Aalto-yliopisto
Insinööritieteiden
korkeakoulu

MEC-E2009 - Marine Risks and Safety L

Lecture 4: Goal-based ship design

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Intended learning outcome

To make you able to

- explain the role of rules and regulations in ship design
- explain the difference between prescriptive-based design and goal-based design
- explain pros and cons of prescriptive-based design and goal-based design
- list some practical applications of goal-based design

Contents

- Design terminology (~10 min)
- Prescriptive-based design (~10 min)
- Goal-based design (~ 40 min)
- Break (30 min)
- Regulations, methods, and principles related to goal-based design (~ 50 min)
- Summary and discussion (~10 min)

Reading material

- Papanikolaou, A. (Ed.), 2009. *Risk-Based Ship Design Methods, Tools and Applications*, pp 1-31 + pp 97–147 (Regulatory framework)
- Jenkins, V., 2012. *Goal / Risk Based Design – Benefits and Challenges*. Dubai, Interferry
- Hermanski, G., Daley, C., 2010. *On formal safety assessment (FSA) procedure*

Motivation

Viking Sky incident in 2019.
Photo: Eva Frisnes /abcnews.go.com

Costa Concordia disaster in 2012.
Photo: Reuters

MS Explorer sinking in 2007. Photo: AP

Sally Albatross grounding in 1994.
Photo: Lehtikuva/arkisto/Peter Stone/

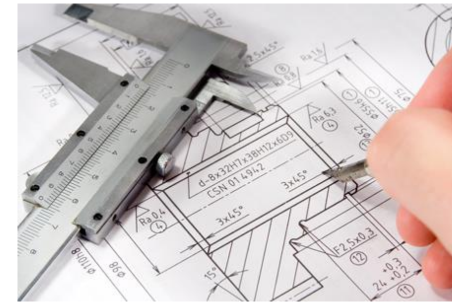
MS Estonia disaster in 1994.

Design terminology

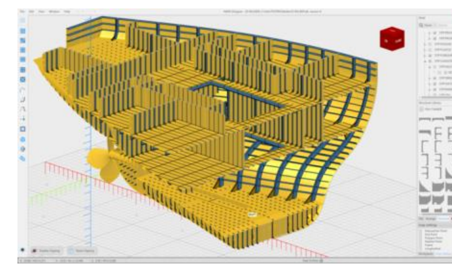
What is design?

No exact definition

- The application of knowledge/science to solve a problem
- Knowledge synthesis
- Optimization
- Engineering



Picture: www.asme.org



Picture: www.napa.fi

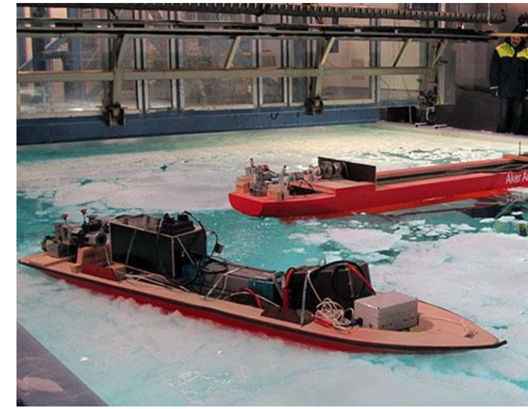
Design model

Any design task involves the determination of a design model

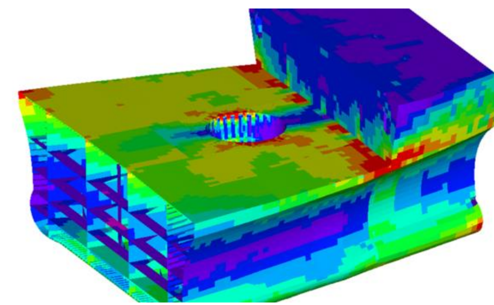
- Can take various forms but is always an abstraction (generalization) of an artefact
- Approximate representation

Should be limited to areas of interest

- The level of detail (model fidelity) should be adapted to the design task
- A higher level of detail/complexity is not necessarily better

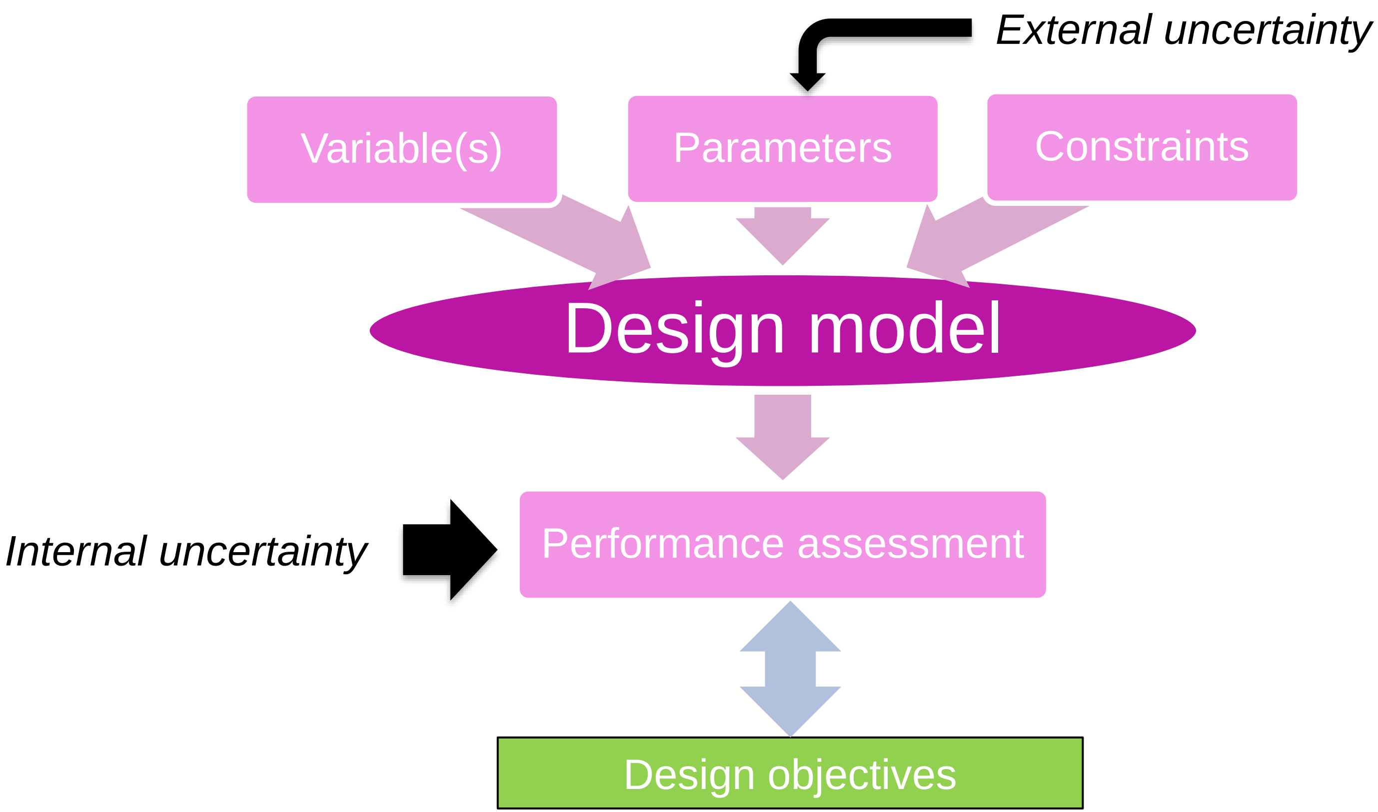


Picture: http://akerarctic.fi/



Picture: https://mec.ee

Design model components

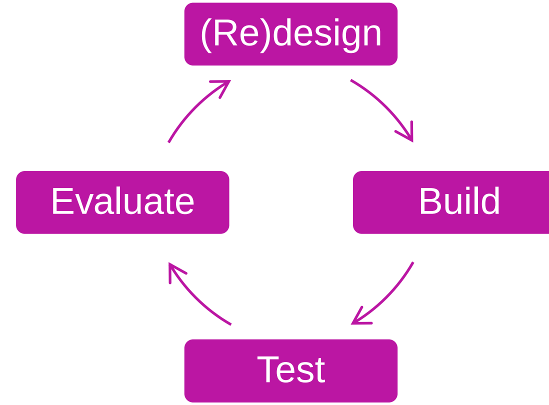


Prescriptive-based design

Prescriptive regulations

Ship design is traditionally regulated by prescriptive design rules and regulations

- Dates back to a time when ship design was more art than science
  - *Often determined based on experience*
- Determined in the form space, specifying the required means of achieving safety objectives
- Alternative names
  - *Deterministic rules, i.e., rules that require a specific solution assumed to provide a specific deterministic performance*
  - *Specification rules, i.e., rules that specify the required solution*



Picture: Willy Stöwer

SOLAS (The International Convention for the Safety of Life at Sea) convention (1st version)

Prescriptive regulations

Examples of prescriptive rules:

- To avoid structural failure
  - *Minimum scantlings, corrosion margins, design loads, etc.*
- To avoid loss of stability
  - *GZ-curve requirements, etc.*
- To mitigate the consequences of a collision
  - *Longitudinal bulkheads, etc.*
- To mitigate the consequences of grounding
  - *Double bottom requirements*
- To mitigate the consequences of a fire
  - *Max allowed fire zone length, etc.*

Prescriptive rules → Prescriptive-based design

Prescriptive rules often include formulas:

$$W_{ds} = 0.5 + \frac{DWT}{20000}$$

$$t_b \geq (2 + f_{bkt}\sqrt{Z})\sqrt{\frac{R_{eH-stf}}{R_{eH-bkt}}}$$

$$t = 667\,s\sqrt{\frac{f_1 \cdot p_{PL}}{\sigma_y}} + t_c\,[\mathrm{mm}]$$

$$Z = \frac{f_5 \cdot p \cdot h \cdot l^2}{m \cdot \sigma_y} 10^6\,[\mathrm{cm}^3]$$

Pros of prescriptive-based design

Quick and straight-forward to apply, and to verify compliance

- Well suited for "standard" designs
  - *Jenkins (2012): "For vessels which are standard and where there is high confidence that the prescriptive regime achieves a good level of safety, there is little reason to change from a wholly prescriptive approach"*

Based on real life experience (what works) → small risk of ending up with a very bad design (at least for standard designs)

Jenkins, V., 2012. Goal / Risk Based Design – Benefits and Challenges. Dubai, Interferry

Cons of prescriptive-based design

Limited feasible design space

- Rules act as design constraints, potentially preventing new innovative solutions

The efficiency of the solution depends on the efficiency of the rules

- Traditionally failed to be proactive
  - *Rule development traditionally driven by individual catastrophic events, often in response to public outrage*
  - *Cost-efficiency not always considered*
- Often determined based on existing designs (empirical data)
  → *The rules might not be effective/optimal for new types of designs or operations*
- The level of safety provided by the rules is not known (the objective is generally not defined)
  → *Responsibility transferred to rule maker*
  → *Does not encourage "safety thinking" or safety above the minimum required level*

Cons of prescriptive-based design

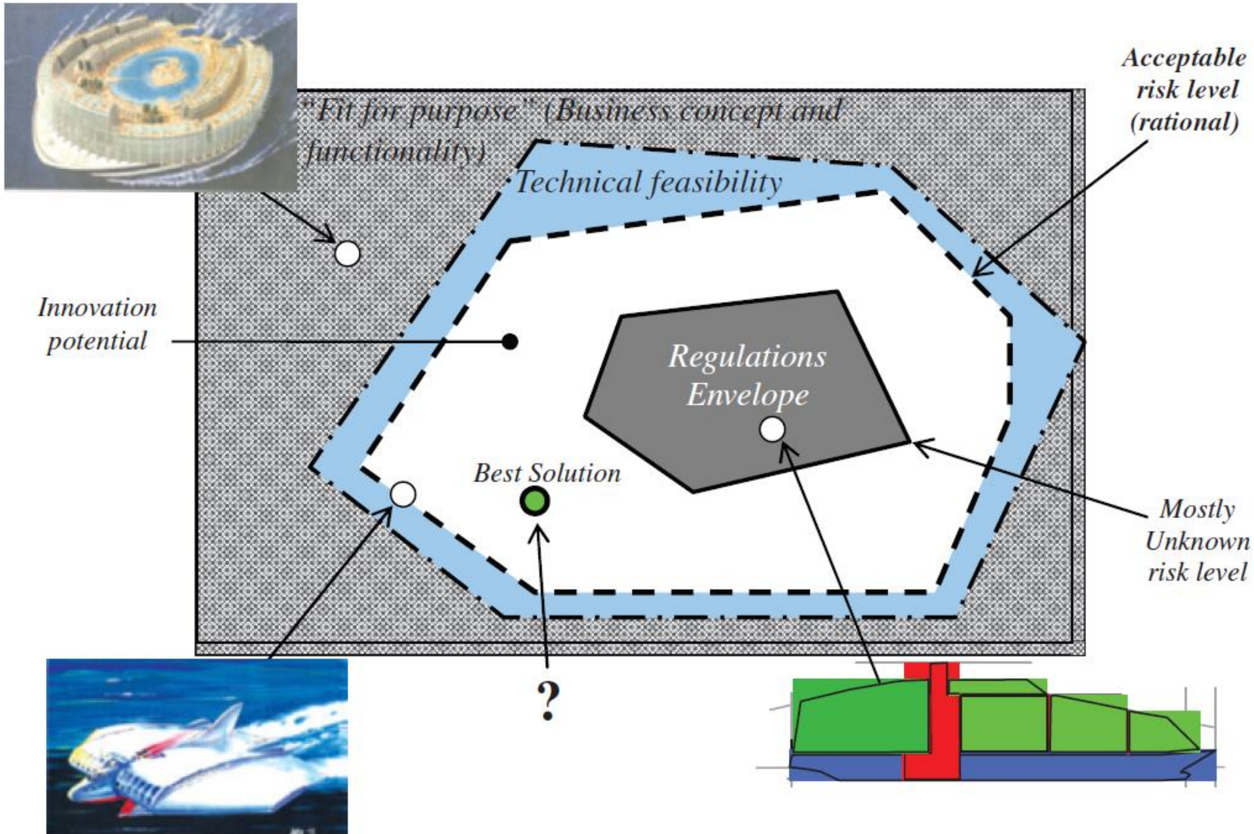


Figure: Papanikolaou et al., 2009

Goal-based design

Goal-based regulations

In goal-based regulations, design criteria are determined in the function space in terms of goals and functional requirements (FRs) to meet the goals

- *The goal(s) defines the overall aim(s)*
  - Example goal: to ensure adequate subdivision and stability in both intact and damaged conditions.
- *The FRs define the performance required to meet the goal(s)*
  - Example FRs: (a) ships shall have sufficient stability in intact conditions when subject to ice accretion; and (b) ....

Goal-based regulations → Goal-based design (GBD)

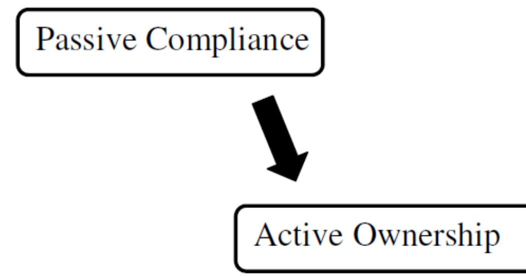


Figure: Jenkins (2012)

Jenkins, V., 2012. Goal / Risk Based Design – Benefits and Challenges. Dubai, Interferry

Goal-based regulations

Goals and functional requirements can also be defined in risk terms

- Example: the maximum accepted individual risk is 10^{-3}

→ Risk-based design (RBD)

- Can be considered as a subcategory of goal-based design
- Other / broader definitions of RBD:
  - *Design under uncertainty*
  - *RBD integrates systematically risk assessment in the design process with prevention/reduction of risk embedded as a design objective, alongside "conventional" design objectives (Papanikolaou et al., 2009)*

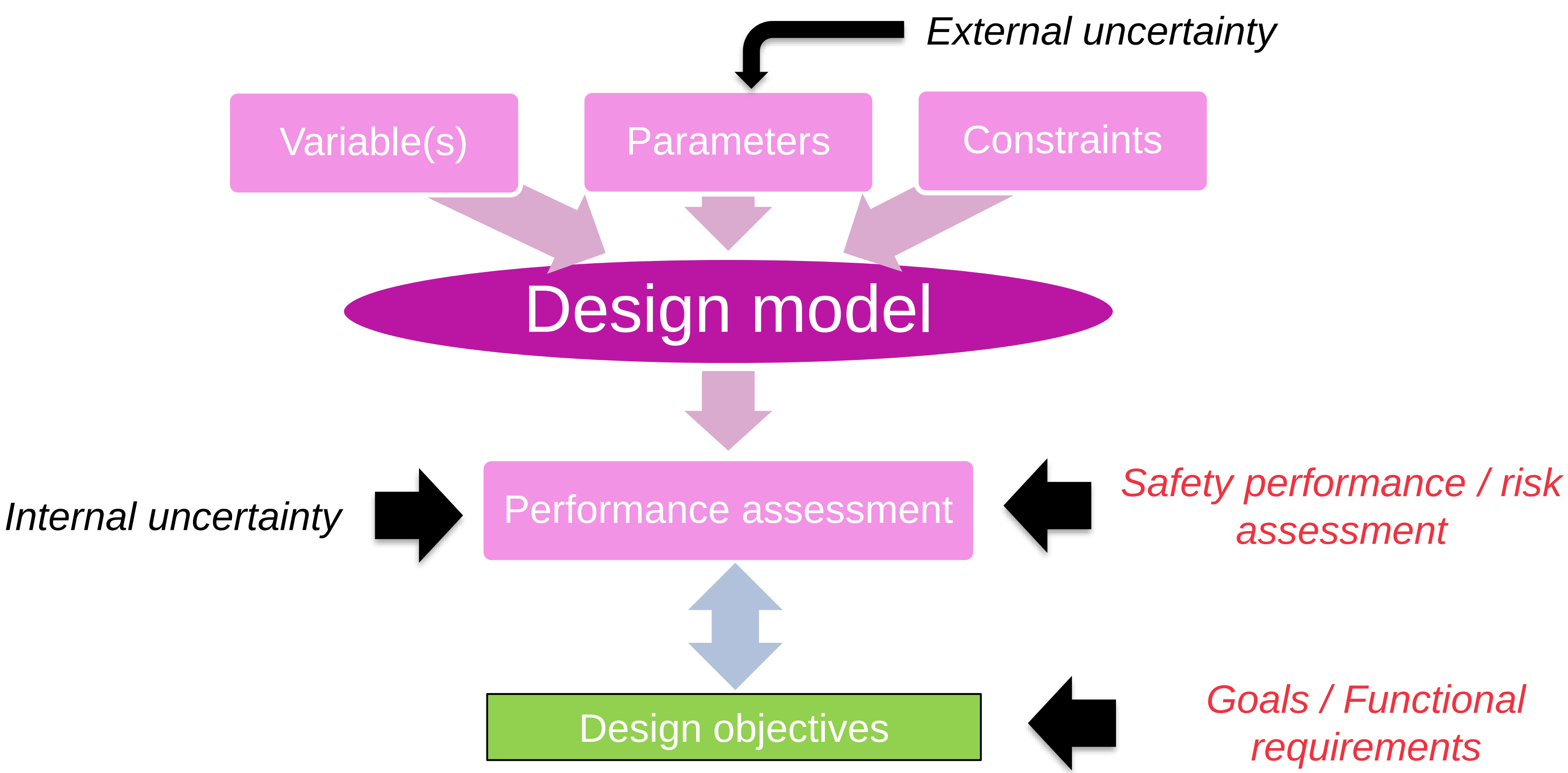
Papanikolaou, A. (Ed.), 2009. Risk-Based Ship Design Methods, Tools and Applications.

Why goal-based regulations?

Ongoing trend towards goal-based maritime regulations

- This trend is not only driven by the mentioned issues with prescriptive regulations but also by multiple other factors including
  - *Ever-increasing and improving knowledge and performance assessment tools → Ever-improving ability to assess various types of ship performance including safety performance*
  - *Larger, more complex ships*
  - *Strong competition, low profit margins → Need for design optimization*
  - *Increased "safety thinking" (corporate social responsibility)*
    - Accidents are bad for business, safety pays off

Goal-based design



Prerequisites for goal-based ship design

To enable goal-based design the following prerequisites must be present:

- A regulatory framework that enables/supports GBD
- Design framework and (safety) performance assessment tools or other methods to very conformity
- Qualified engineers

Safety performance assessment

- Safety performance is often measured in terms of risk
- Risk can be defined in various ways depending on the circumstances
  - *Likelihood, probability, frequency,…*
  - *Quantitatively or quantitatively*
- Different risk categories
  - *Risk to human life and health*
  - *Environmental risk*
  - *Operational risk*
  - *Financial risk*
  - ….

$$\boldsymbol{Risk} = \sum(\boldsymbol{L_i C_i})$$

$\boldsymbol{L_i}$= the likelihood of all plausible risk events
$\boldsymbol{C_i}$= the related consequences

Safety performance assessment

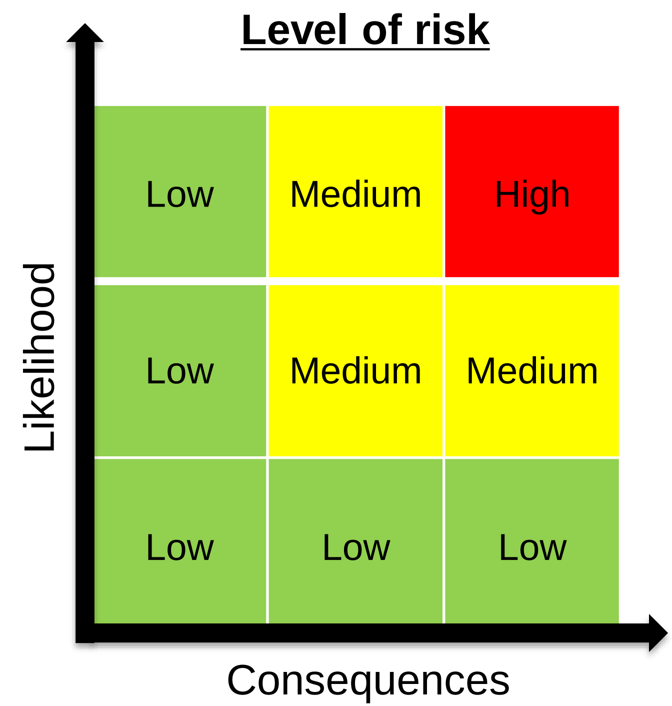
ISO: Risk is a positive or negative effect of uncertainty on objectives

$$\boldsymbol{Risk} = \sum(\boldsymbol{L_i C_i})$$

$\boldsymbol{L_i}$= the likelihood of all plausible risk events
$\boldsymbol{C_i}$= the related consequences

Plausible risk events

- Collision, fire, grounding,...



ISO, 2009. IEC 31010:2009 Risk management – Risk assessment techniques. International Organization for Standardization.

Risk assessment

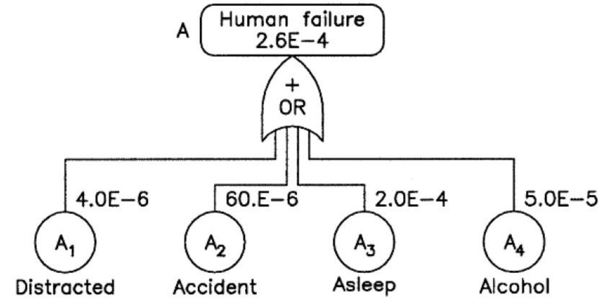
A risk assessment must answer three questions

- What can happen? / What can go wrong?
- How likely is it?
- What are the consequences?

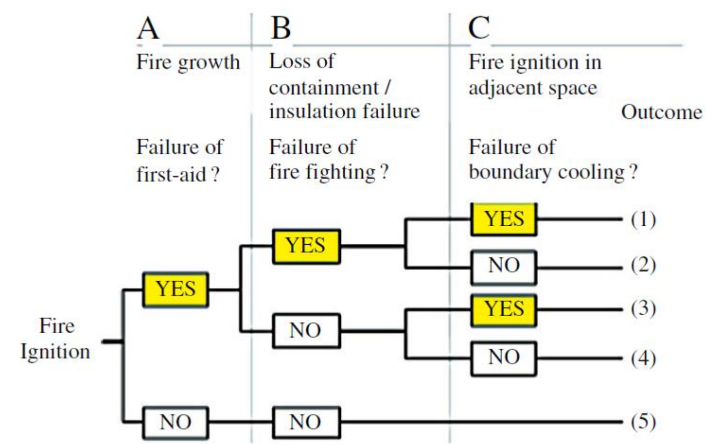
The level of risks can be assessed by various means

- Risk models
  - *Fault Tree Analysis (FTA)*
  - *Event Tree Analysis (ETA)*
  - *Bayesian networks*
  - ...
- Expert opinion
- Empirical data
- Simulations
- ...

Example FTA



Example ETA



Figures: Papanikolaou et al. (2009)

General risk acceptance criteria

Safe design ~ a design with an acceptable/low level of risk

$$(R_{design} \leq R_{acceptable})$$

- For human safety and environmental risks: $R_{acceptable}$ specific by authorities
- For other types of risk (e.g., operational risk): $R_{acceptable}$ specified by the owner

Risk control measures (RCM)

Risks are managed by Risk Control Measures (RCM) that either or both

- Reduce the likelihood of an accident
- Mitigate its consequences

Risk control measures (RCM)

Passive risk control measures

- Design
  - *Watertight compartments, double hull,..*
- Equipment
  - *Lifeboats, life rafts,...*

Active risk control measures

- Operational measures
  - *Crew training, risk avoidance,...*

Goal-based regulations encourage the use of a combination of passive and active risk control measures

Image: www.gard.no

Image: www.usmships.com

Pros of goal-based design

Pros:

- ”Any” solution that meet the goal(s) and the related functional requirement(s) is acceptable → Expanded feasible design space
  - *Design constraints → Design objectives*
- Safety becomes measurable → Possible to determine goals, application of the most cost-efficient risk control measures

  → *Safety performance optimization (removal of excess safety margins or “fat”)*
- Proactive risk management not limited to experience
- Safety responsibility is transferred from the regulator to the designer (owner) → Encourages “safety thinking”

Cons of goal-based design

Cons:

- Time and resource consuming (requires a significant investment)
  - *Only motivated if necessary to enable a specific design, or if there is a significant gain potential*
- Risk of misleading performance assessments
  - *Larger, more expensive ships → increased risk*
    - The reliability of the applied risk assessment approach must reflect the scale of the potential consequences
- If both passive (design) and active (operational) risk control measures applied

  → *The ship need to be operated as planned throughout its lifetime*
    - Challenging for instance in the case of change of ownership → New safety culture, operating conditions, different (lower) level of competence,…
    - Sufficient documentation needed

Goal- or risk-based regulatory systems in other industries

UK offshore industry

- Regulatory system based on mandatory ‘Safety Cases’
  - *Objective: “to ensure an adequate level of safety for a particular installation, based upon the management and control of the risks associated with it”*
  - *Includes a detailed description of the installation itself as well as of its operation and operational environment. Based on this description, the ‘Safety Case’ must identify and assess related risks, and describe how these are controlled*
    - Based on the principle that owner takes responsibility for assessing the risks associated with his installation, and for documenting how his safety management system limits those risks to an acceptable level
    - Application usually in accordance with the principle of *As Low As Reasonably Practical* (ALARP)
    - Regular review, updating as necessary
    - Operations cannot start or continue without a by the authorities approved ‘Safety Case’

Goal- or risk-based regulatory systems in other industries

Norwegian offshore industry

- Self-regulatory system
  - *The operator is responsible for meeting the rules*
    → No responsibility is transferred to the regulator
    → The operator has full responsibility
  - *Compliance is achieved through a combination of audits, verifications, investigations, meetings, and surveys by the regulator*
    - Authorities allowed insight into the decision-making process, access to relevant documentation
    - Authorities act on unacceptable situations, but do not approve any documentation or targets

(http://www.offshoreenergytoday.com)

Offshore vs. maritime industries

Offshore industry

- Very large investment per installation
- Few installations, few operators
- Extensive planning and construction time, long lifetime

Maritime industry

- Large number of ships, large number of operators
- Short production series
- Short time from order to delivery
- Strong competition, low profit margins
- A truly global industry

→

Infeasible to

- perform extensive, case-specific safety assessments
- maintain an ongoing and close interaction with all involved authorities

Regulations, methods, and principles related to goal-based design

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Regulations, methods, and principles related to goal-based design include

- Goal-based standards (GBS)
- Formal safety assessment
- Safety equivalence
- Probabilistic damage stability
- Probabilistic oil outflow performance
- Polar Code
- IGF Code

In the following we will have a quick look at each of these

Regulations, methods, and principles related to goal-based design

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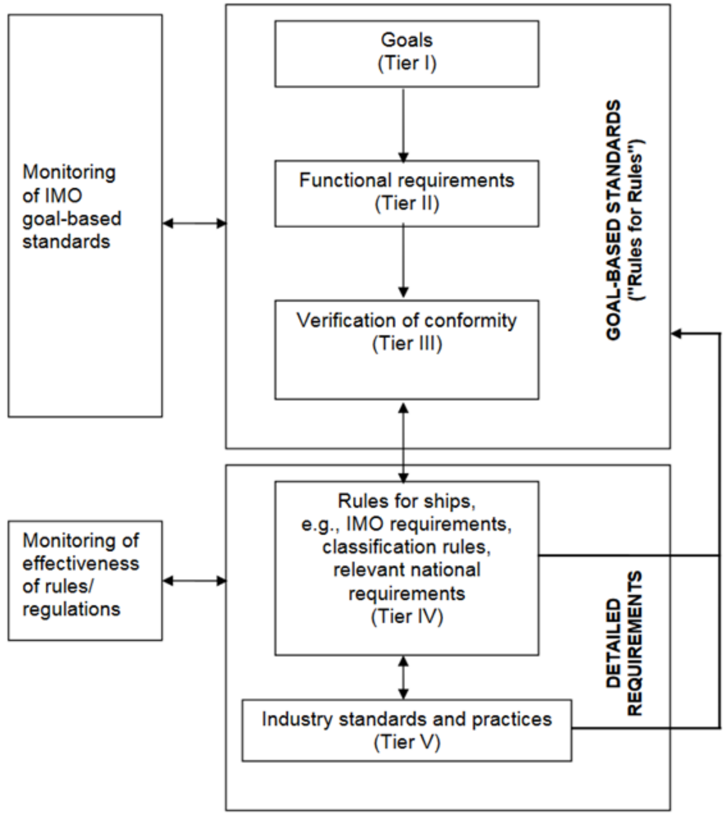
Goal-based standards (GBS)

GBS= The International Maritime Organization's (IMO) rules for how to develop goal-based rules

- Rules for rules

Comprises

- Tier I: Goal(s)
- Tier II: Functional requirement(s) associated with the goal(s)
- Tier III: Verification of conformity
- Tier IV: Rules and regulations
- Tier V: Industry standards and practices
- Monitoring

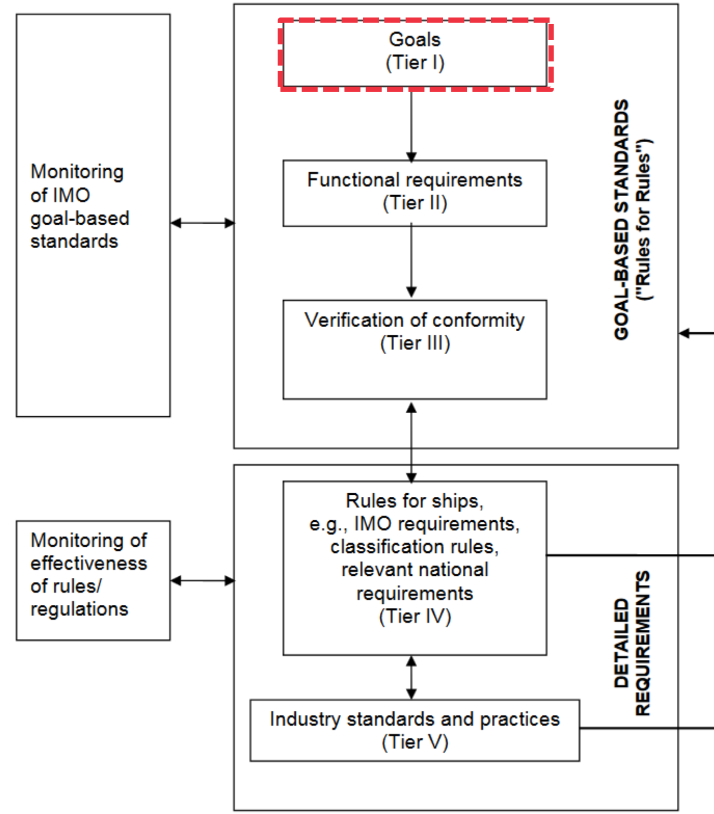


GOAL-BASED STANDARDS FRAMEWORK

Goal-based standards (GBS)

Tier I: Goals

- Goals are high-level objectives to be met
- A goal should address the issue(s) of concern and reflect the required level of safety
  - *Examples of (top-level) goals*
    - No accidents leading to total ship loss (collisions, groundings, stranding, fires, etc.)
    - No loss of human life due to ship related accidents
    - Low impact to the environment (no air emissions, low noise, low wash)
    - Minimum impact to the environment in case of a ship accident

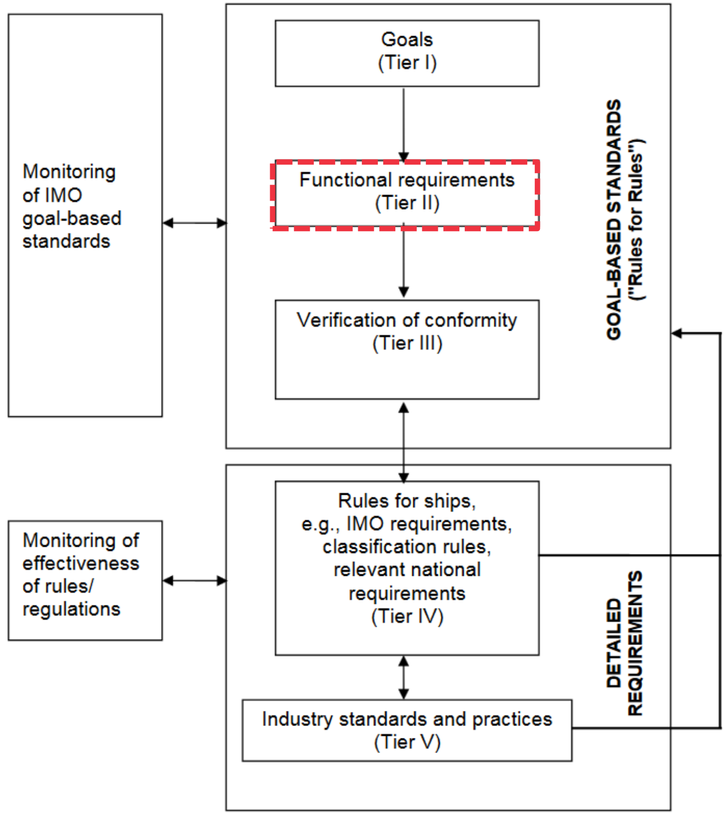


GOAL-BASED STANDARDS FRAMEWORK

Goal-based standards (GBS)

Tier II: Functional requirements (FRs)

- FRs provide the criteria to be satisfied in order to meet the goals
  - *The FRs should cover all functions/areas necessary to meet the goal, and be developed based on experience, an assessment of existing regulations, and/or systematic analysis of relevant hazards*

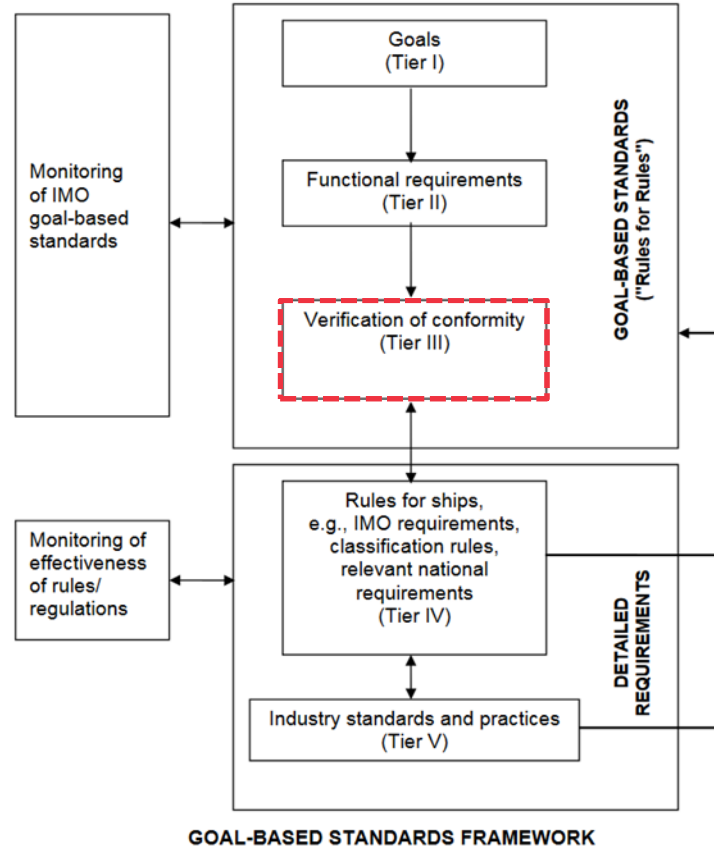


GOAL-BASED STANDARDS FRAMEWORK

Goal-based standards (GBS)

Tier III: Verification of conformity

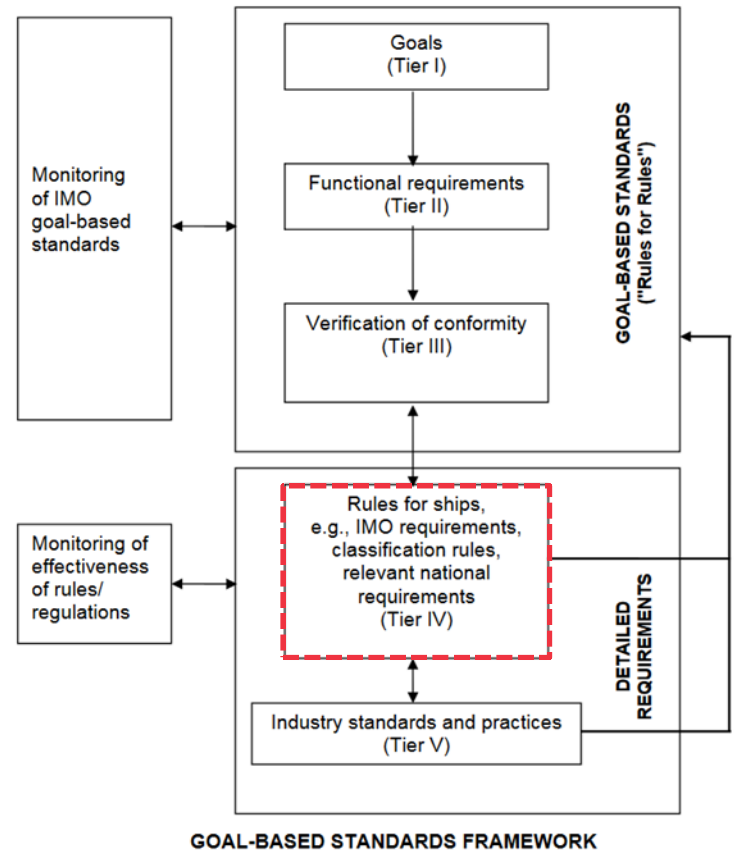
- Instruments necessary for demonstrating and verifying that the associated rules and regulations for ships conform to the goals and functional requirements
- The verification process should be transparent and result in a consistent outcome irrespective of the evaluator



Goal-based standards (GBS)

Tier IV: Rules and regulations

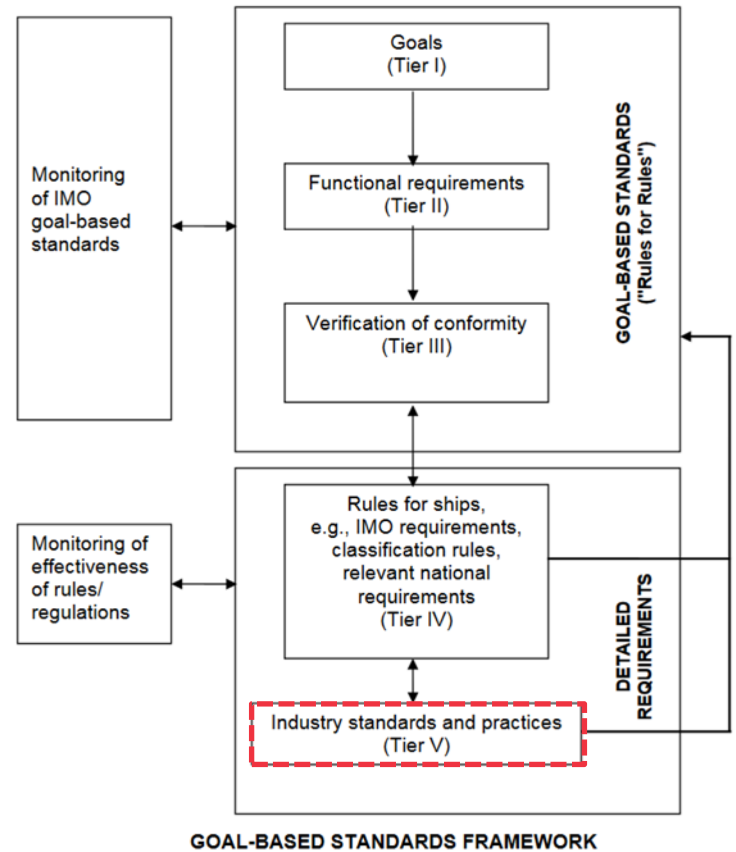
- Detailed requirements to meet the goals and functional requirements



Goal-based standards (GBS)

Tier V: Industry practices and standards

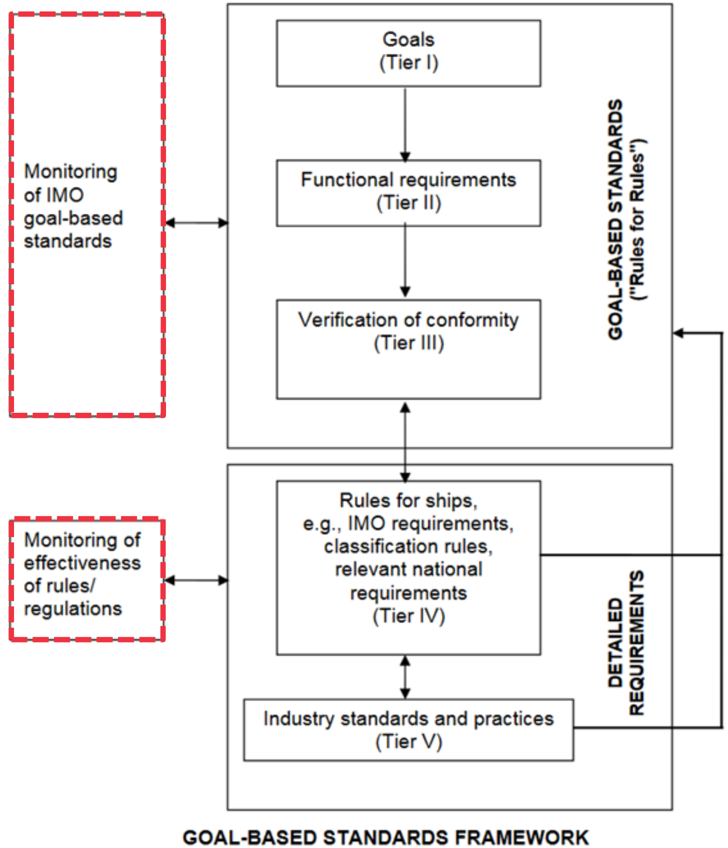
- Industry standards, codes of practice and safety and quality systems for shipbuilding, ship operation, maintenance, training, etc.,
- These may be incorporated into or referenced in the rules/regulations



Goal-based standards (GBS)

Monitoring

- Continuous evaluation the effectiveness of Tier I–V
- Identification of risks not addressed in the present rules and regulations



Example structure of a goal-based regulation

Preamble

The International Code of...

General

...

Introduction

This part of the Code contains the...

Definitions

...

Application

Goals

The goal of this Code is to...

Functional requirements

In order to achieve its goal, this Code...

Regulation A-1

Goals

The goal of this regulation is to...

Functional requirements

To achieve the above mentioned goals, the following FRs...

Regulations/requirements

In order to comply with the functional requirement of…

Regulation A-2

Goals

The goal of this regulation is to...

Functional requirements

To achieve the above mentioned goals, the following FRs...

Regulations/requirements

In order to comply with the functional requirement of**…**

Regulations, methods, and principles related to goal-based design

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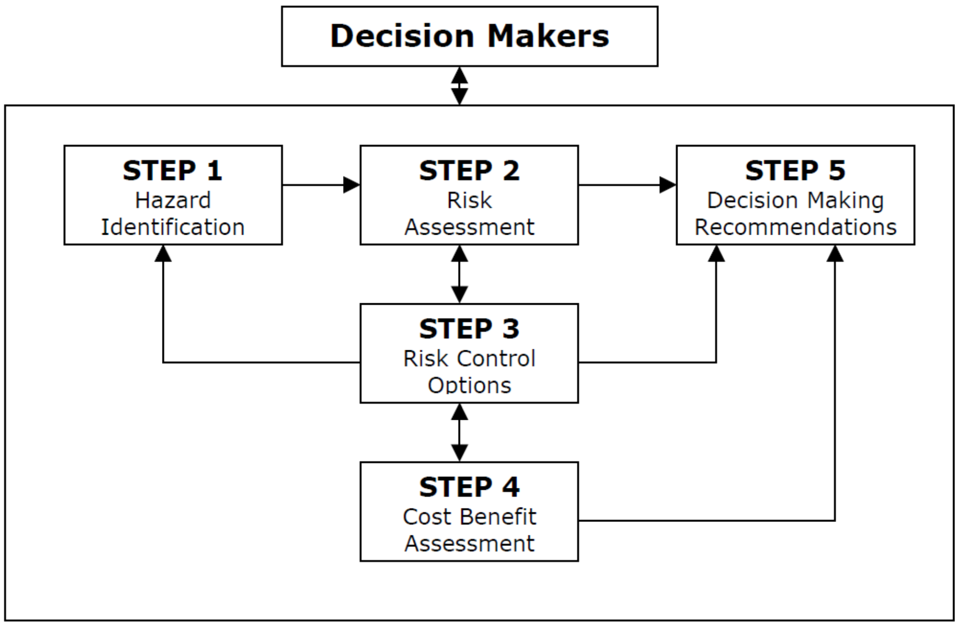
Formal safety assessment (FSA)

An approach for the determination of new or modified rules at IMO using risk analyses and cost benefit assessments

- Transparent and systematic comparison of various risk control options

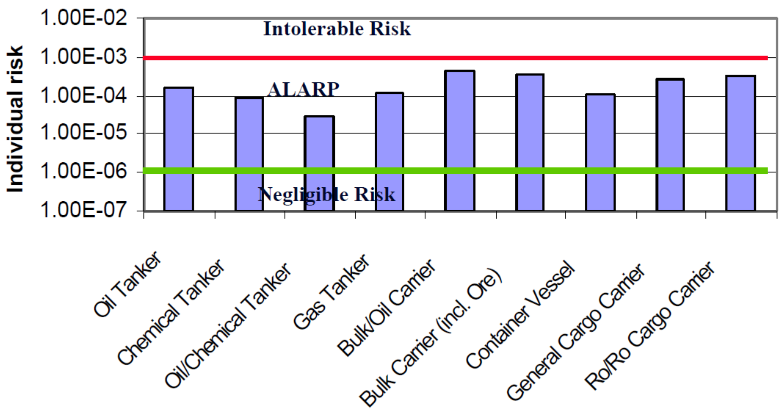


"FSA is a structured and systematic methodology, aimed at enhancing maritime safety, including protection of life, health, the marine environment and property by using risk analysis and cost benefit assessment" (IMO)

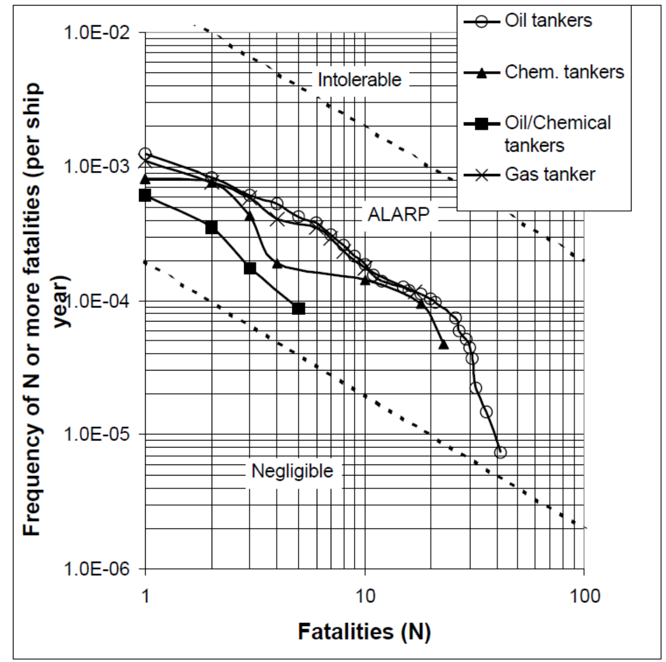
Formal safety assessment (FSA)

Different risk acceptance criteria

- The max accepted individual risk
- The max accepted societal risk
- The max expenditure to avoid a statistical fatality in accordance with the principle of As Low As Reasonably Practicable (ALARP)
  - *Not static, approx. USD 1.5-3 million*



Societal risk



Figures: Papanikolaou et al., 2009

Formal safety assessment (FSA)

The acceptable individual risk depends on if the risk is taken voluntarily or involuntarily

- Risk acceptance criteria proposed by Norway
  - *Max tolerable risk for crew members:* 10^{-3} *per year*
  - *Max tolerable risk for passengers:* 10^{-4} *per year*

Costs connected to managing individual and societal risks are expressed in terms of the <u>Cost of Averting a Fatality (CAF)</u>

- CAF = cost per-life-saved, value of life
- CAF values will depend on geographic location, local economy, type of activity, and public tolerance of risk

$$\text{GrossCAF} = \frac{\Delta C}{\Delta R}$$

and

$$\text{NetCAF} = \frac{\Delta C - \Delta B}{\Delta R}$$

Where,

ΔC is the cost per RCO

ΔB is the economic benefit per ship from the implementation of RCO (this might include pollution prevention)

ΔR is the risk reduction per ship, in term of fatalities averted, implied by RCO.

Formal safety assessment (FSA)

Limited application of FSA

- Probably because the FSA process is highly technical and complex, taking approx. 1 year to complete

FSA has to date not been applied on environmental risk control measures

- No agreed on environmental risk measures or criteria

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Safety equivalence

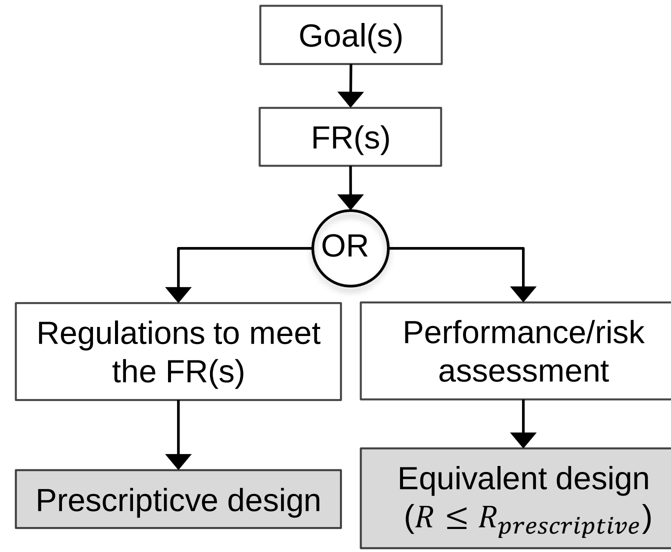
General principle

- A solution may deviate from the prescriptive requirements if the alternative design meet the intent of the goal and functional requirements concerned and provide an equivalent level of safety as the prescriptive design

To prove equivalency, a design must be analyzed, evaluated, and approved in accordance with IMO guidelines

- "Guidelines for the approval of alternative and equivalents as provided for in various IMO instruments", MSC.1/Circ.1455
- Related challenges
  - *How to assess and compare the safety performance of the prescriptive solution with that of an alternative solution?*

Safety equivalent designs are often referred to as "alternative designs"



Safety equivalence

Application example

- Alternative design and arrangements for fire safety
  - *Prescriptive rule*
    - Max allowed length of fire zone: 40 m
  - *Application of the principle of safety equivalence enables large open public spaces*
  - *Equivalency demonstrated by numerical fire simulations + evacuation simulations*

Photo: Color line

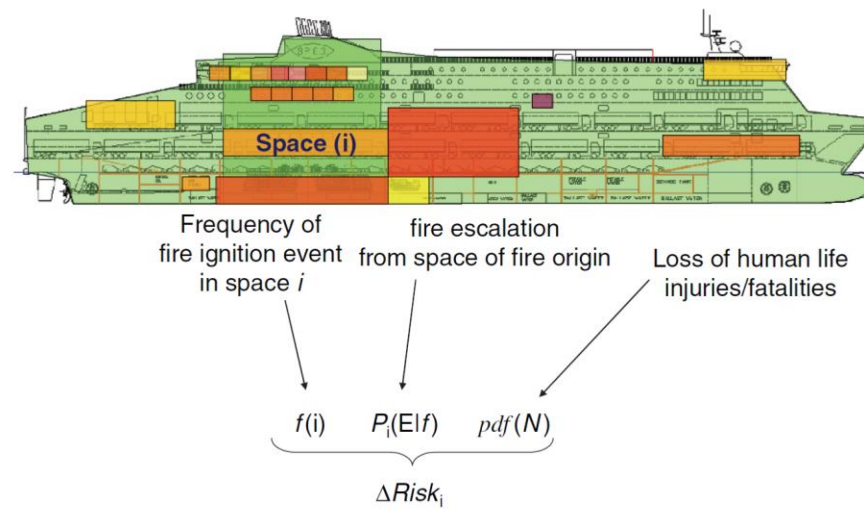


Figure: Papanikolaou et al., 2009

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Propabilistic damage stability

Objective: to ensure sufficient damage stability

- A ship's ability to survive various flooding scenarios is quantified in terms of the subdivision index A (degree of subdivision)

$$A=\sum(p_i s_i), A \geq R$$

p_i= the probability that the compartment or group of compartments under consideration may be flooded

s_i= the probability of survival after flooding of the compartment or group of compartments in question (calculated based on a ship's GZ curve for the damage scenario in question)

R= minimum required subdivision

- Determined based on real-life accidents
- Different designs with the same index value are considered equally safe
- R is determined based on ships whose damage stability is considered satisfactory → Not related to any specific level of safety risk (!)
- Operational aspects (active measures) not considered

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Propabilistic oil outflow performance

Objective: to limit accidental oil outflow

- A ship's ability to limit an oil outflow is quantified in terms of a measure referred to as oil outflow performance
  - *Also referred to as pollution prevention index*
- Determined based on a probabilistic approach utilizing damage statistics of real-life incidents
  - *Related calculations are complex and extensive and therefore carried out using dedicated software tools*
- Weakness: the index does not relate to any explicit level of environmental risk
  - *The IMO has not agreed on any environmental risk measures or criteria*

Regulations, methods, and principles related to goal-based design

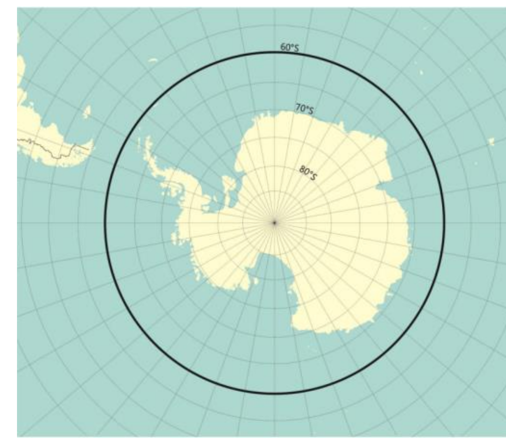
Regulations, methods, and principles related to goal-based design include

- Goal-based standards (GBS)
- Formal safety assessment
- Safety equivalence
- Probabilistic damage stability
- Probabilistic oil outflow performance
- Polar Code
- IGF Code

Polar Code

The International Code for Ships Operating in Polar Waters (Polar Code)

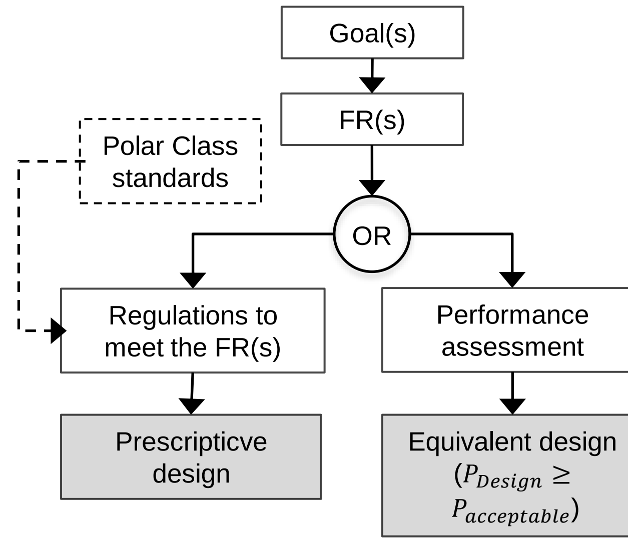
- The first international regulatory framework mitigating arctic shipping related risks
  - *Enforced January 1, 2017*
  - *Concerns all merchant ships operating in the polar areas (as defined by the IMO)*



Polar Code

Overall goal: to ensure the same level of safety for ships, persons and the environment in polar waters as in other waters

- Supplements the SOLAS and MARPOL conventions to account for Arctic specific safety hazards such as sea ice and low temperatures
- Based on the goal-based standards
  - *Determines goals and functional requirements for various "systems"*
    - Ship structure
    - Subdivision and stability
    - Watertight and weathertight integrity
    - Machinery installations
    - ...
- Regulations concern the design, construction, equipment, operations, training, and pollution prevention, i.e., both active and passive risk prevention and mitigation are considered



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IGF Code

International code of safety for ships using gases or other low-flashpoint fuels (IGF Code)

- Enforced January 1, 2017
- Based on the goal-based standards
- Overall goal
  - *to provide for safe and environmentally-friendly design, construction and operation of ships and in particular their installations of systems for propulsion machinery, auxiliary power generation machinery and/or other purpose machinery using gas or low-flashpoint fuel as fuel*
- General functional requirements
  - *The safety, reliability and dependability of the systems <u>shall be equivalent to that achieved with new and comparable conventional oil-fuelled main and auxiliary machinery</u>*
  - …

Low flashpoint fuels such as methanol, hydrogen, ammonia, among others, are vital for decarbonizing the maritime industry

End of lecture - Summary

Lecture summary

Goal-based ship design

- Determines design criteria in the function space in terms of design goals and functional requirements to meet the goals
- Turns passive compliance of prescriptive rules into active ownership of risks
- Extends the feasible design space → Allows innovative and optimized solutions
- Is associated with a high time and resource consumption and the risk of misleading safety assessments
- Can be part of a holistic design process
- Can and will co-exist with prescriptive regulations
  - *Application of prescriptive rules where appropriate*

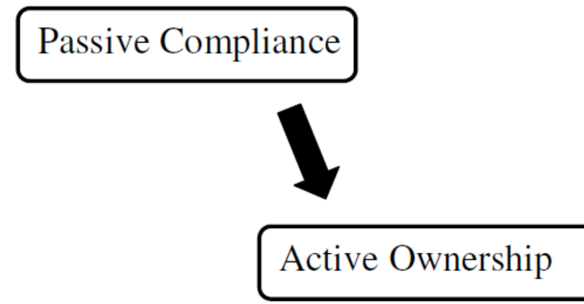

Figure: Jenkins (2012)