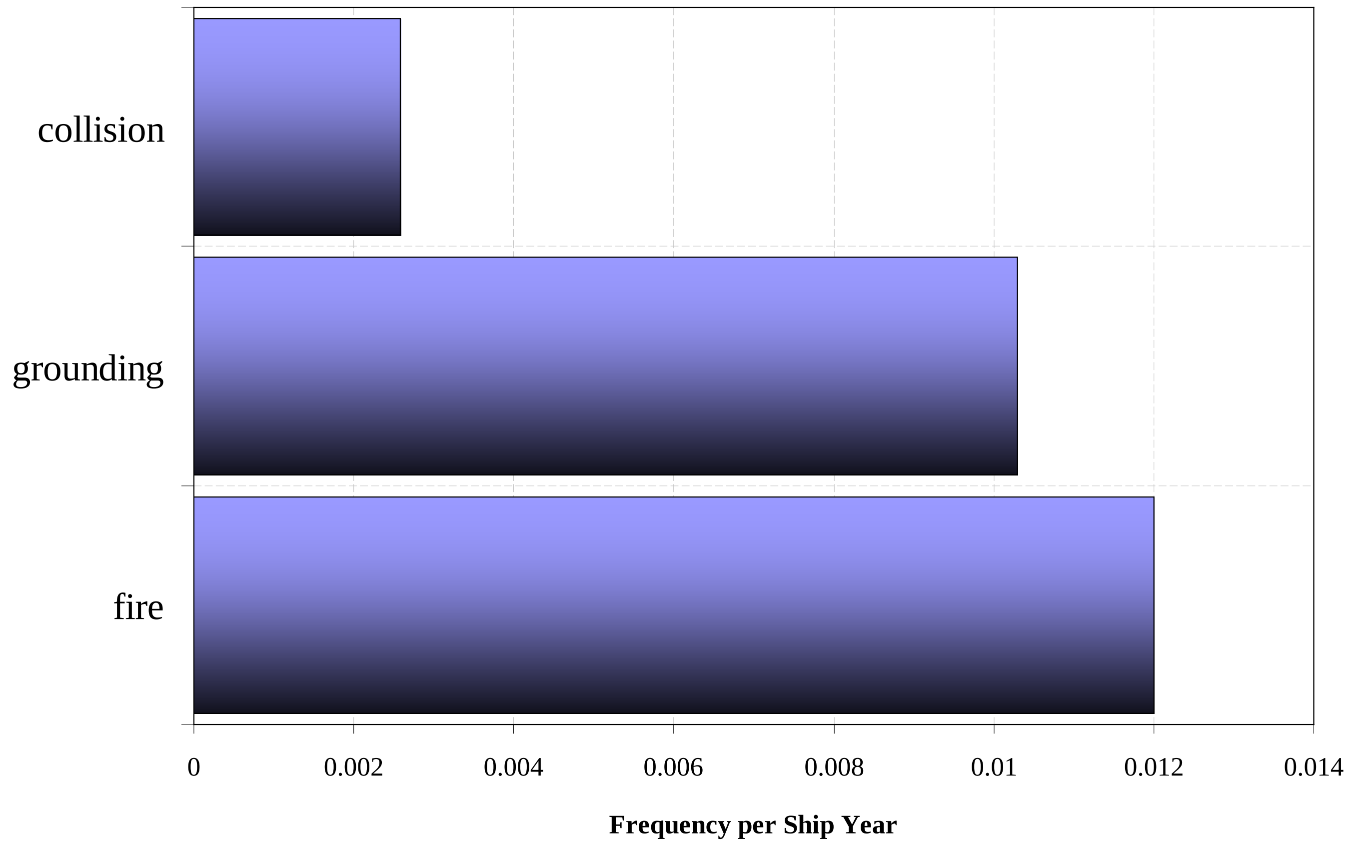
Source: DNV

$$fr_{hz}(hz_1)$$

1.148 E-3 1/sy

FSA Cruise ships (SAFEDOR, FSA, 2007):
1 event every 871 ship years

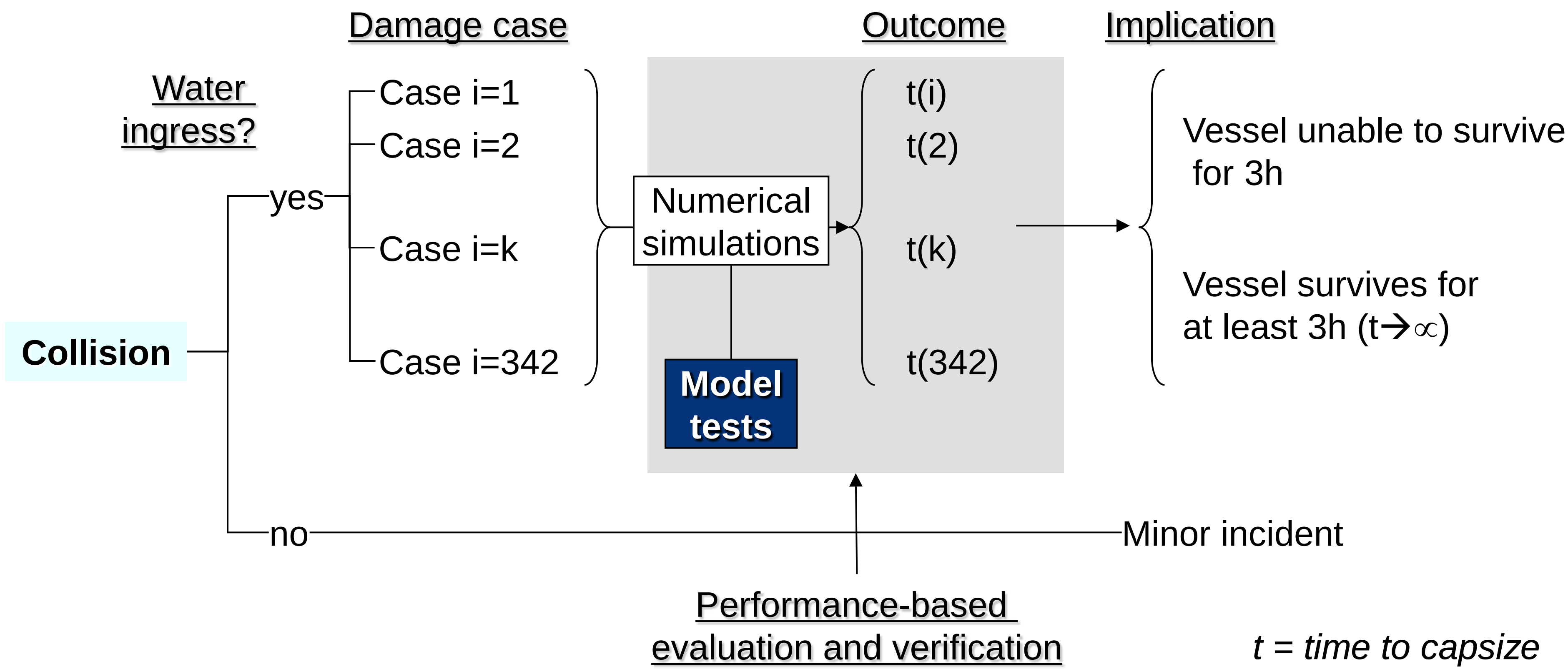
RCCL:
no occurrences in 111 ship years of records



Frequency of event occurrence

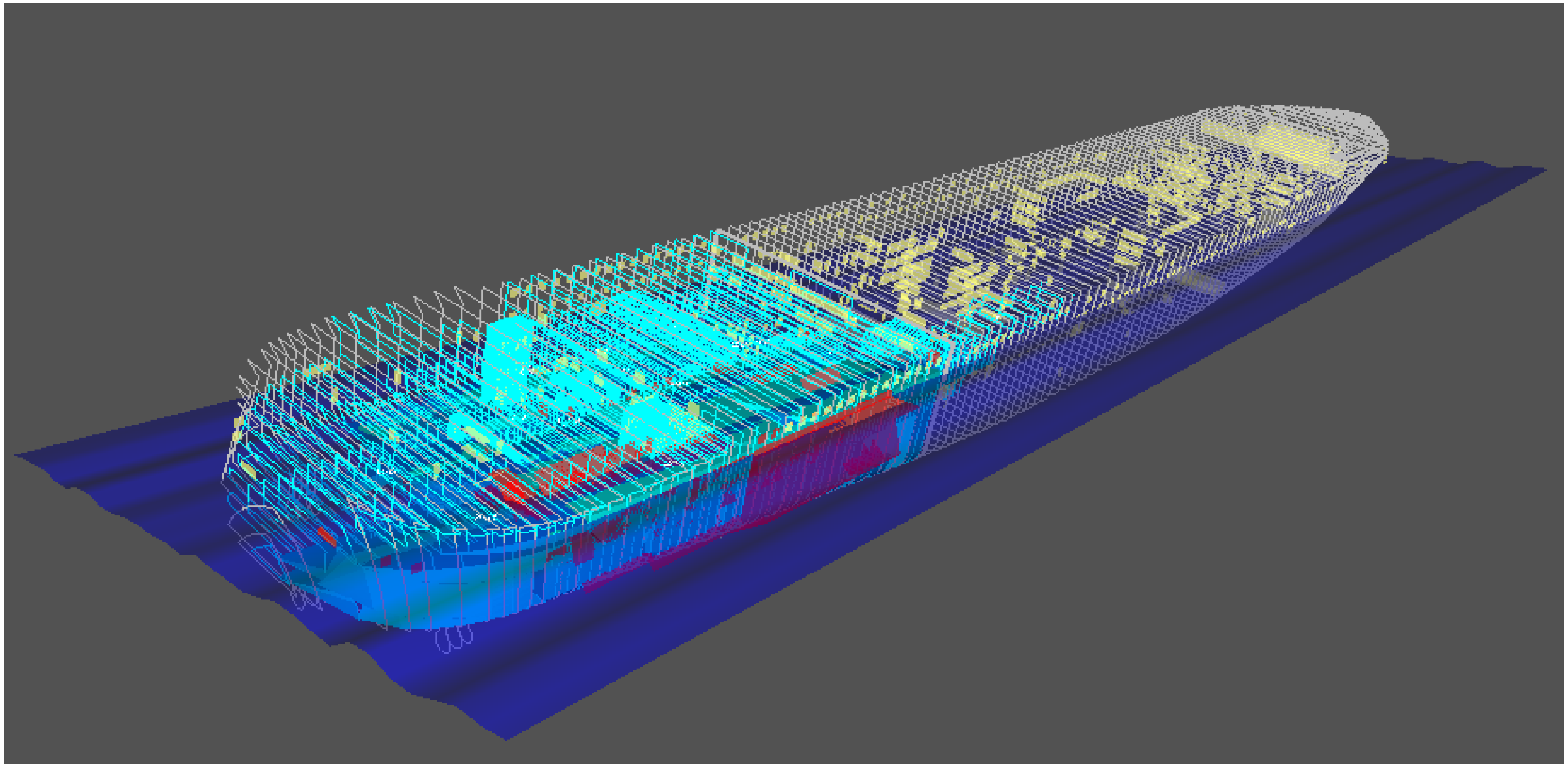
RBD Impimplementation Example

Oasis of the Seas – Flooding Risk Analysis t_{cap}



RBD Impimplementation Example

Oasis of the Seas – Flooding Risk Analysis



Case by case explicit dynamic flooding simulation

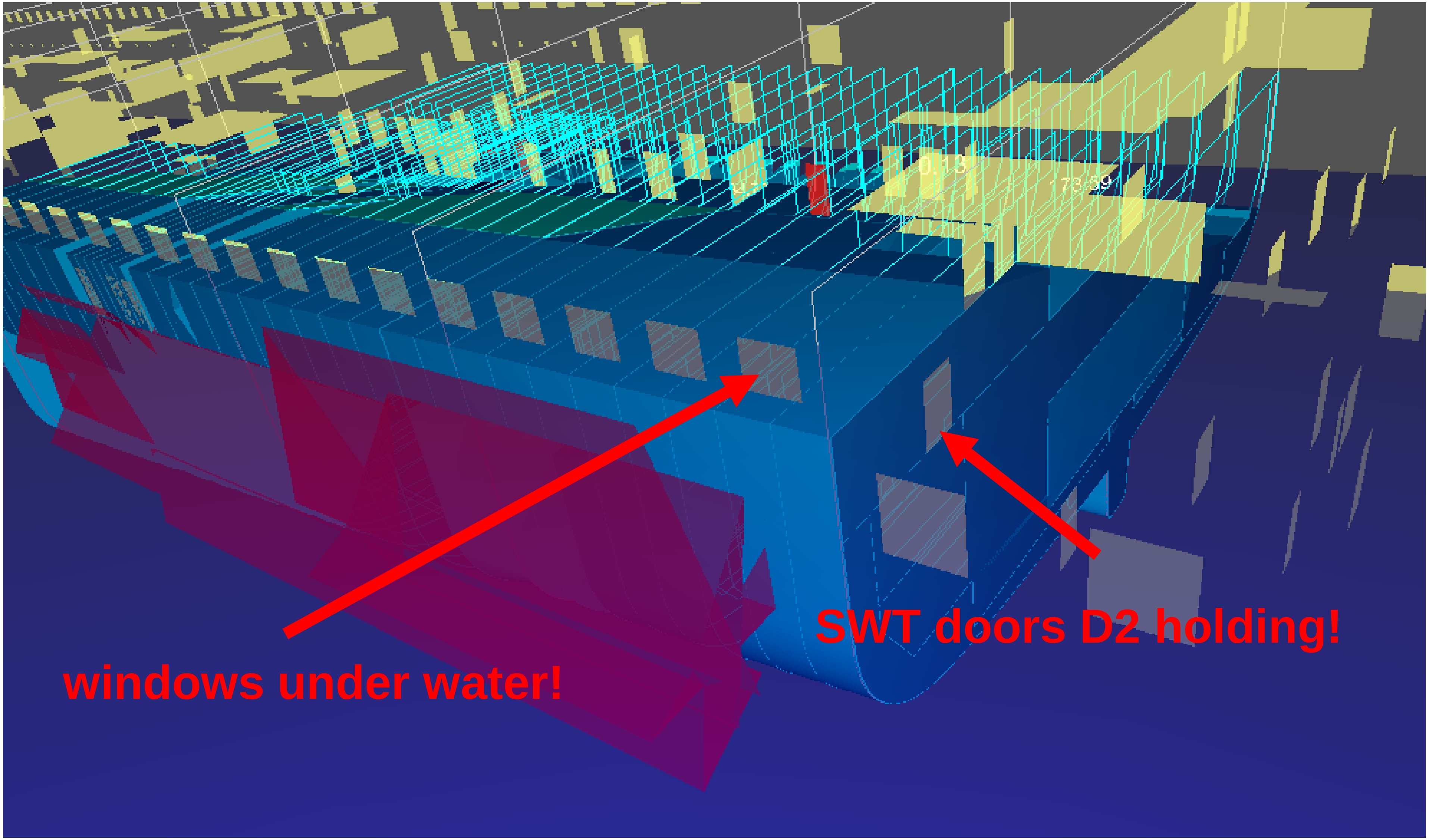
Transient and progressive flooding

Impact of multi free-surfaces

Impact of watertight and semi-watertight doors and arrangements

RBD Impimplementation Example

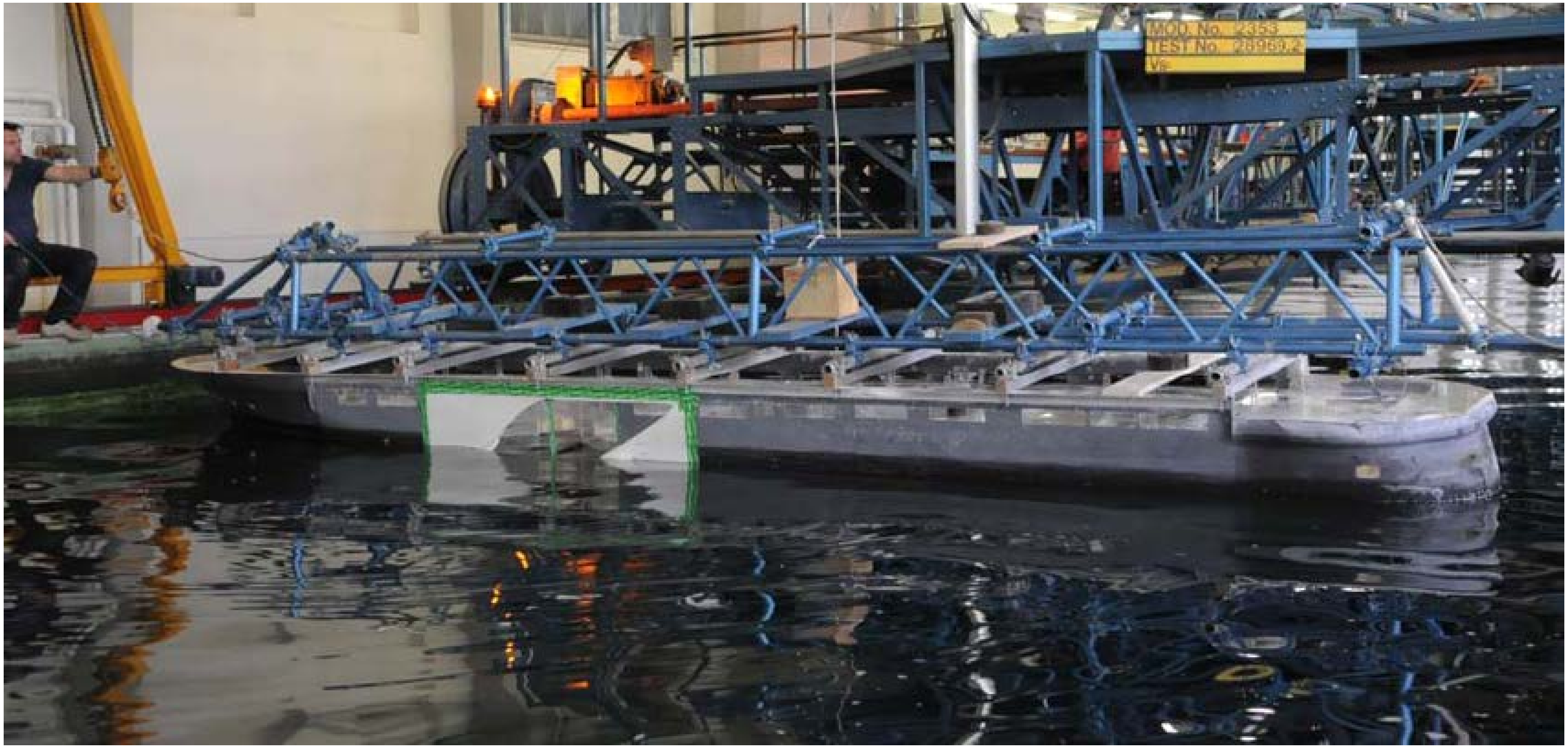
Oasis of the Seas – Flooding Risk Analysis



RBD Impimplementation Example

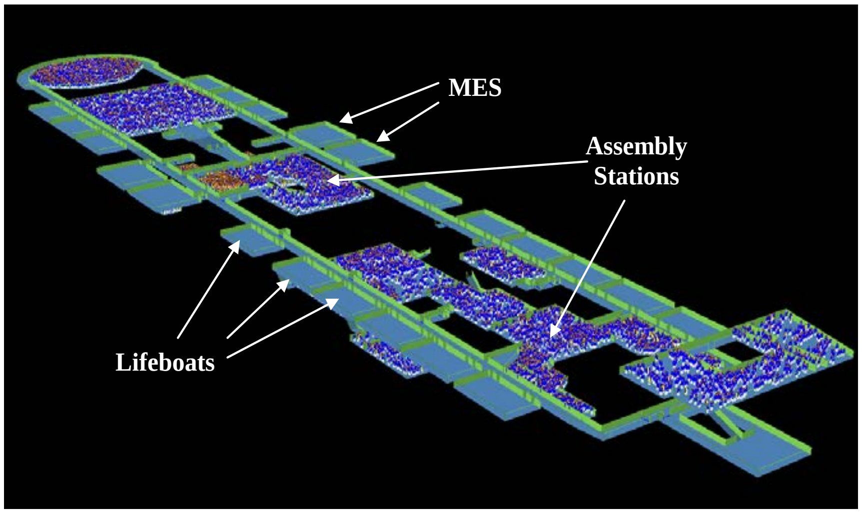
Oasis of the Seas – Flooding Risk Analysis

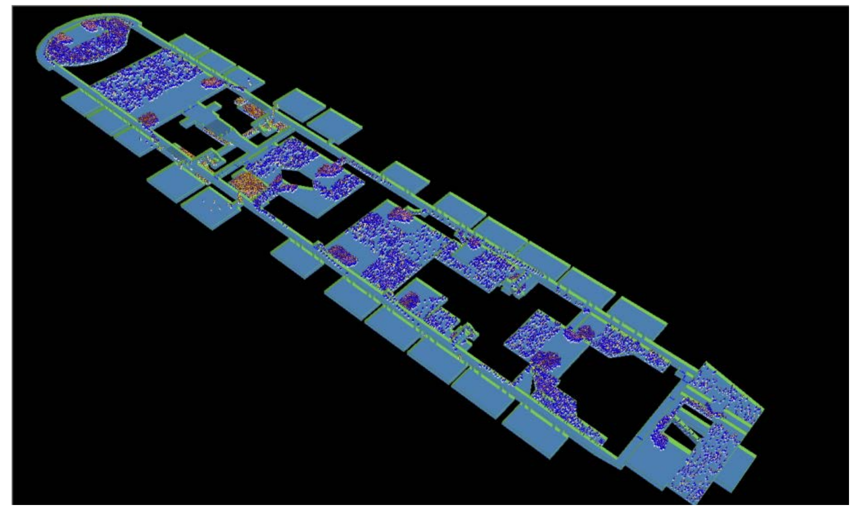
717 compartments, 1160 openings (1:50 scale – verification)



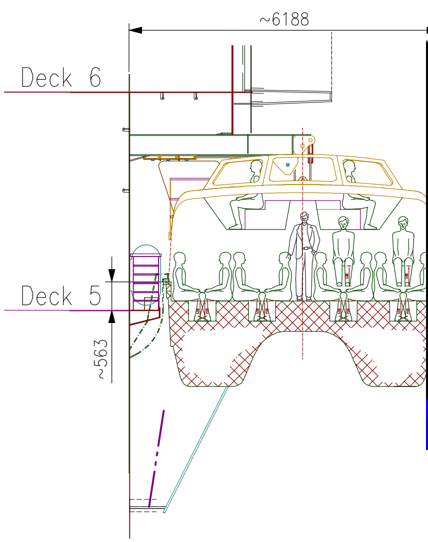
RBD Impimplementation Example

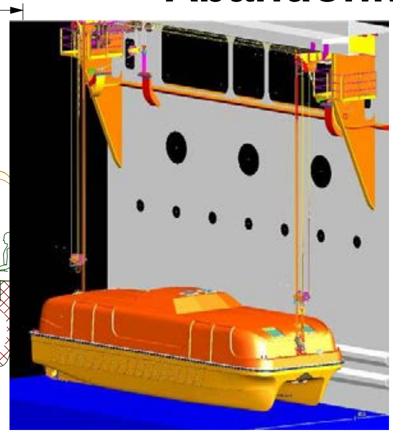
Oasis of the Seas – E&A Studies

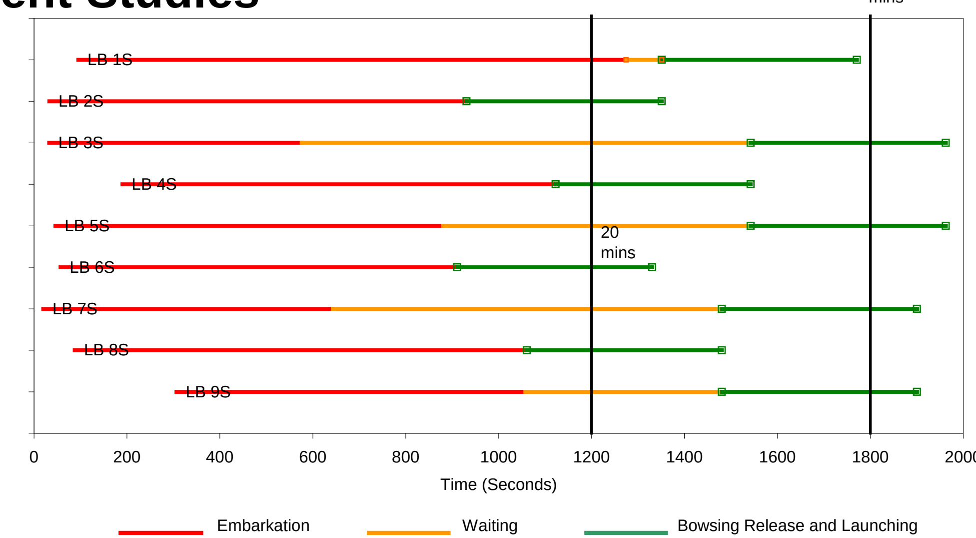




Abandonment Studies

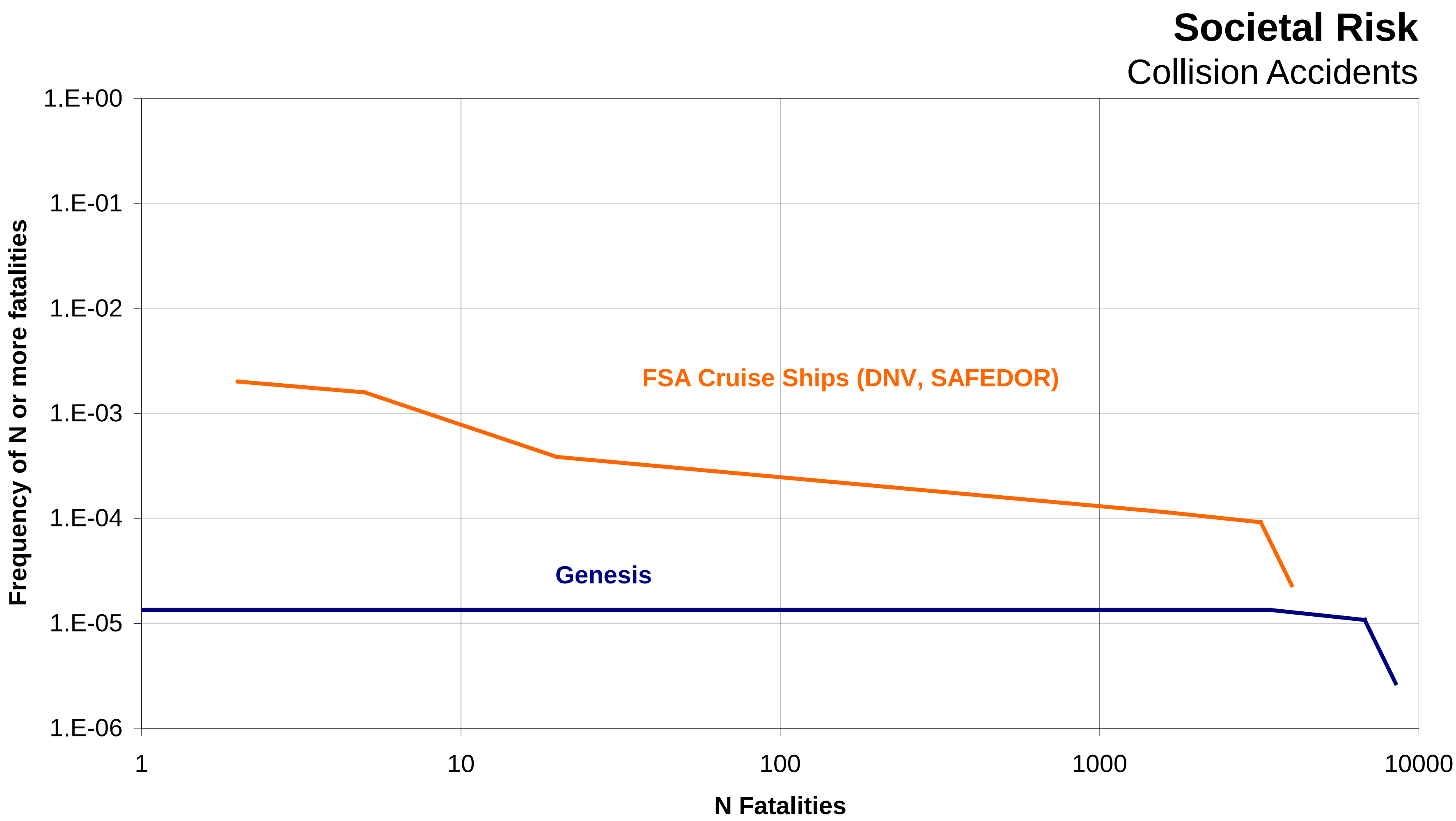






RBD Impimplementation Example

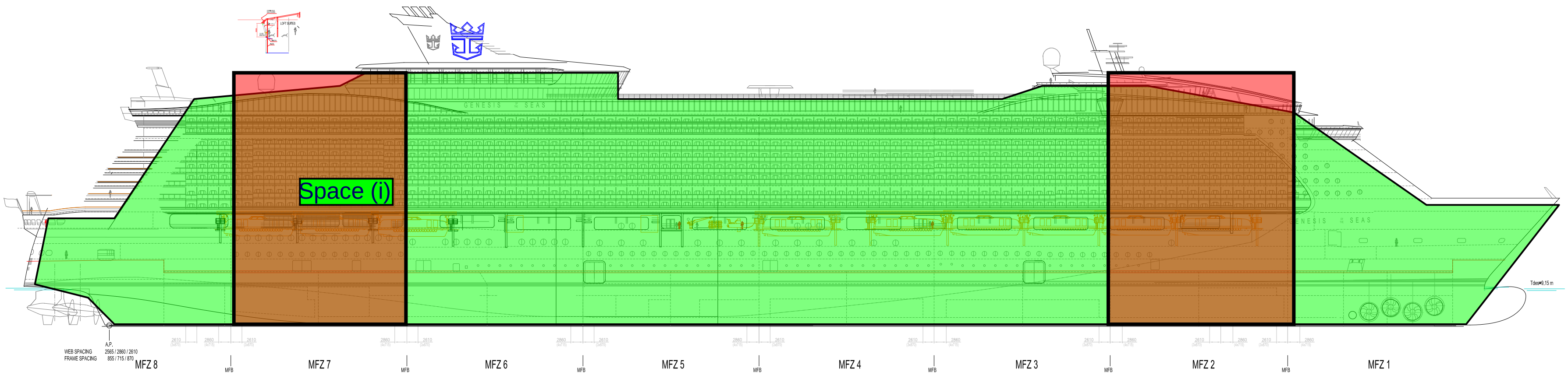
Oasis of the Seas – Societal Risk (Flooding)



RBD Impimplementation Example

Oasis of the Seas – Fire Safety Analysis $fr_{hz}(hz_2)$

144 Fire Zones – 80 in excess of SOLAS



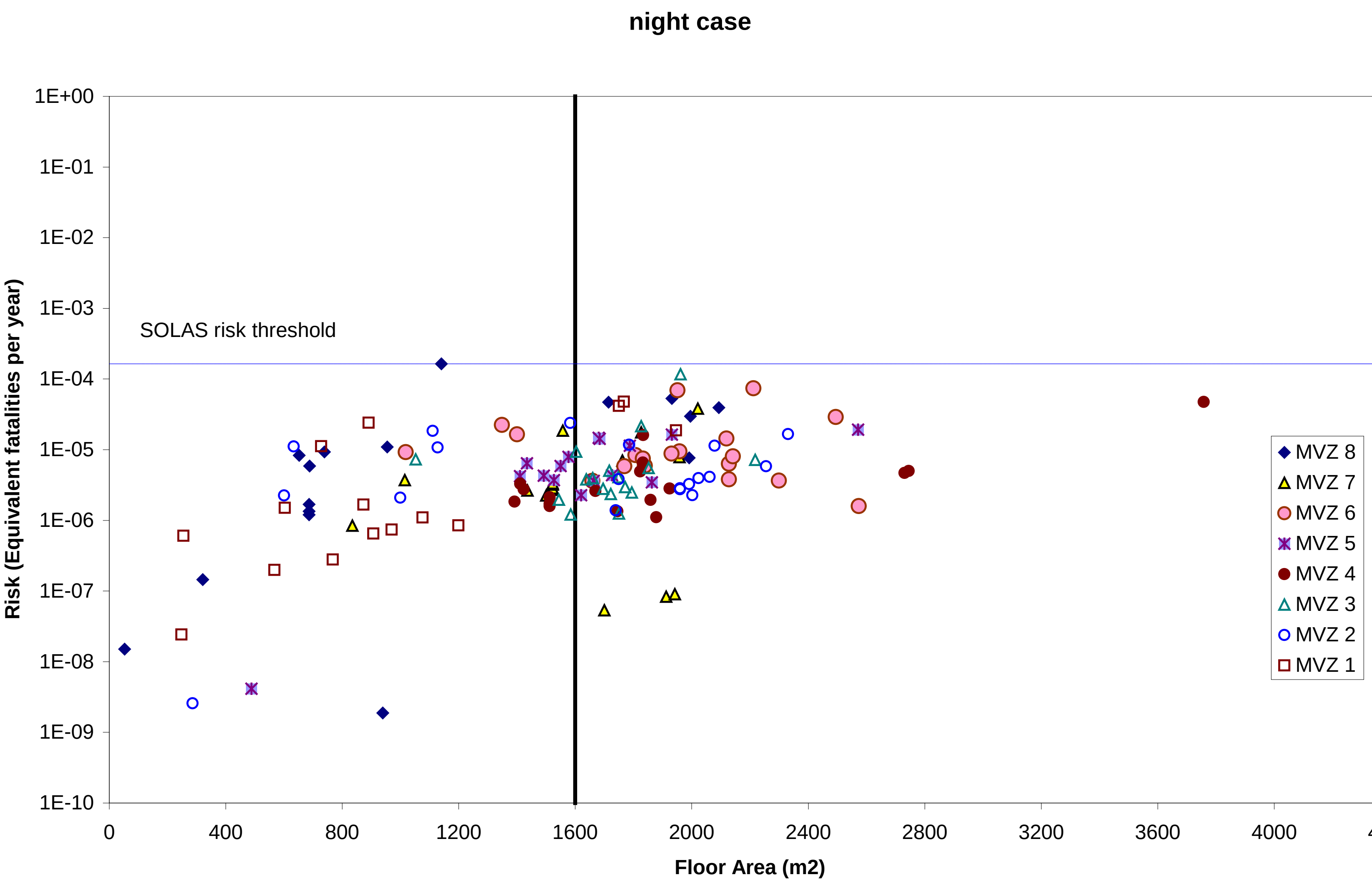
8,236 spaces

SAFEDOR cruise ship FSA

$fr_{hz}(hz_2)$ 0.92 E-2 1/sy

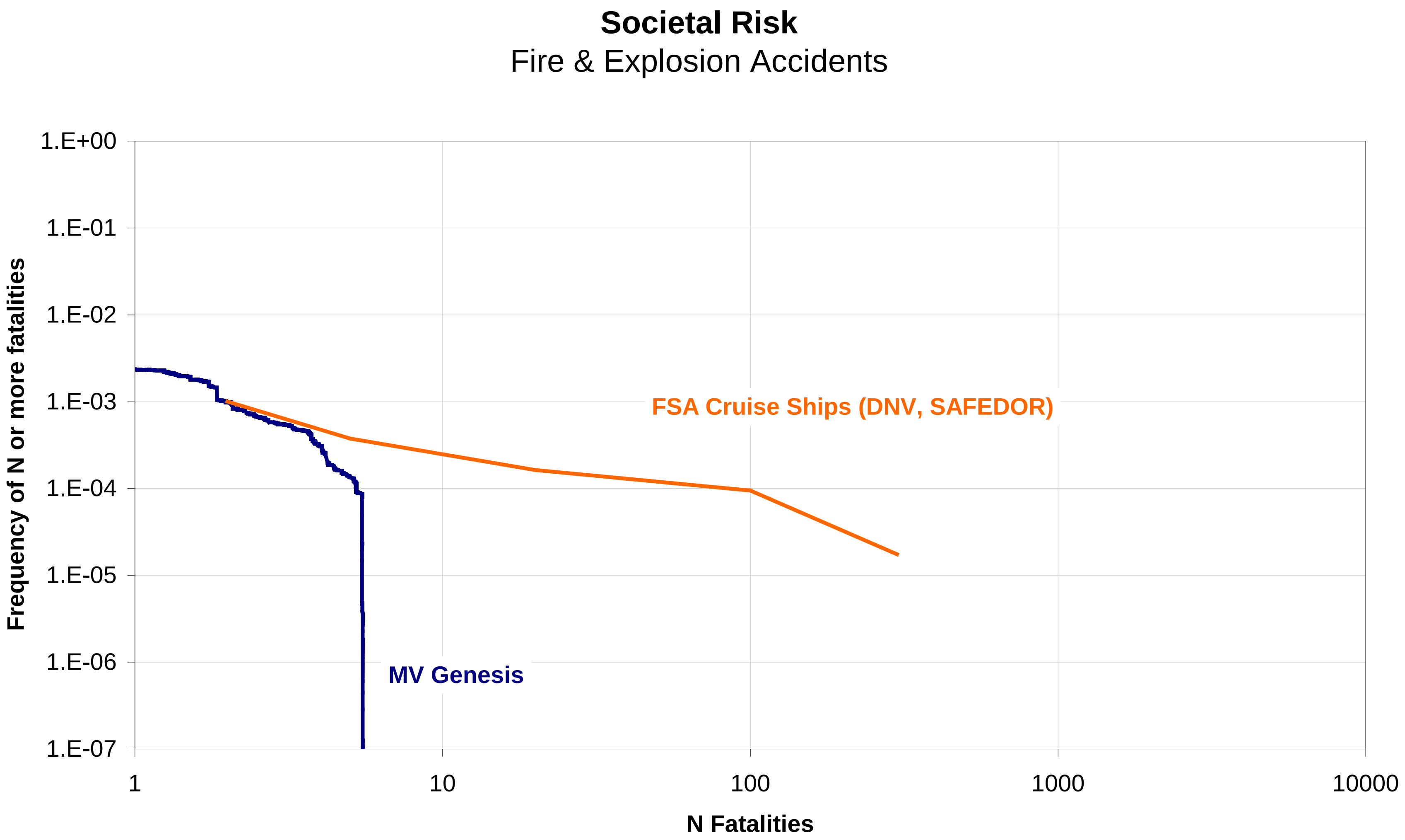
RBD Impimplementation Example

Oasis of the Seas – Fire Safety Analysis $pr_N\left(N\middle|hz_2\right)$



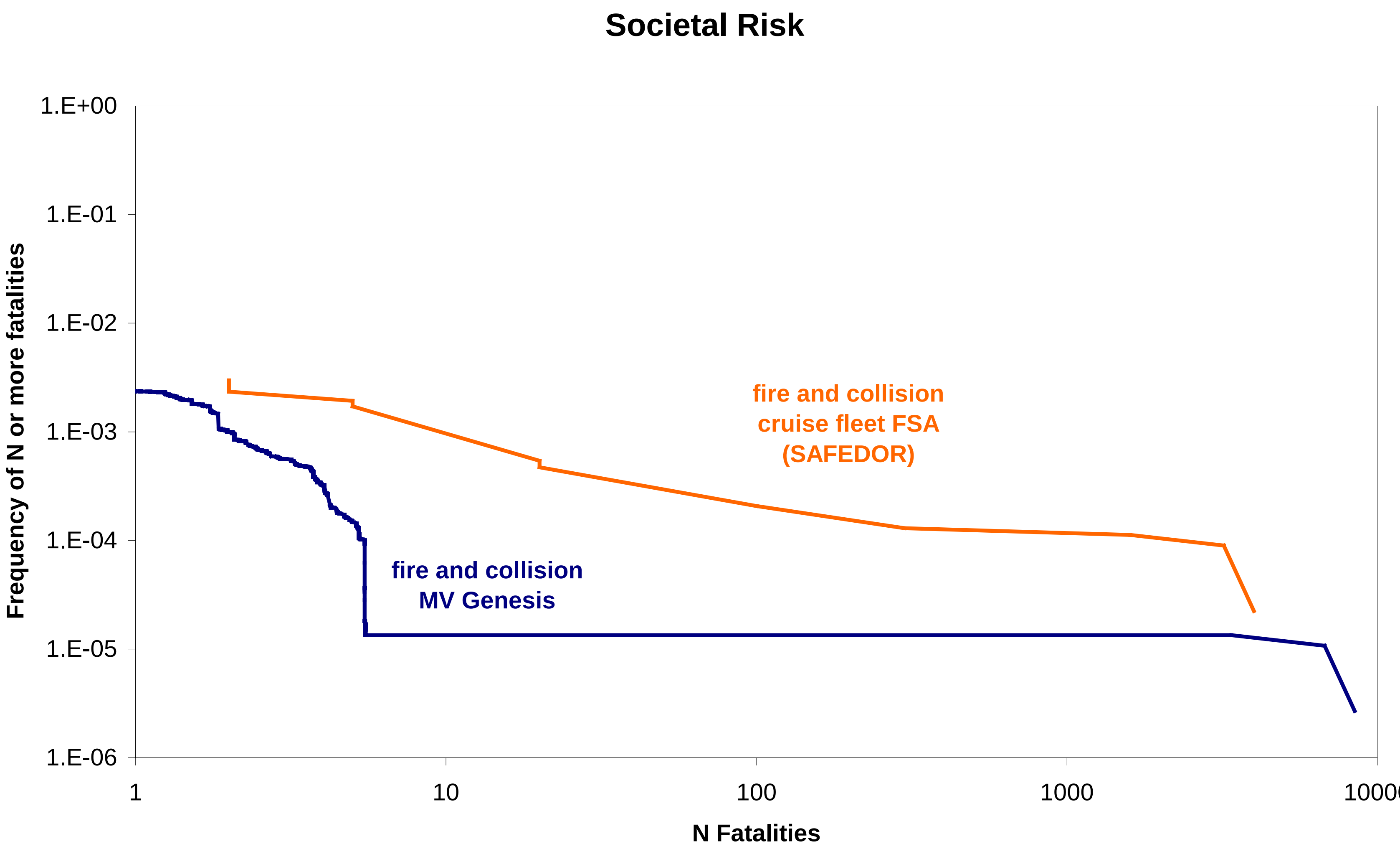
RBD Impimplementation Example

Oasis of the Seas – Societal Risk (Fire)



RBD Impimplementation Example

Oasis of the Seas – Safety Level (Total Risk – Societal)



RBD Impimplementation Example

LCRM (Operation): Oasis of the Seas Pilot Study

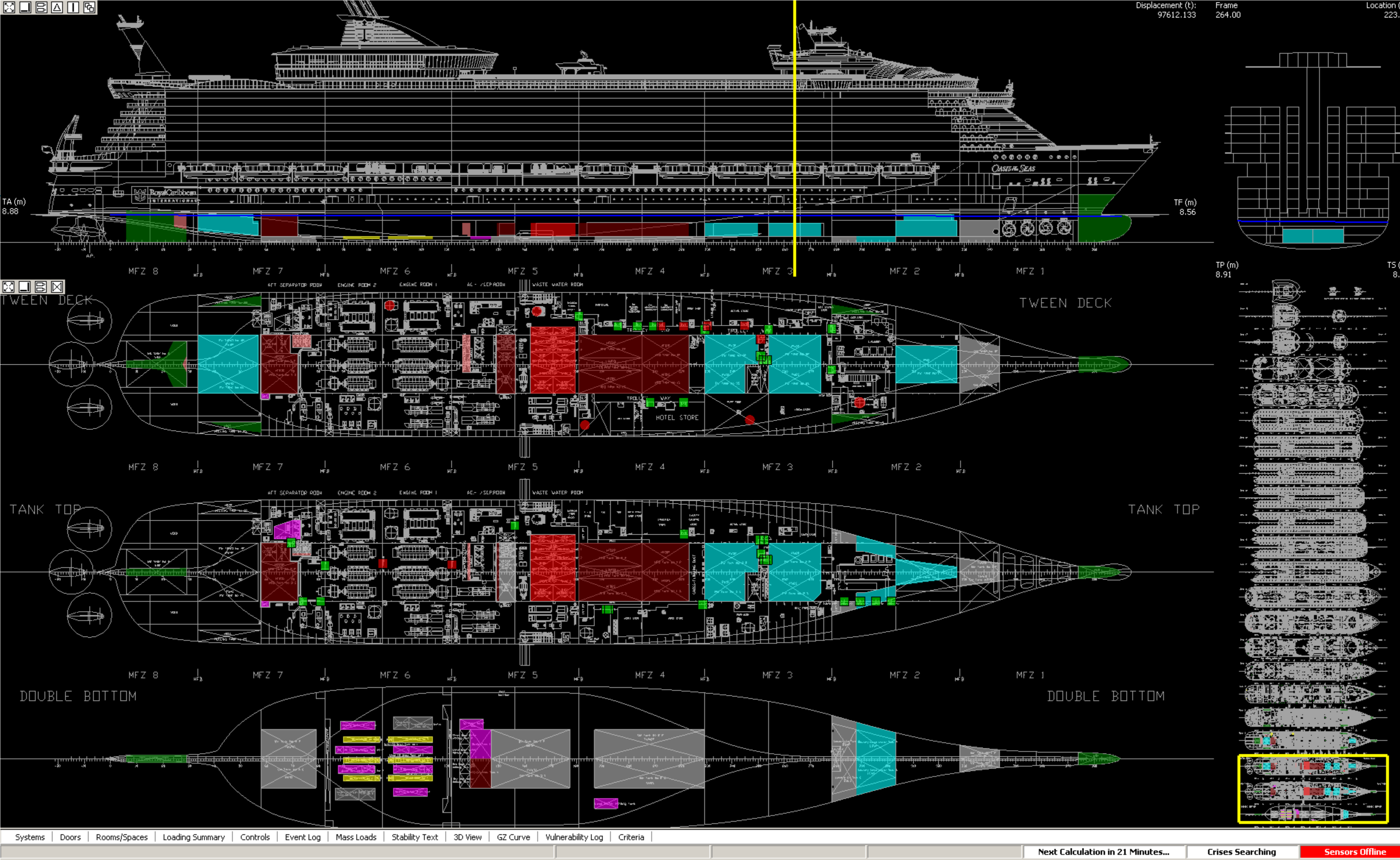
- Can the extensive knowledge acquired during the design development be used to manage operational (residual) risk and to address ER?

RBD Impimplementation Example

LCRM (Operation): Oasis of the Seas DSS

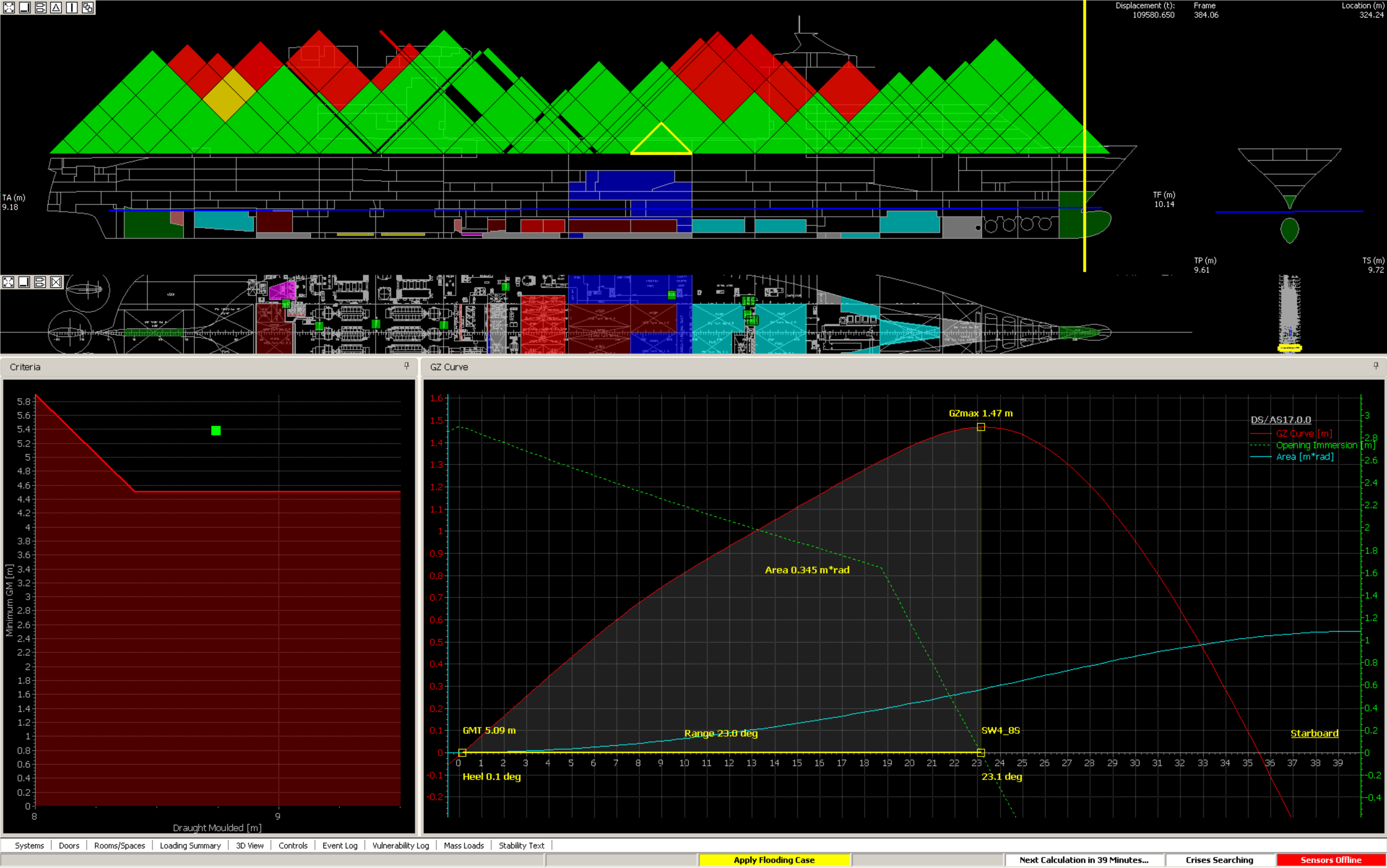
Key features include:

- **Real time sensors** and hardware integration (link to ship's SMS): tank levels, draughts, door status, water ingress alarms, wind and waves
- **Vulnerability log:** global and local ship vulnerability to flooding and fire
- **Criticality assessment**: survival time, escape and evacuation time (crises management)
- **Corrective action search:** evaluation of the impact of corrective actions.
- **Essential systems availability** post-flooding/fire (verification of compliance of SRtP requirements)



iStand | loading computer

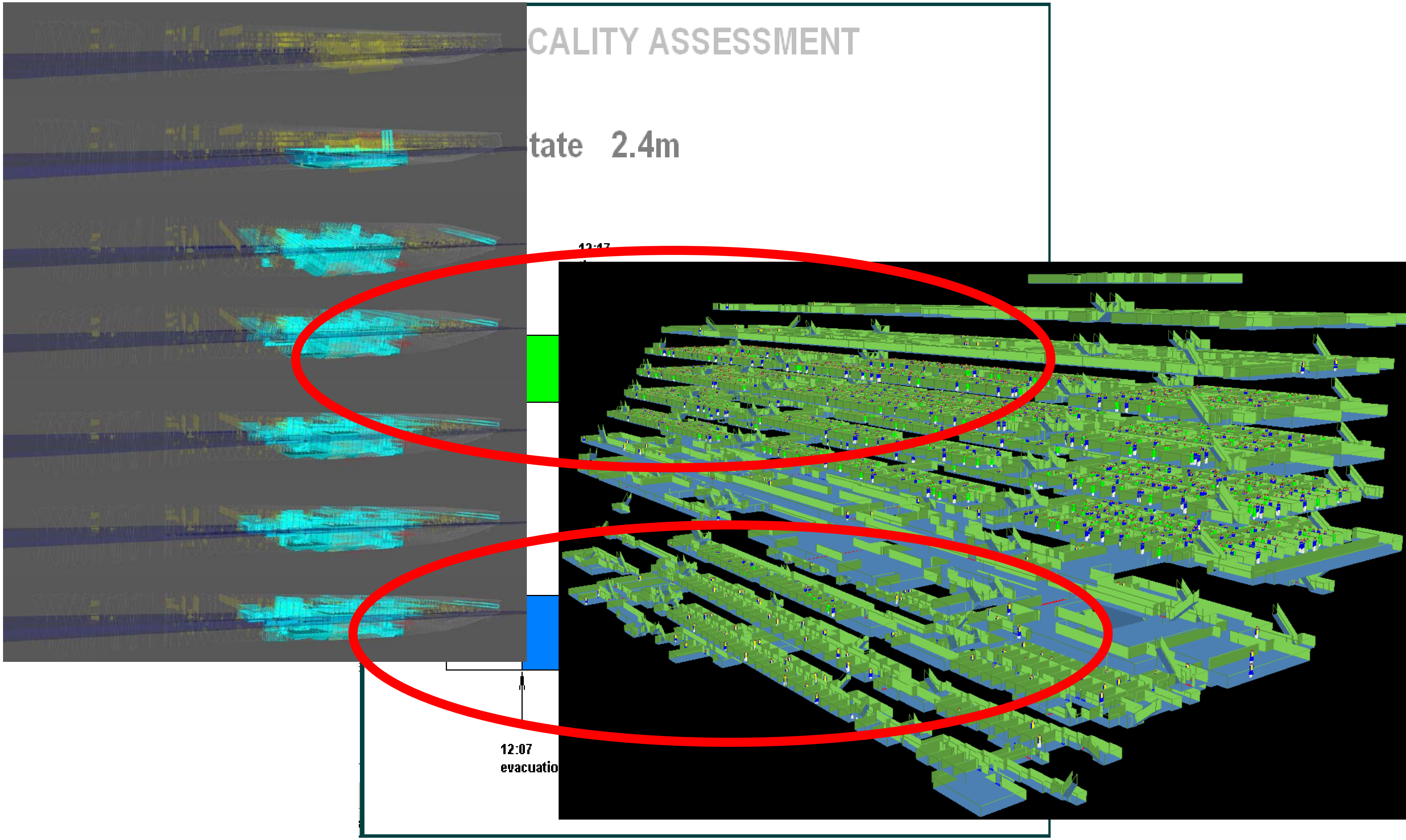
75



iStand | stability monitoring

RBD Impimplementation Example

LCRM – Oasis of the Seas Crisis Management



Concluding Remarks

- “Design for Safety: Risk-Based Design (RBD)” enables ship safety to be dealt with in a systematic and all embracing way by **treating safety as an objective in the design process.**
- RBD opens the door to innovation and offers competitive advantage to the maritime industry by facilitating cost-effective safety, **without RBD optimal design solutions are not possible!**
- Adopting a risk-based framework is synonymous with promoting rational decision making; in this respect, such an approach can support and guide contemporary regulatory developments at IMO, e.g., **Goal-Based Standards**.

Concluding Remarks

- Life-cycle Risk Management is a formal process providing a holistic framework, to embrace all phases of the life-cycle of the vessel from **design** (risk reduction/mitigation) to **operation** (management of residual risk) and **emergency response** (preparedness/crisis management), leading to safety assurance in the most cost-effective way possible.
- Such a formal process facilitates **measurement of safety performance**, which constitutes the kernel for continuous safety improvement and the foundation for instigating and sustaining a safety culture in the maritime industry.