The Maritime Journey Towards Autonomy

A Model-Based System Engineering Approach

Anita Teo

13th Dec 2017

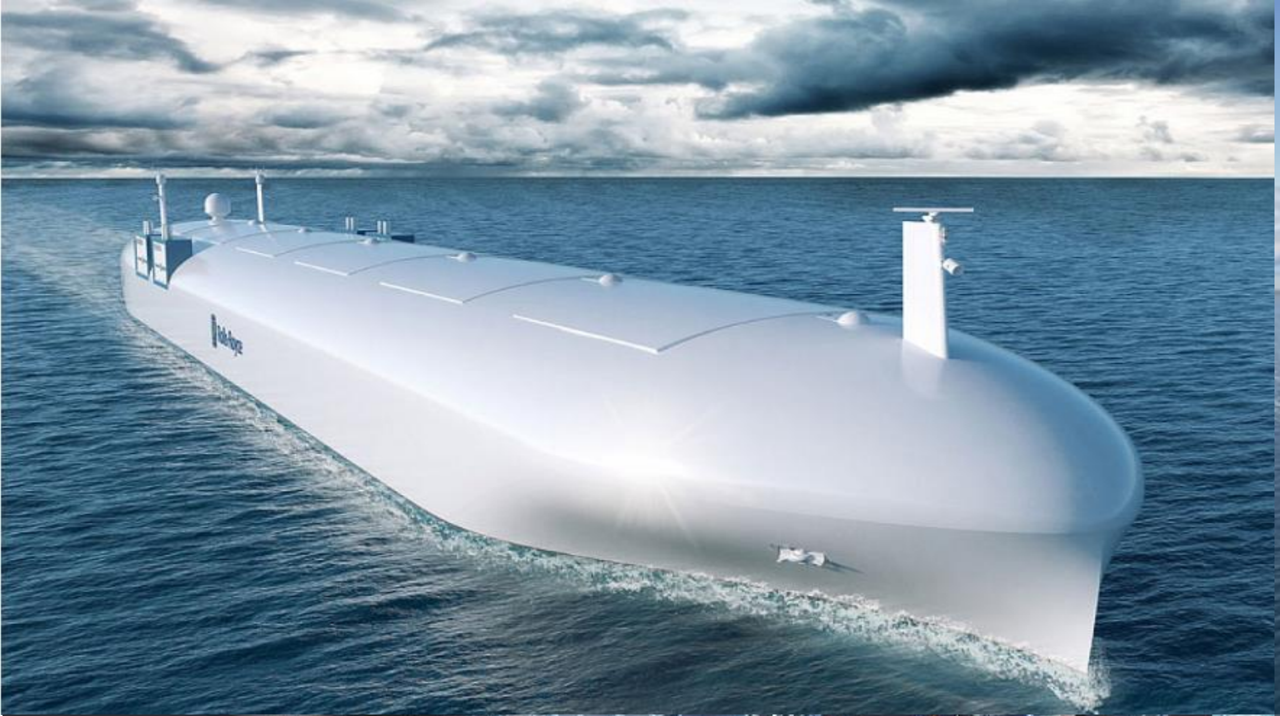
Version 1

Trusted to deliver excellence

Rolls-Royce

Contents

- Journey towards Autonomy - Maritime Vision
- Key Engineering & System Engineering principles for autonomous infrastructure
- Challenges:
  - Understanding the "Product" – System of Interest (SoS, Enabling & Interoperating Systems)
  - Define Future products (Autonomy)
- How Autonomous is the System?
- Lesson learned - Autonomy Framework from other sectors
- Proposed Maritime Autonomy Framework (MAF)
  - The interpretation of level of autonomy
  - The attributes of an effective maritime autonomy framework
  - The integration of MAF & Enterprise Framework
- A Model-Based System Engineering Approach
- Key Take Away

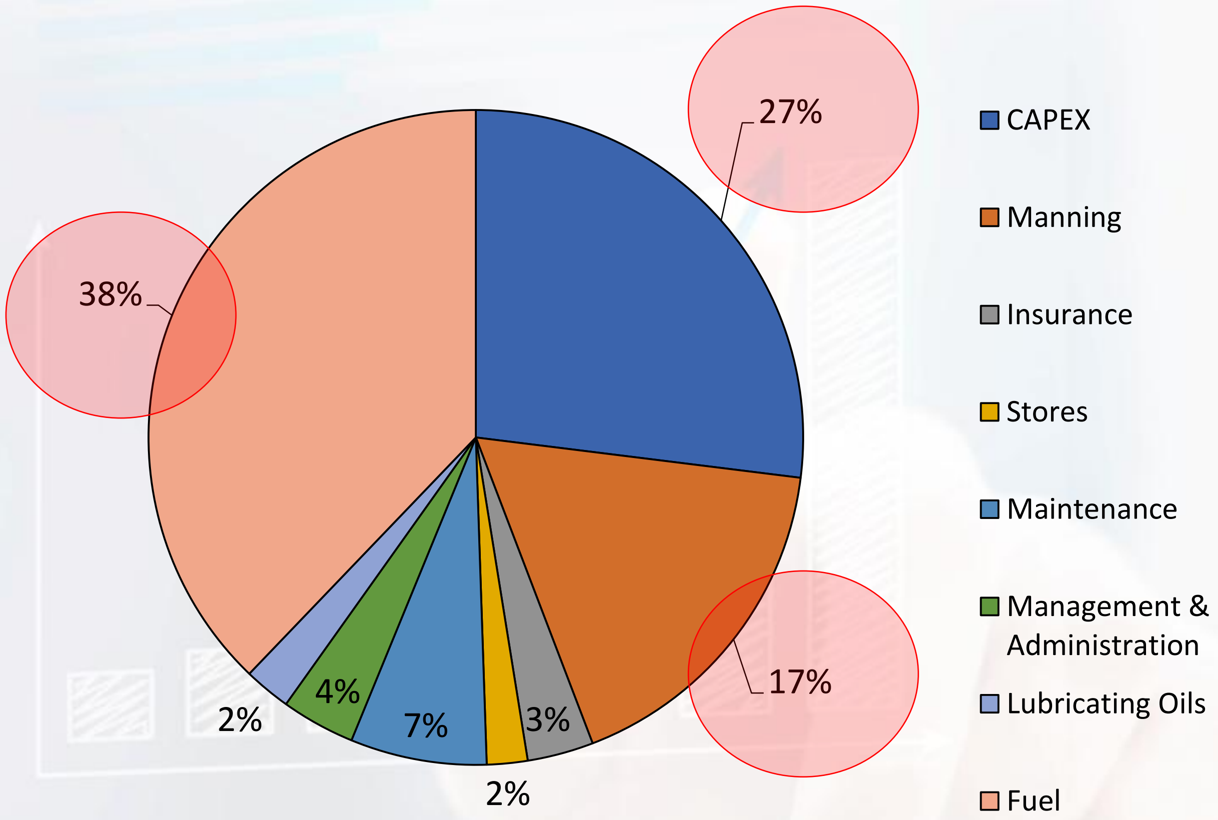



SAT-GRID


Battery
Battery
LNG
LNG
LNG

Why R&A Vessels - Cost structure

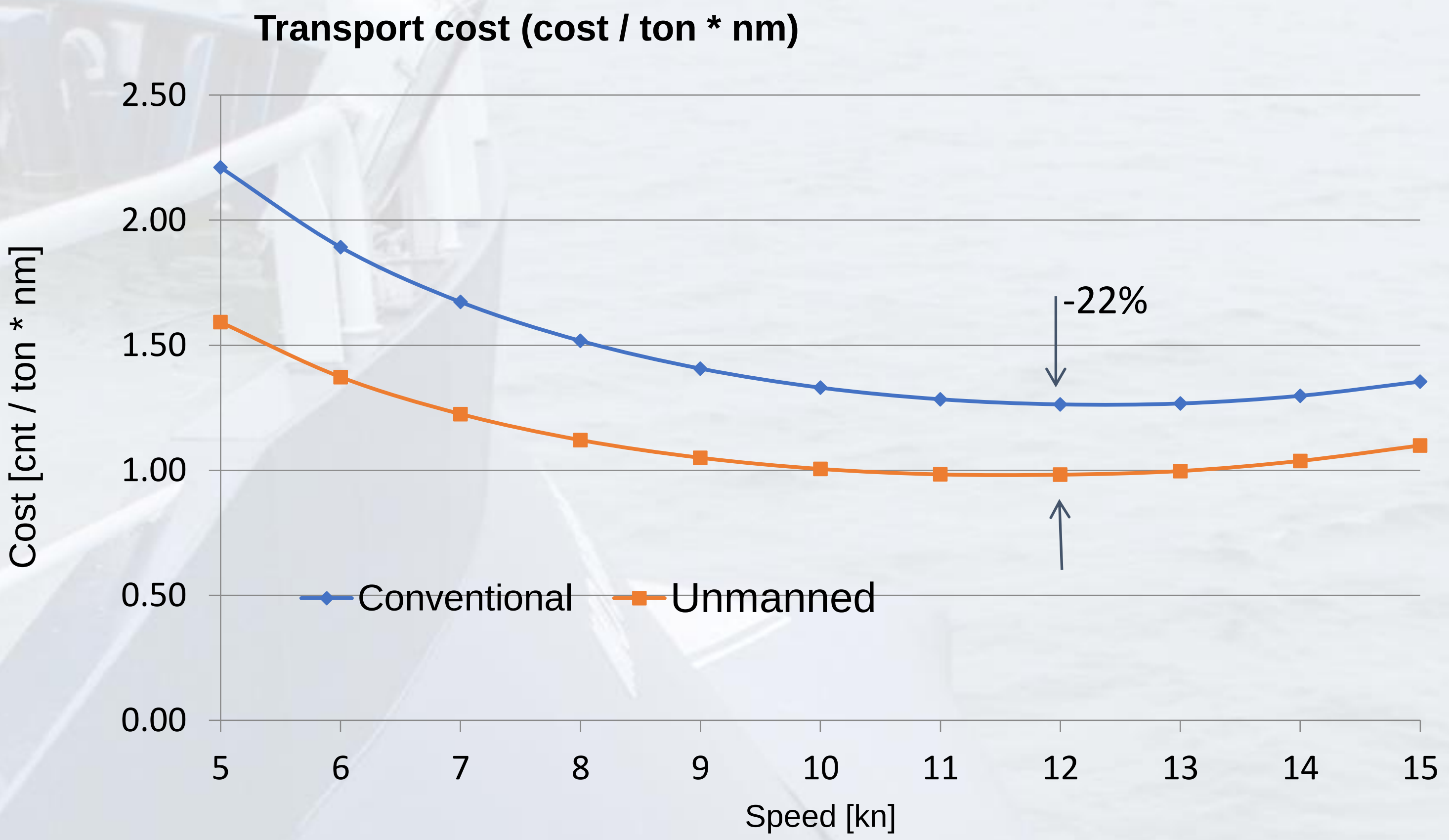
General cargo annual costs



Source: RR internal study

RR Internal Study of 20 000 dwt general cargo vessel

Why R&A Vessels – Transport Cost



RR Internal Study of 20 000 dwt general cargo vessel

Why R&A Vessels - Energy/Emissions reduction

Rolls-Royce

Machine Learning

Lower weight: 700 – 1,000 tonnes

Wind resistance: ~1% saving

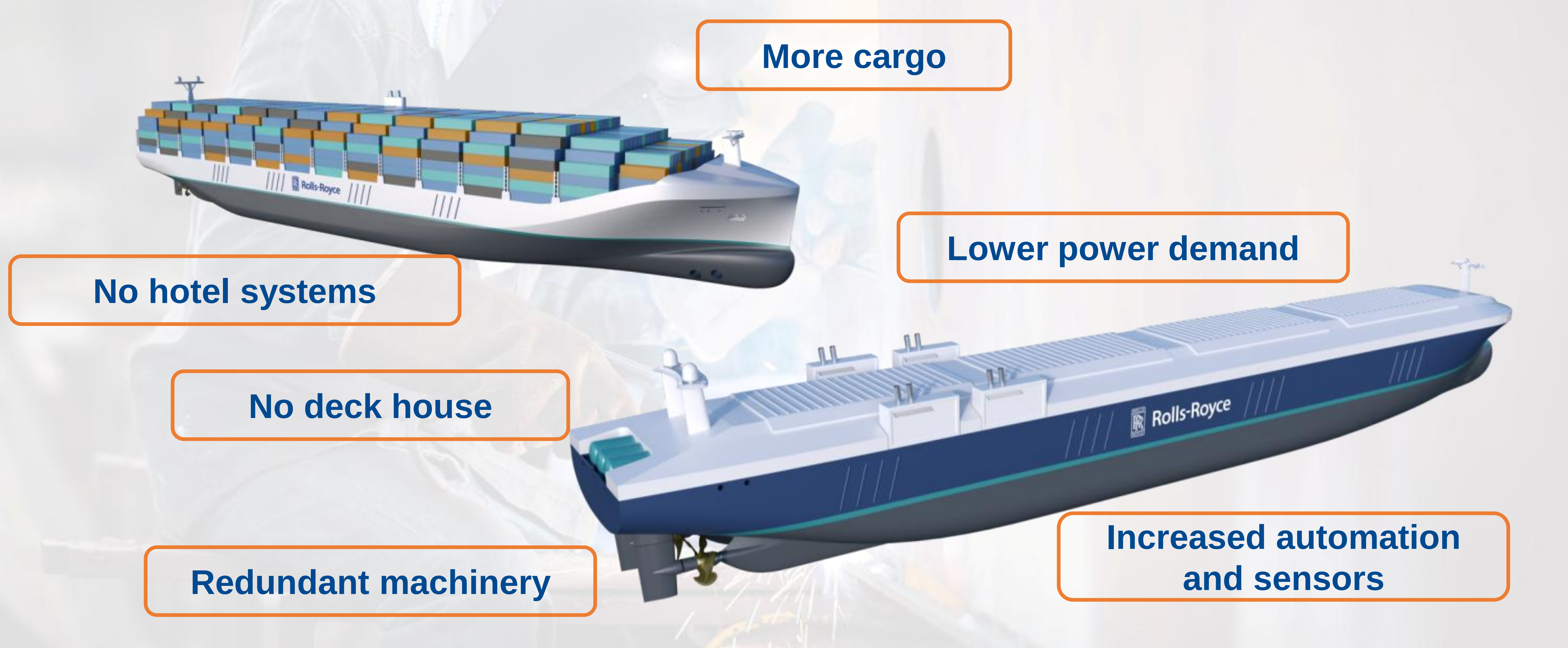
Reduced hotel load: 200 – 270 kW

10-15% fuel savings

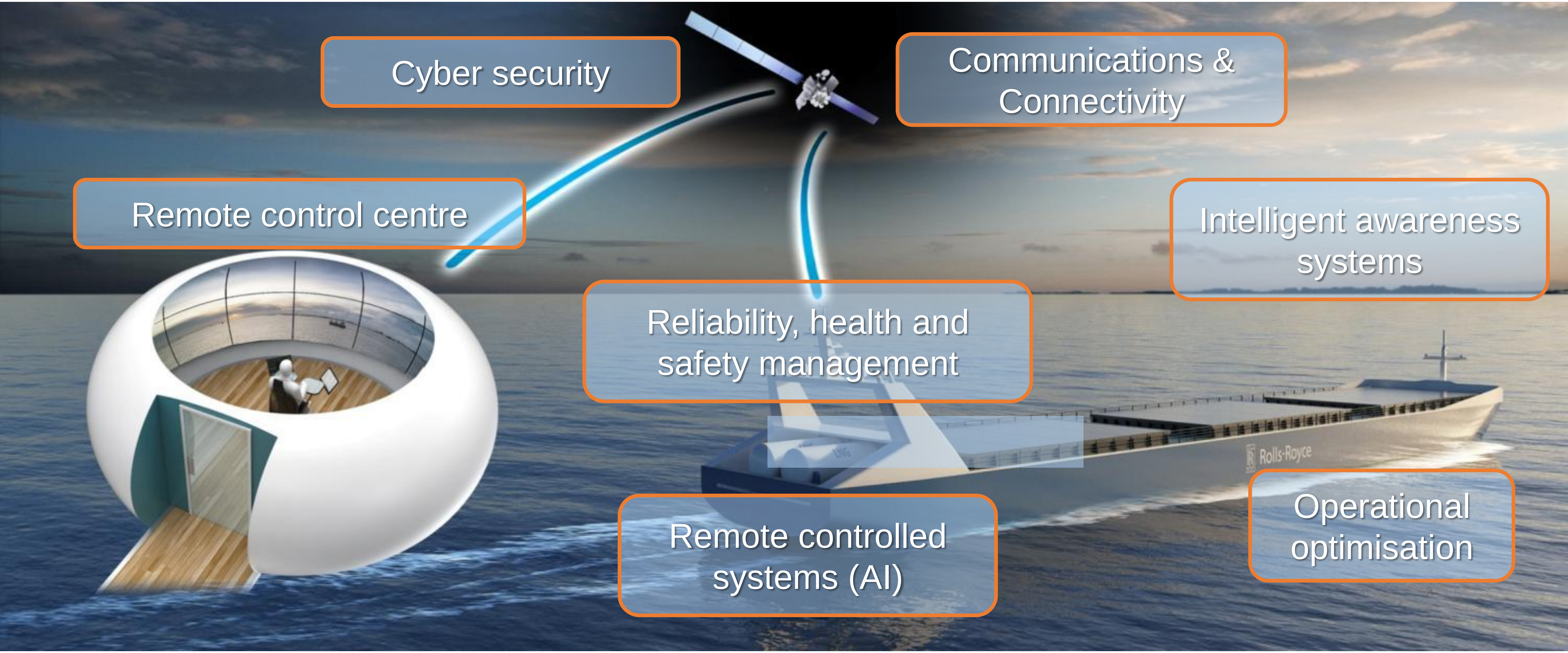
Source: RR internal study

RR Internal Study of 20 000 dwt general cargo vessel

Remote and Autonomous ships - features

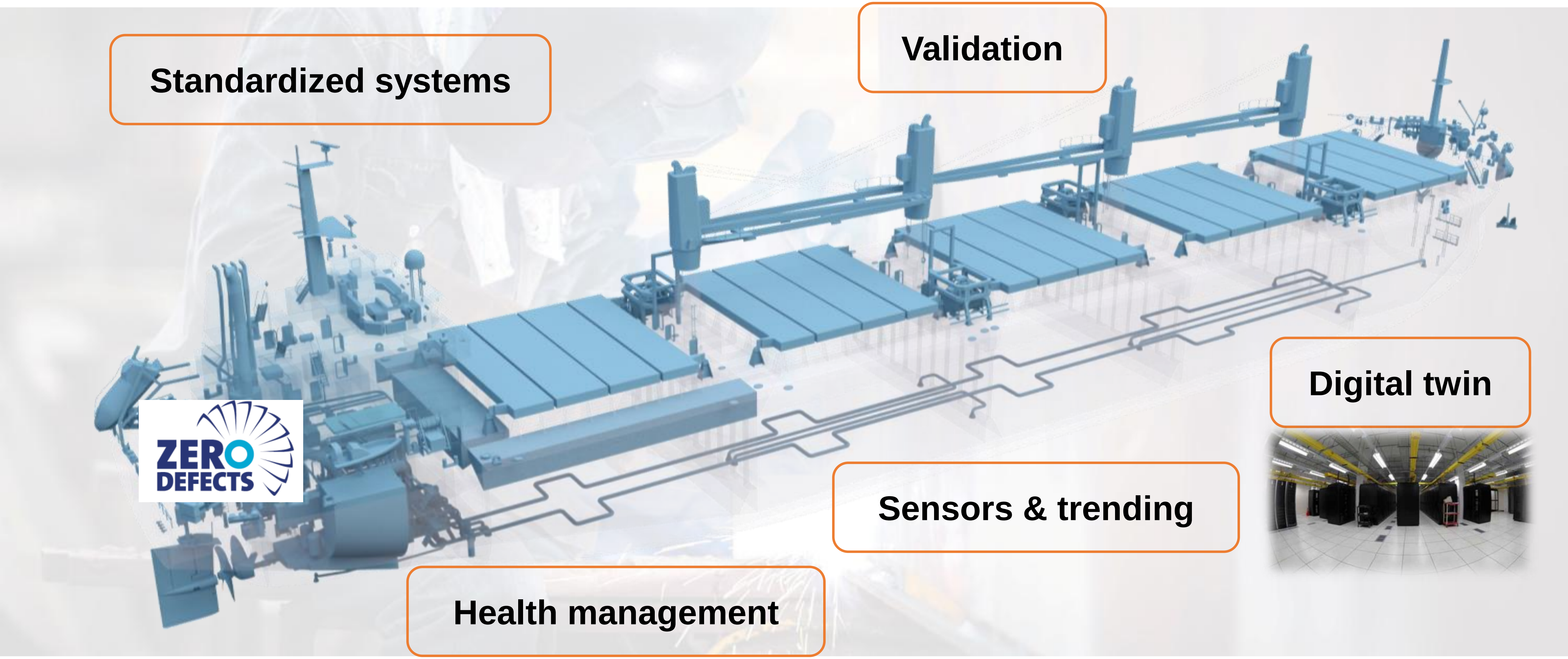


Technology Development Areas

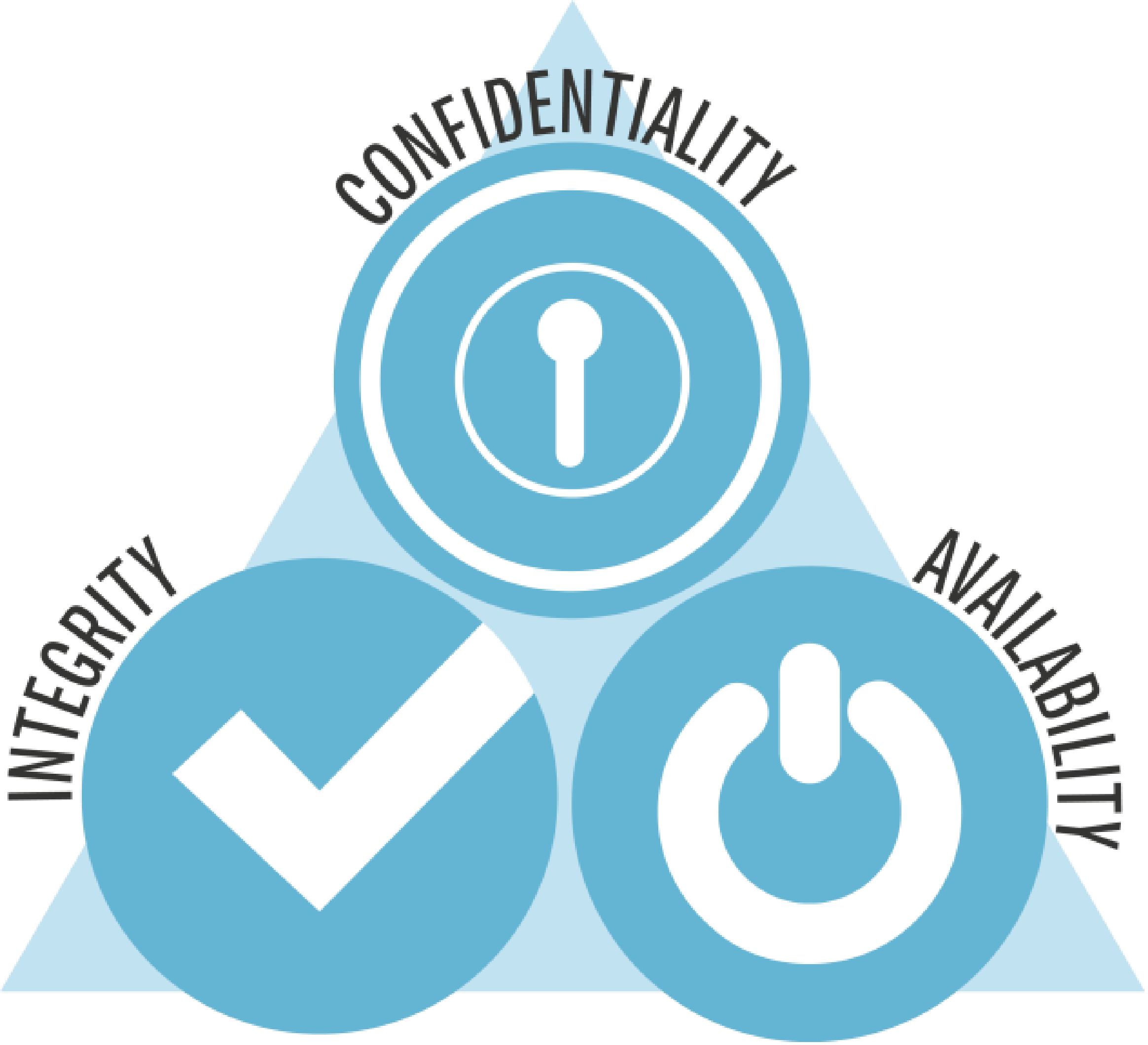


Reliability

Rolls-Royce



Cyber security

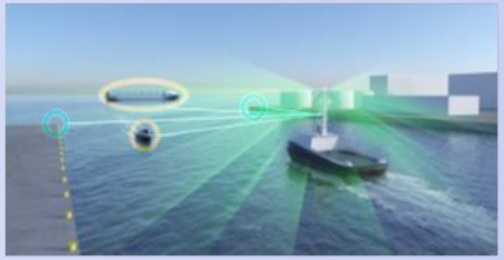


Safety

A fundamental question for us: ‘can it be trusted?’

A phased market adoption plan

ADVISORY → CONTROL → AUTONOMOUS



‘ALARP’ - As Low As Is Reasonably Practicable safety philosophy

Fundamental Principles for Safety

Fundamental Principles		
FP1	Responsibility for Safety	The prime responsibility for safety must rest with the person or organisation responsible for the activities that give rise to the risk.
FP2	Leadership and Management for Safety	Effective leadership and management for safety must be established and sustained throughout the systems life cycle
FP3	Safety Assessment	The ‘dutyholder’ must demonstrate effective understanding of the potential hazards and their control for the autonomous infrastructure through a comprehensive and systematic process of safety assurance
FP4	Prevention of Accidents	All reasonable practicable steps must be taken to prevent and mitigate accidents.
FP5	Emergency Preparedness and Response	Arrangements must be made for emergency preparedness and response in the event of a total failure of the ships or its infrastructure.

Assuring Safety – 'Defence in Depth' for Marine Autonomous Infrastructures.

The concept of defence in depth should be applied so that:

a) deviations from normal operation and failures of the ship, systems and autonomous infrastructure are prevented;

b) any deviations from normal operation are allowed for by design that enable timely detection and action that prevents escalation;

c) inherent safety features, fail safe design and safety measures are provided to protect against fault conditions progressing into accidents; and

d) additional measures are provided to mitigate the consequences of accidents, especially severe accidents.

Objective of each level of protection;

- **Objective** Level 5 Mitigation of accident consequences through emergency responses.
  - **Defence/Barrier** Emergency control and on- and off-site emergency response (e.g. Salvage, fire-fighting tugs, transfer of control from the ROC, Security procedures in place, etc).
  - Examples: Vessel out of operation (not under command) and drifting towards a main shipping lane. Terrorist attack, earthquake, flooding event

Additional Requirements (Constrains & Opportunities)

Rolls-Royce

Technology

Legal

Regulations

Insurance

Liability

When?

Jobs

Qualifications

Systems Engineering principles for Autonomous Infrastructure

- Based on Principles derived from the Royal Academy of Engineering:-
  - Principle 1: Debate, define, revise and pursue the purpose
  - Principle 2: Think holistically
  - Principle 3: Follow a systematic procedure
  - Principle 4: Be creative
  - Principle 5: Take account of the people
  - Principle 6: Manage the project and the relationships

System Thinking

Holistic Thinking

- I have to look at the whole situation – the system and its environment
- I have to understand the purpose and the context of the situation

Behavioural Thinking

- I have to understand the behaviour of the system before I start the structural thinking (form follows functions)
- I have to consider the feedback and the “delay” structure between the elements

Structural Thinking

- I have to look for structure, and the “connections” and the “dependencies” between the element.

Perception Thinking

- I have to look at the situation from different viewpoints

Abstract Thinking

- I have to manage complexity by prioritising details (separation of concerns)

Principle 5: take account of the people

Rolls-Royce

- People are part of a system and not an external constraint.
- Challenge for the marine autonomous sector as the ‘end user’ can and probably will change.
- Competence and SQEP of the staff will be considerably different. Who will define the levels required?

Challenge 1 - Understanding the "product"

- The "product" is the system of interest.
- ISO 15288 Section 6.4.2.1 Stakeholders needs and requirements definition process – the stakeholders requirements are defined considering the context of the system of interest with the interoperating system and enabling system.
- **System Engineering** is about agreeing the scope and context of the "product" from the outset and applying effective system thinking to understand the problems, managing stakeholders communication & collaboration to enable the correct decision making to derive successful systems.
- Effective system engineering framework, processes, techniques & tools can enhance the efficiency of the system engineering process.
- As the complexity of the system increases, the flexibility and the effectiveness of fit-for-purpose system engineering framework, processes, techniques & tools that will enable complexity management & the creation of multiple viewpoints will become increasingly important.

Challenge 2 – Define Future Products (Autonomy)

- System of Interest that define future products have extended beyond the vessel.
- Vessel becomes the sub-system of the "system of interest".
- The goal of future products is to transition functionality to higher level of autonomy but extended beyond existing onboard operation & ship functions, especially decision support & decision making functionality whether onboard or offboard.
- The majority of classes of functionality of future products will be assigned to cyber-physical systems and physical systems where the **Solutions** will be targeted at autonomy Level 3-4 for a broad range of **Applications** ranging from autonomy Level 1(advisory) to Level 4 (fully autonomous) where human will focus on the sub-tasks level with system taking over the overall responsibility of the main tasks and failsafe tasks.
- **System Engineering** is required to decompose these highly complex systems (infrastructure level), derive and deliver future products, identify & manage risks, facilitate collaboration & complex system integration and address the life cycle needs of the products as the scope of the "system of interest" has changed from our current offerings.

Remote/Autonomous Infrastructure goals

System of Interests

Rolls-Royce

Operational Modes

(Operational Objectives)

Op Mode 1 | Op Mode 2 | Op Mode 3 | Op Mode 4 | Op Mode 5 | Op Mode 6

Operational Task / Infrastructure Functions

Sub-Systems

Vessels | **ROC** | **Connectivity** | **Data Platform** | **Port** | **Others**

Classification of Functions	No Autonomy (L0)	Partial Autonomy (L1)	Conditional Autonomy (L2)	High Autonomy (L3)	Full Autonomy (L4)
Monitoring			➢ Functions ❖ Functions	➢ Functions ❖ Functions	➢ Functions ❖ Functions
Reporting			➢ Functions ❖ Functions	➢ Functions ❖ Functions	➢ Functions ❖ Functions
Decision Support			➢ Functions ➢ Functions	➢ Functions ➢ Functions	➢ Functions ➢ Functions
Decision Making			➢ Functions ➢ Functions	➢ Functions ➢ Functions	➢ Functions ➢ Functions
Decision Execution			➢ Functions ➢ Functions	➢ Functions ➢ Functions	➢ Functions ➢ Functions

Transition functionality to higher level of autonomy including but beyond existing operation & vessel functions

❖ **Cyber-Physical Systems (any location)**

❖ **Physical Systems (any location)**

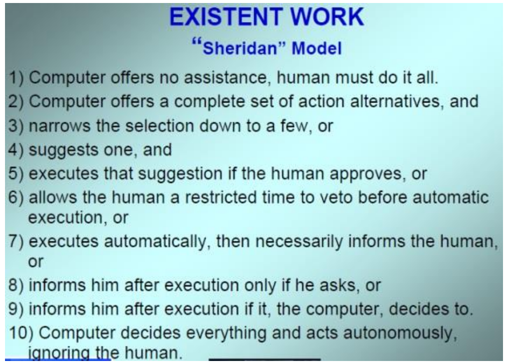
❖ **Human (any location)**

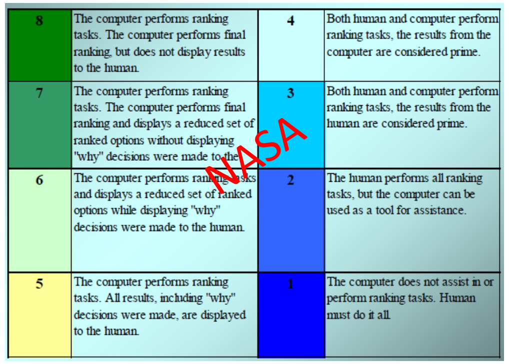
How Autonomous is the System?

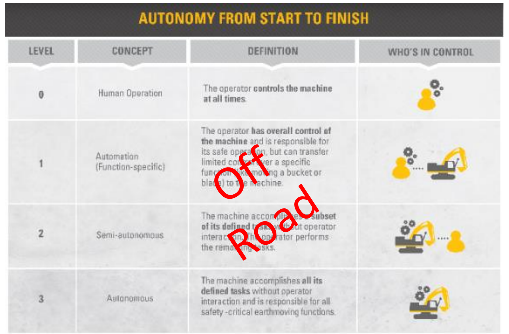
- Broad product range with a mixture of manual, automated, remote control, semi-autonomous and, autonomous features.
- "How autonomous is the system?"
- This question can be answered with an assessment of how independent the system is in accomplishing its tasks without human interaction and human intervention.
- It is not possible to assess how autonomous the system is without the understanding of automation.
- The key questions to be addressed include:
  - "What tasks (types) do we want to automate?"
  - "What are the level of automation intended for the targeted tasks?"
  - "What is the role of the human in the loop?"
  - "Who/what is in control for the sustained operational tasks?"
  - "Who/what takes over control in fail safe situation?"
  - "What is the autonomous capabilities of the platform?"

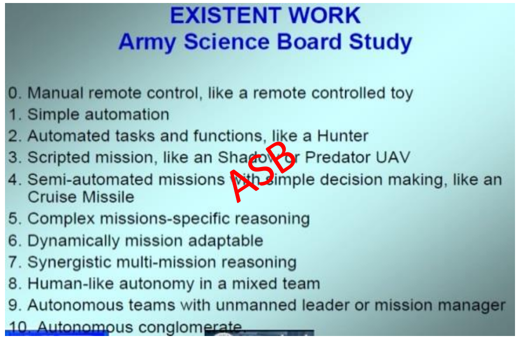
Lesson Learned from other Sectors

Rolls-Royce

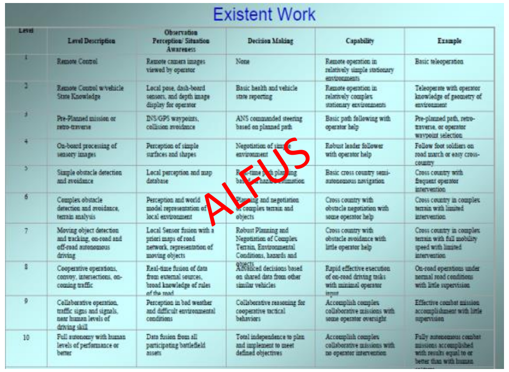


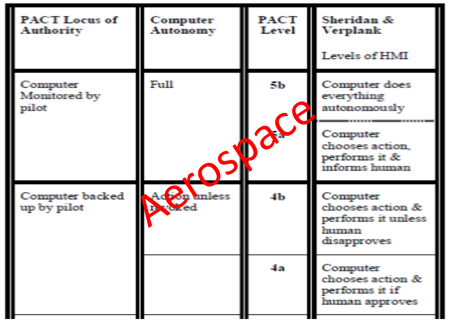


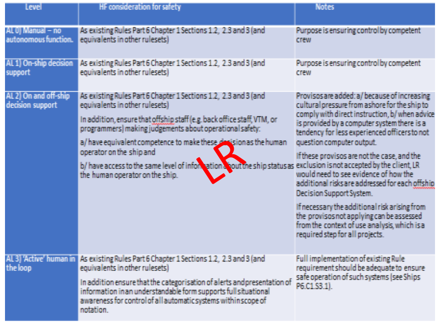


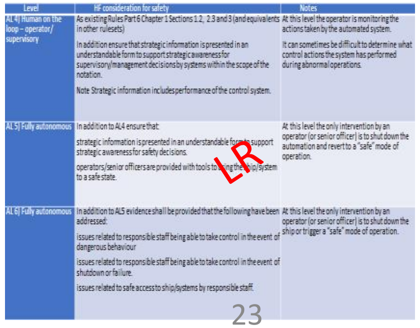


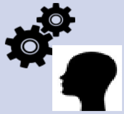
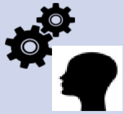
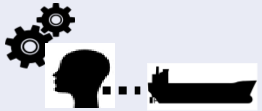
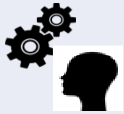
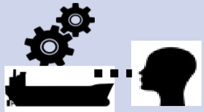
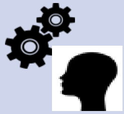
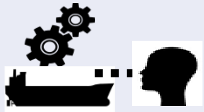
- What tasks (types) do we want to automate?
- What are the level of automation intended for the targeted tasks?
- What is the role of the human in the loop?
- Who/what is in control for the sustained operational tasks?
- Who/what takes over control in fail safe situation?
- What is the autonomous capabilities of the platform?









Level	Name	Definition (Proposed Maritime Autonomy Framework)	Who is in Control? Sustained operational task	Who takes over control? Fail Safe Operational Task	System Capability
0	No Autonomy	All aspects of operational tasks perform by human operator even when enhanced with warning or intervention system. Human operator safely operates the system at all time. (e.g. Select pumps)	 Manual		n/a
1	Partial Autonomy	The targeted operational tasks perform by human operator but can transfer control of specific sub-tasks to the system. The human operator has overall control of the system and safely operates the system at all time. (e.g. start engine sequence)	 Automation		Some Operational Tasks
2	Conditional Autonomy	The targeted operational tasks perform by automated system without human interaction and human operator perform remaining tasks. Human operator is responsible for its safe operation.	 Semi-Autonomous		Majority of Operational Tasks
3	High Autonomy	The targeted operational tasks perform by automated system without human interaction and human operator perform remaining tasks. System is responsible for its safe operation. (e.g. PMS, DP)	 Semi-Autonomous		Majority of Operational Tasks
4	Full Autonomy	All operational tasks perform by an automated system under all defined conditions.	 Full Autonomous		All Operational Tasks

Rolls-Royce

Vessel goals

Operational Modes (Operational Objectives)

Port (Stand by) · Undocking (Manoeuvring) D · Transit · Docking (Manoeuvring) A · Port (Standby)

Operational Task Analysis

Bridge · Deck · Engine Room

Buoyancy & Stability
Manoeuvring
Navigation
Mission equipment control
Payload

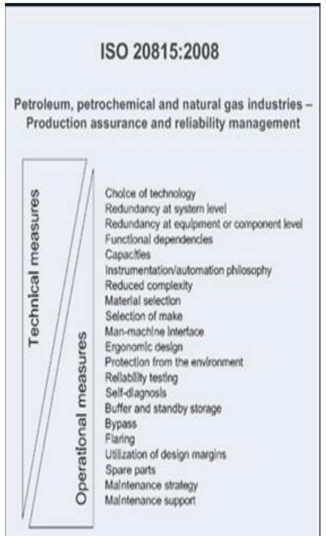
Classification of Functions	No Autonomy (L0)	Partial Autonomy (L1)	Conditional Autonomy (L2)	High Autonomy (L3)	Full Autonomy (L4)
Monitoring	❖ Functions				
Reporting			❖ Functions		
Decision Support	➢ Functions	➢ Functions	➢ Functions		
Decision Making	➢ Functions				
Decision Execution			➢ Functions		

- ❖ Systems In ROC
- ❖ Human In ROC

- ➢ Systems On Vessel
- ➢ Human on Vessel

Infrastructure (Connectivity, Data)
Technology
HMI/Handover
Risk

Classification	No Autonomy (L0)	Partial Autonomy (L1)	Conditional Autonomy (L2)	High Autonomy (L3)	Full Autonomy (L4)
Monitoring	➢ Functions ➢ Functions ❖ Functions	➢ Functions ➢ Functions	➢ Functions ➢ Functions ➢ Functions	➢ Functions ➢ Functions ➢ Functions	➢ Functions ➢ Functions
Reporting		➢ Functions ➢ Functions	➢ Functions ➢ Functions	➢ Functions ➢ Functions	➢ Functions ➢ Functions
Decision Support	➢ Functions ➢ Functions ❖ Functions	➢ Functions ➢ Functions	➢ Functions ➢ Functions	➢ Functions ➢ Functions	➢ Functions ➢ Functions
Decision Making	➢ Functions ➢ Functions ❖ Functions	➢ Functions ➢ Functions	➢ Functions ➢ Functions	➢ Functions ➢ Functions	➢ Functions ➢ Functions
Decision Execution		➢ Functions ➢ Functions	➢ Functions ➢ Functions	➢ Functions ➢ Functions	➢ Functions ➢ Functions



Functional Criticality Assessment

Strategic Objective | Operational Objective | Safety Objective

Support assessment of business, operational and safety risk

Control Measure

Technical Measure
(e.g. Choice of Technology, System redundancy, component redundancy)

Operational Measure
(e.g. reliability testing, use of design margin, maintenance support,)

Monetise risk control measure

The Interpretation of the Level of Autonomy

- A System engineering approach to use case generation for risk assessment:
  - The context include the infrastructure – vessels, ports and remote operational centres
  - Identify the vessel / fleet objectives or goals
  - Identify the vessel operational modes
  - Determine functions for all targeted vessel operational modes
  - Classify functions type
  - Assign level of autonomy to functions
  - Assign functions to be performed to actors (an actor can be human or system)
  - Determine location of the actors (location can be remote or onboard)
- There is a need to segregate the interpretation of level of autonomy according to:
  - **Specific function(s)** (e.g. different functions may have different level of autonomy, functions may change their level of autonomy over time)
  - **Specific solution(s) in question** (e.g. how functions with different level of autonomy integrated to form a solution (e.g. sub-system) with a defined level of autonomy)
  - **The specific vehicle platform in addressing its overall strategic objective(s) or goal(s)** (e.g. how different solutions with varying level of autonomy integrated to deliver the vessel autonomous capability to accomplish its overall mission).
- Having an appropriate taxonomy to define the level of autonomy for maritime operation enable safety critical function and safety critical system to be identified.

The Attributes of An Effective Maritime Autonomy Framework

An effective MAF should be:

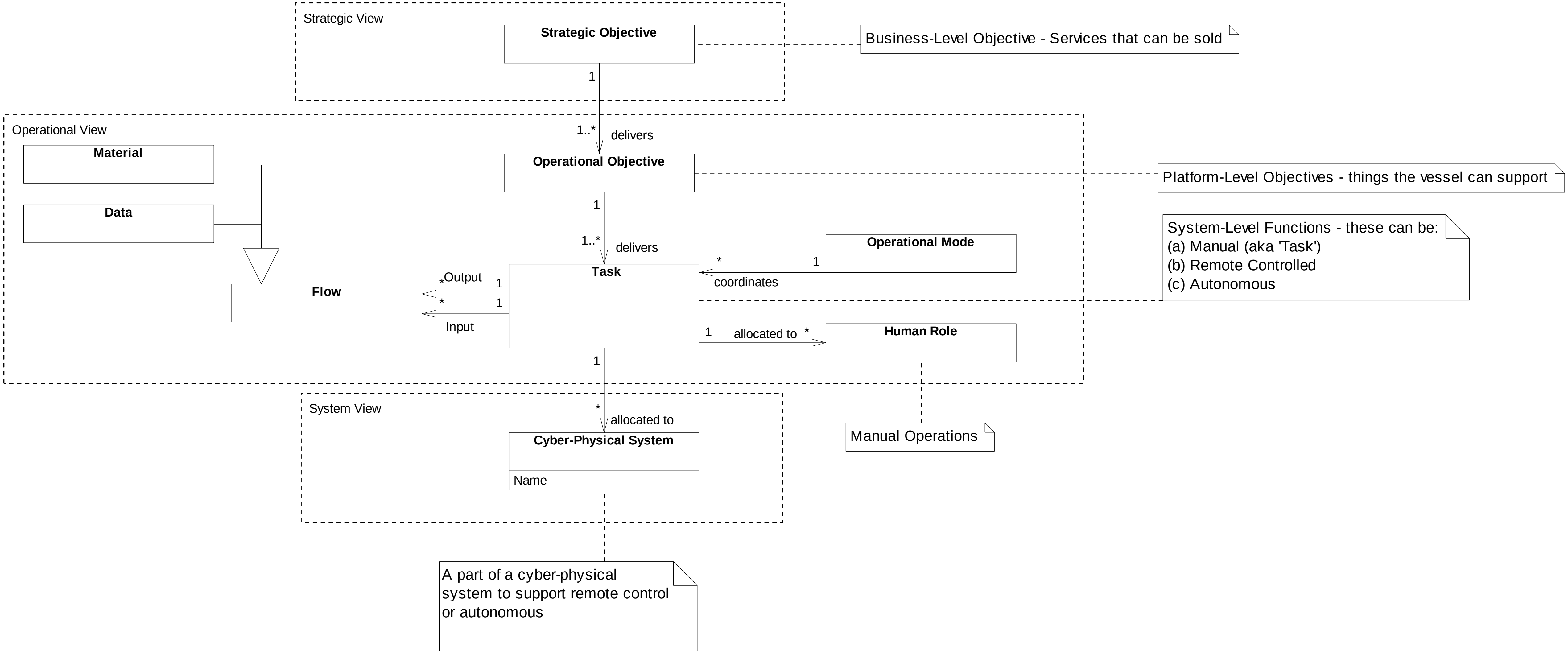
- **Simple** enough to be understood and remembered.
- **Practical** enough to be used in the design process & implementation.
- **Flexible** enough to cover a wide range of operational scenario and solutions at all levels (function, sub-system, system, platform level) with mixtures of autonomous features. The framework can be further extended to show technology readiness.
- **Robust** enough to provide consistency, traceability, evidence and argument to support strategic, operational, safety objectives.
- **Transparent** enough to be understood by the regulators how the safety argument has been achieved. Support customers map the value creation to the level of autonomy.

Method & Tool

- **System Engineering** defines an approach for realising successful systems.
- **Model-based System Engineering (MBSE)** provides an approach for using Models to realise the artefacts of a System based on a set of modelling Views.
- We are using MBSE to model the artefacts of the Maritime Autonomous Enterprise System (infrastructure) where the **Enterprise Architecture Framework / Maritime Autonomy Framework (MAF)** provides a standardised way of defining the Enterprise (structure & content).
- We are using **MBSE tool** to implement the Enterprise Architecture Framework / MAF for the Maritime Autonomous Enterprise System.

Domain-Neutral Terminology

Rolls-Royce



Domain-Specific Terminology

Example Task: **Leaving…**

- **Berth**
- **Dock**
- **Anchor**
- **Mooring**

- Each task description is different
- Post-condition of task is similar (if not the same)

Agreement on domain-specific terminology is essential for integration and interoperability

Key Take Away

- System Thinking – how do we nurture system thinking in our enterprise community?
- Autonomy - To help us truly understand the engineering challenges of autonomy, look beyond engineering
  - Neuroscience, psychology and computer science – combine their theories, findings, evidence to derive new insights
- Managing complexity - Einstein's "everything should be as simple as possible, but no simpler".
- Four stages of competence:
  - Unconscious incompetence
  - Conscious incompetence
  - Conscious competence
  - Unconscious competence
- We can't afford to be unconscious incompetence when designing & deploying autonomy. Our starting position need to be at least Conscious Incompetence, conscious about what we don't know and don't know enough, understand the limitation & opportunities, know where the risks are and how to manage them to ensure safe deployment.