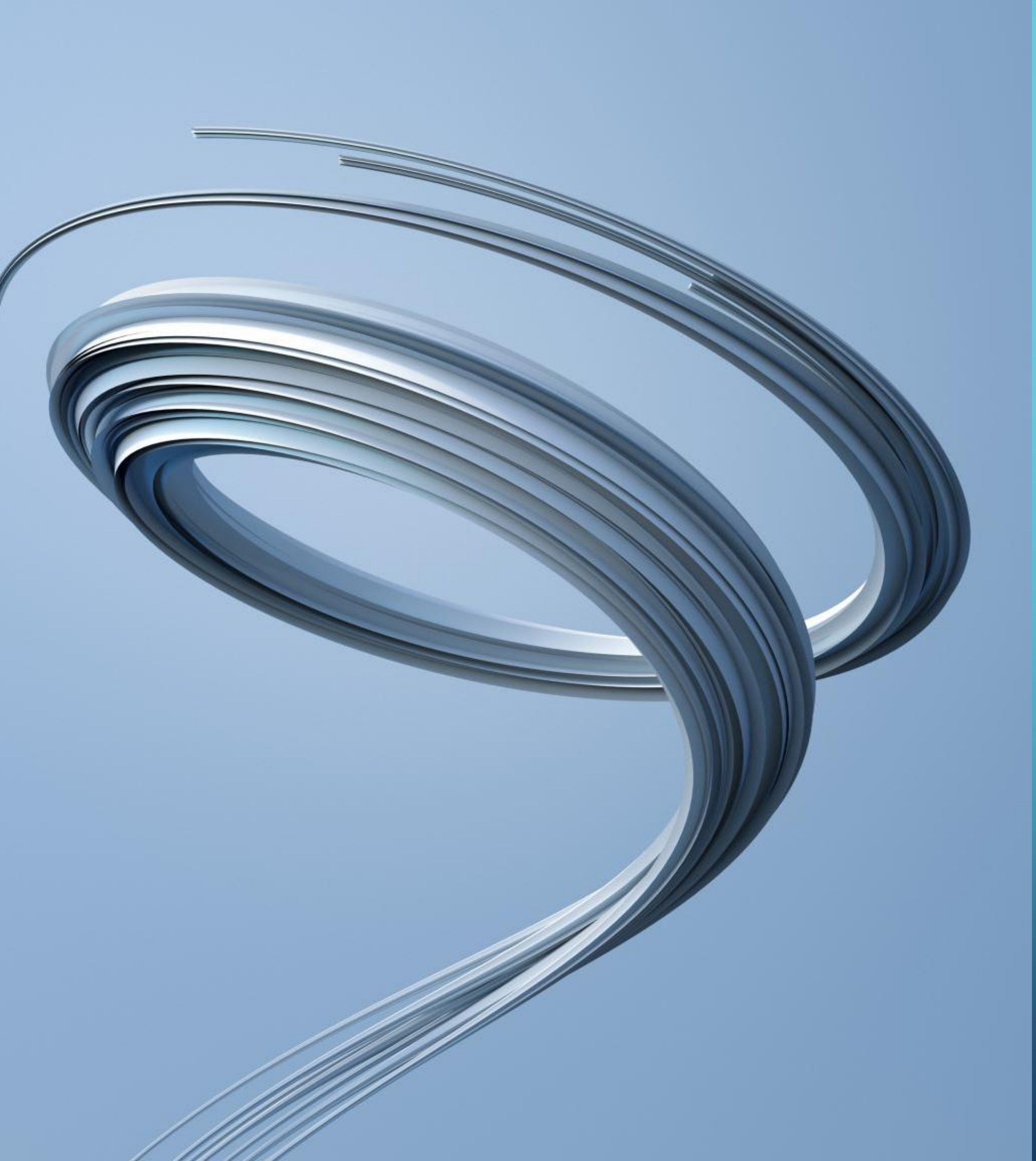


MODEL BASED SYSTEMS ENGINEERING. FROM THE DESIGN SPIRAL TO THE LIFE CYCLE SPIRAL

JOSÉ TORRES GARCÍA

DIGITAL TRANSFORMATION COMMISSION AINE

“SYSTEMS ENGINEERING IS A TRANSDISCIPLINARY AND INTEGRATIVE APPROACH TO ENABLE THE SUCCESSFUL REALIZATION, USE, AND RETIREMENT OF ENGINEERED SYSTEMS, USING SYSTEMS PRINCIPLES AND CONCEPTS, AND SCIENTIFIC, TECHNOLOGICAL, AND MANAGEMENT METHODS. (INCOSE, 2025)”

Definition of Systems Engineering according INCOSE (International Council on Systems Engineering)

- Approach to engineered system realization
- All engineering domains
- Whole life cycle
- Systems principles and concepts
- Scientific, technological and management methods

“

AN ENGINEERED SYSTEM IS A SYSTEM DESIGNED OR ADAPTED TO INTERACT WITH AN ANTICIPATED OPERATIONAL ENVIRONMENT TO ACHIEVE ONE OR MORE INTENDED PURPOSES WHILE COMPLYING WITH APPLICABLE CONSTRAINTS. (INCOSE, 2025)

”

Engineered System Definition according INCOSE (International Council on Systems Engineering)

- For a purpose
- Operational environment
- Complying applicable constraints

"A DIGITAL MODEL REPRESENTS AN ACTUAL OR CONCEPTUAL SYSTEM THAT INVOLVES PHYSICS, MATHEMATICS, OR LOGICAL EXPRESSIONS. A SIMULATION IS A METHOD FOR IMPLEMENTING A MODEL OVER TIME. (DOD, 2025)"

Definition of model (US Department of Defense)

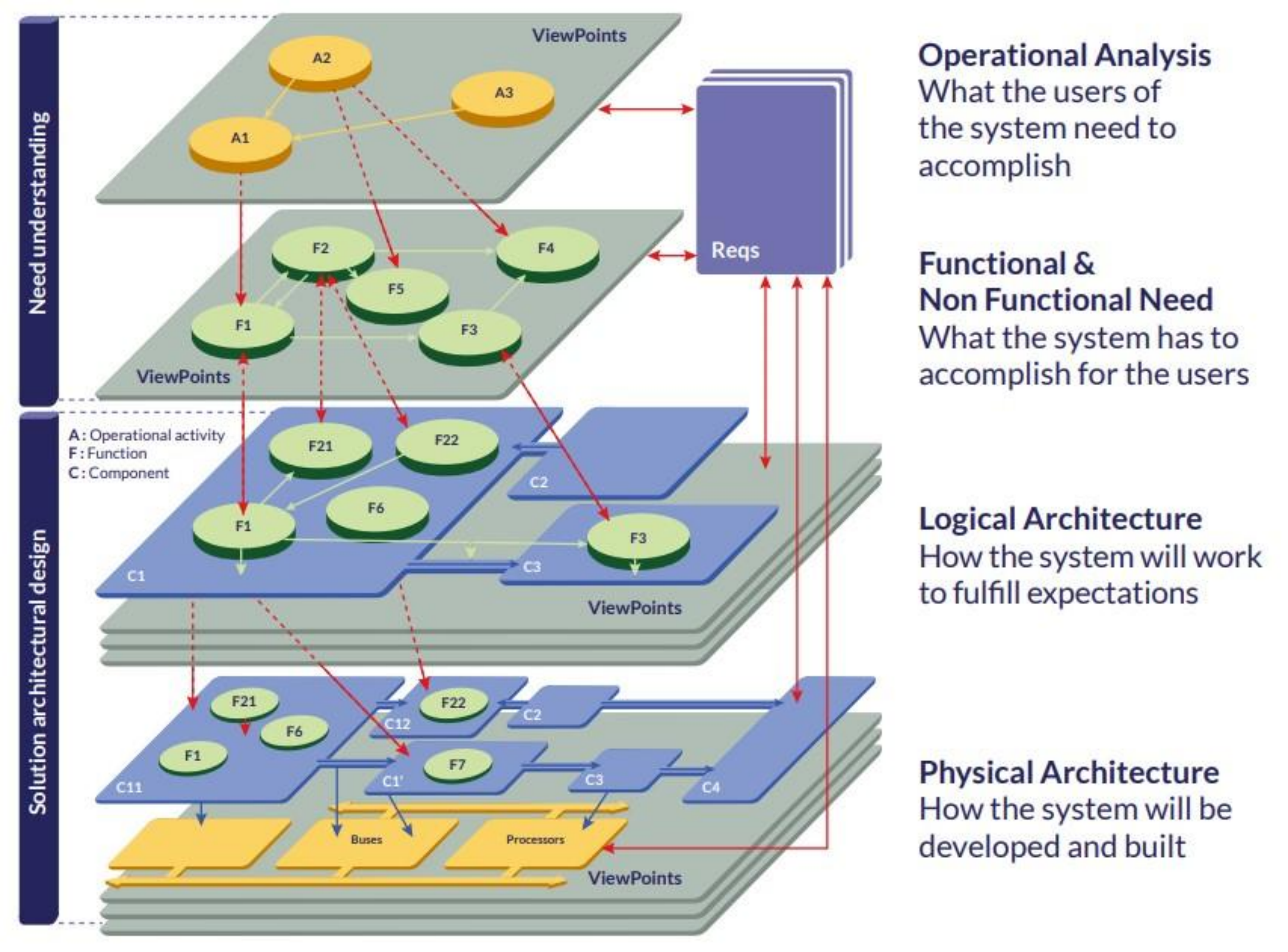
- System representation
- Physics, mathematics or logical expressions

"MODEL-BASED SYSTEMS ENGINEERING (MBSE) IS THE FORMALIZED APPLICATION OF MODELING TO SUPPORT SYSTEM REQUIREMENTS, DESIGN, ANALYSIS, VERIFICATION AND VALIDATION ACTIVITIES BEGINNING IN THE CONCEPTUAL DESIGN PHASE AND CONTINUING THROUGHOUT DEVELOPMENT AND LATER LIFE CYCLE PHASES. (INCOSE T. O., 2007)"

Model Based Systems Engineering Definition (INCOSE Technical Operations)

- Formalized application of modelling
- To Support System requirements, design, analysis, verification and validation
- Whole life cycle

THE ARCADIA METHODOLOGY



(ARChitecture Analysis and Design Integrated Approach)

¿What's needed from the system?
Need definition

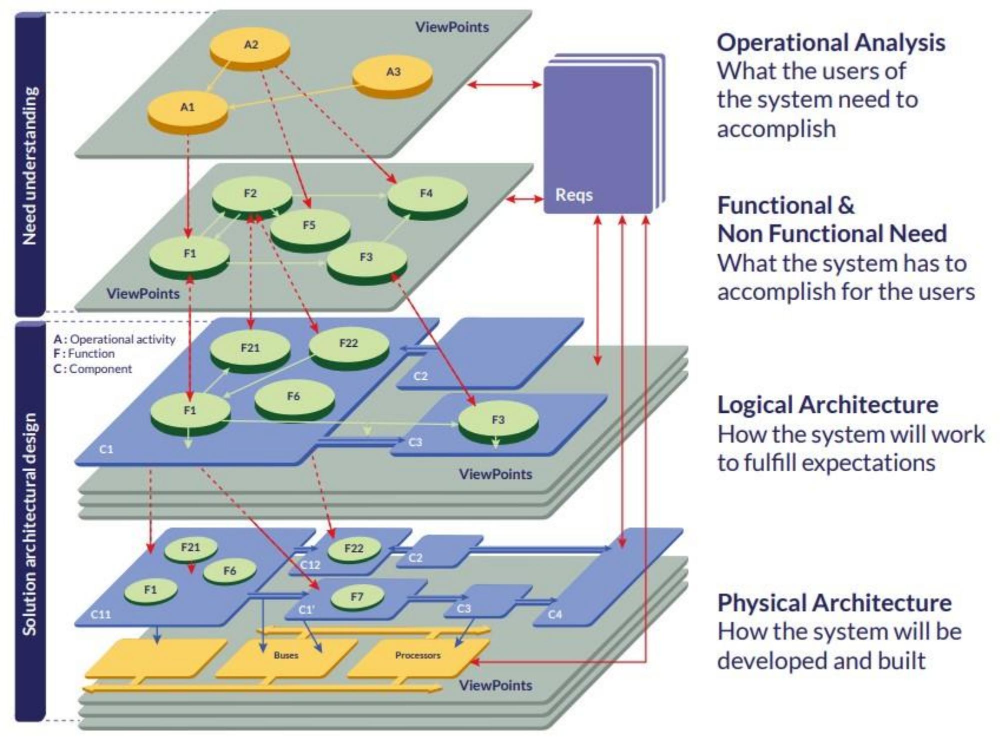
¿What has to do the system to accomplish the needs?
Breakdown of the needs in technologicaly viable functions

¿How the system will be arranged to accomplish the needs?
How will system functions be grouped to fulfill the needs

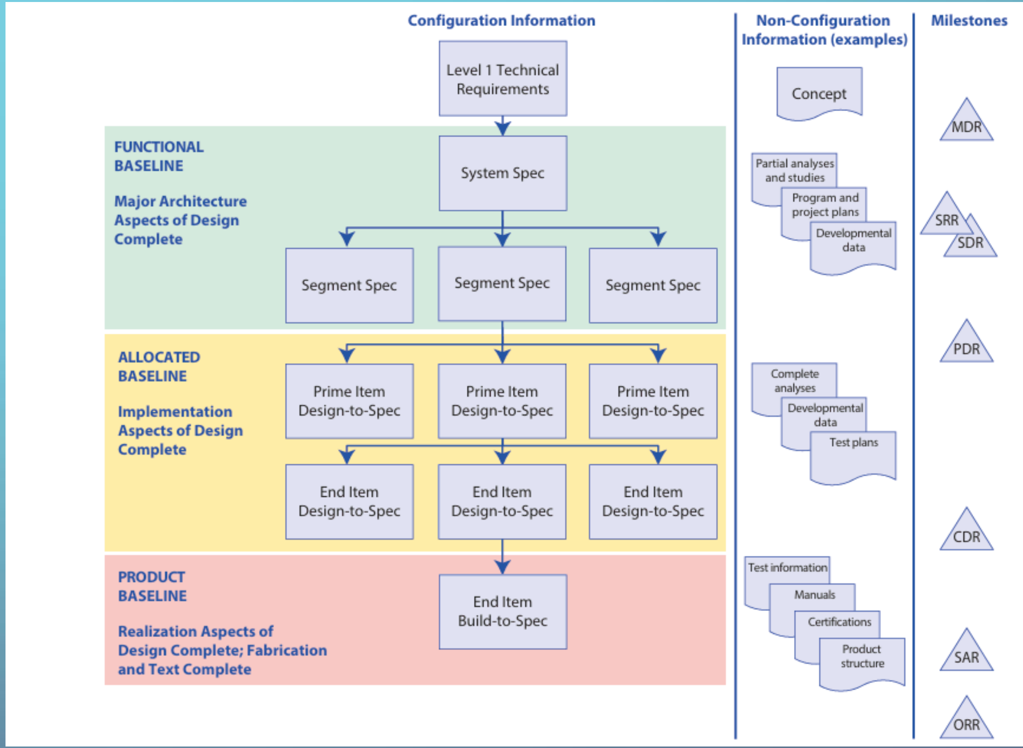
¿How will the system be developed and built to accomplish the needs?
How will the system functions be allocated to components to fulfill the needs

64th International Congress of Naval Architecture and Maritime Industry
Digital Transformation Commission AINE

THE ARCADIA METHODOLOGY VS THE SYSTEM ENGINEERING PROCESS

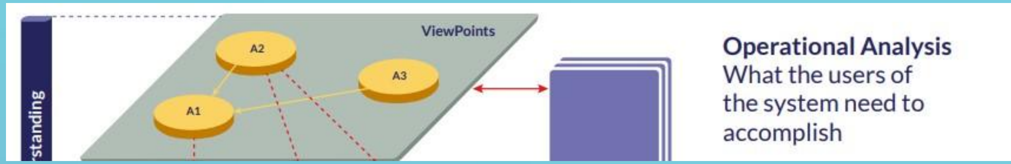


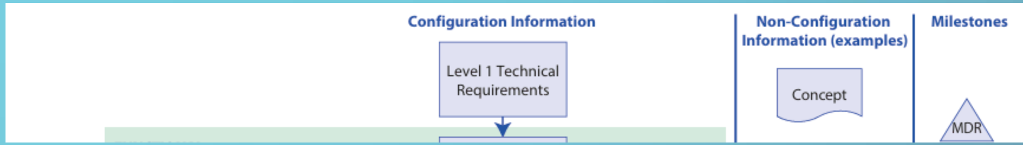
ARCADIA methodology stages



Project phases according NASA Systems Engineering Handbook

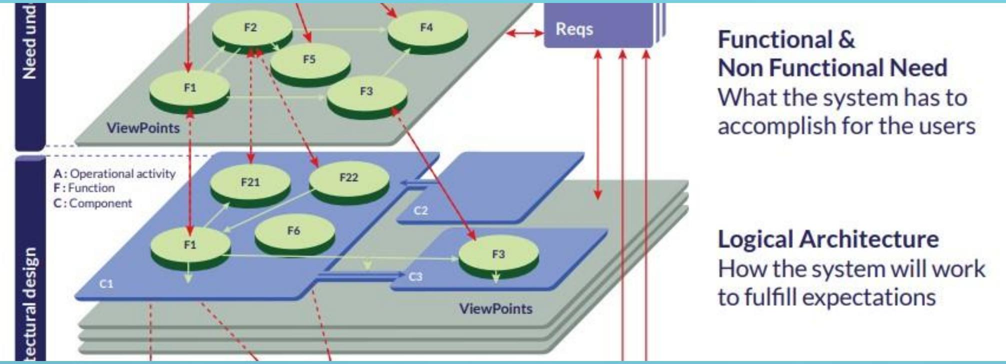
THE ARCADIA METHODOLOGY VS THE SYSTEM ENGINEERING PROCESS

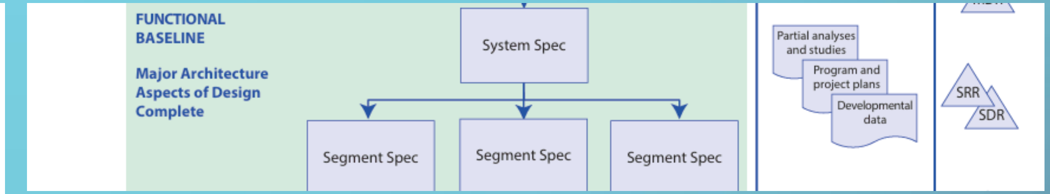




The operational analysis corresponds with the definition of the technical requirements of the system, the complete definition of those requirement is reviewed in the Mission Definition Review (MDR)

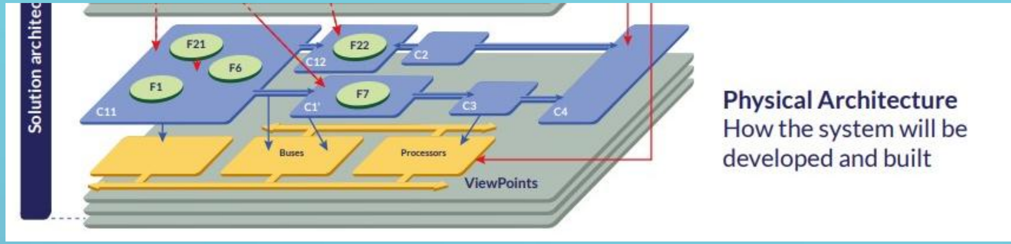
THE ARCADIA METHODOLOGY VS THE SYSTEM ENGINEERING PROCESS

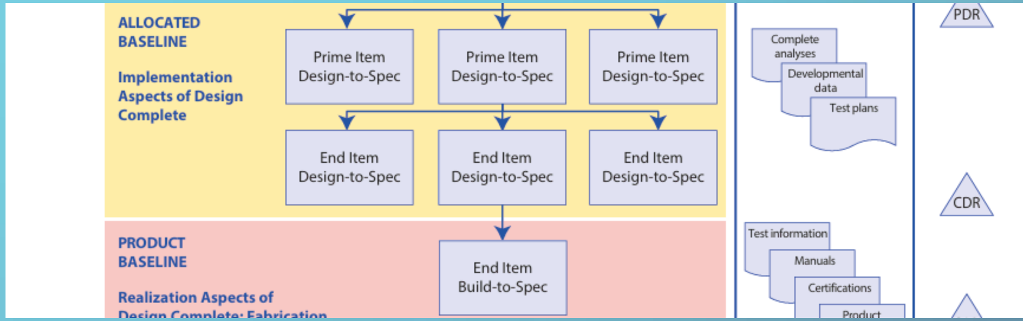




The system analisys and the logical architecture in the ARCADIA methodology define the contract specification, the definition of the functions and the design generated in this phase are configured in a Functional Baseline that will be reviewed in the System Definition Review (SDR), an intermediate review by the end of the functional analysis can be performed and it’s called System Requirements Review (SRR).

THE ARCADIA METHODOLOGY VS THE SYSTEM ENGINEERING PROCESS

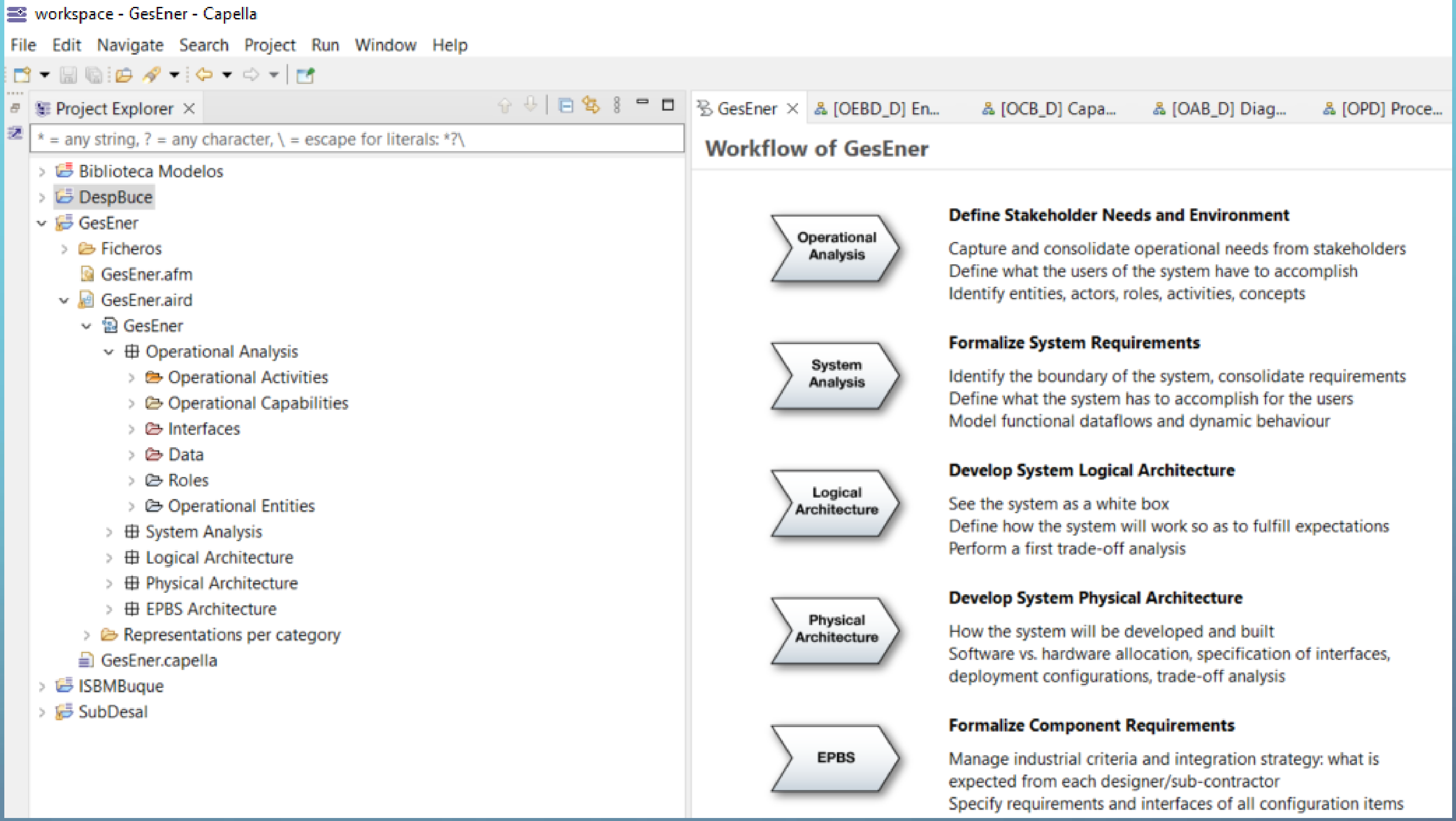




The physical architecture creates the components that will be executing the functions of the system, the resulting model and design are released in the Allocated Baseline after the Preliminary Design Review (PDR).

The extended physical architecture adds the definition and verification details that complete the Product Baseline that will be approved in a Critical Design Review (CDR)

THE CAPELLA TOOL AND THE ARCADIA METHODOLOGY



THE CONCEPT. ENERGY MANAGEMENT SYSTEM

A Notional Energy Management System design process will be presented

Needs

- Plan the energy consumption to increase efficiency
- Monitor the energy plant for operation and maintenance

Restrictions

- Integrated in a ship control system which controls the energy plant

THE ENGINEERING PROCESS. ENERGY MANAGEMENT SYSTEM

- Model the complete system (a basic ship to sail and transport payload) to the functional analysis level
- Model the energy management system (EMS) to the physical breakdown level
- Identify variables relevant for the design
- Identify variables relevant for the operation
- Identify variables relevant for the maintenance

DESIGN. SHIP OPERATIONAL ANALYSIS

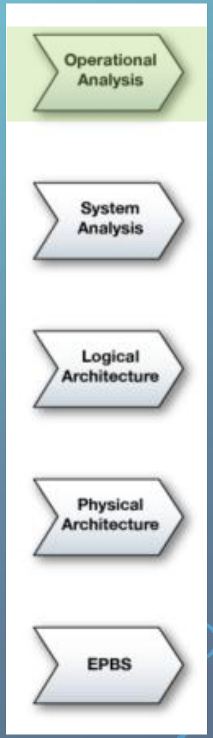
¿WHAT THE USERS OF THE SYSTEM NEED TO ACOMPLISH?

Inputs:

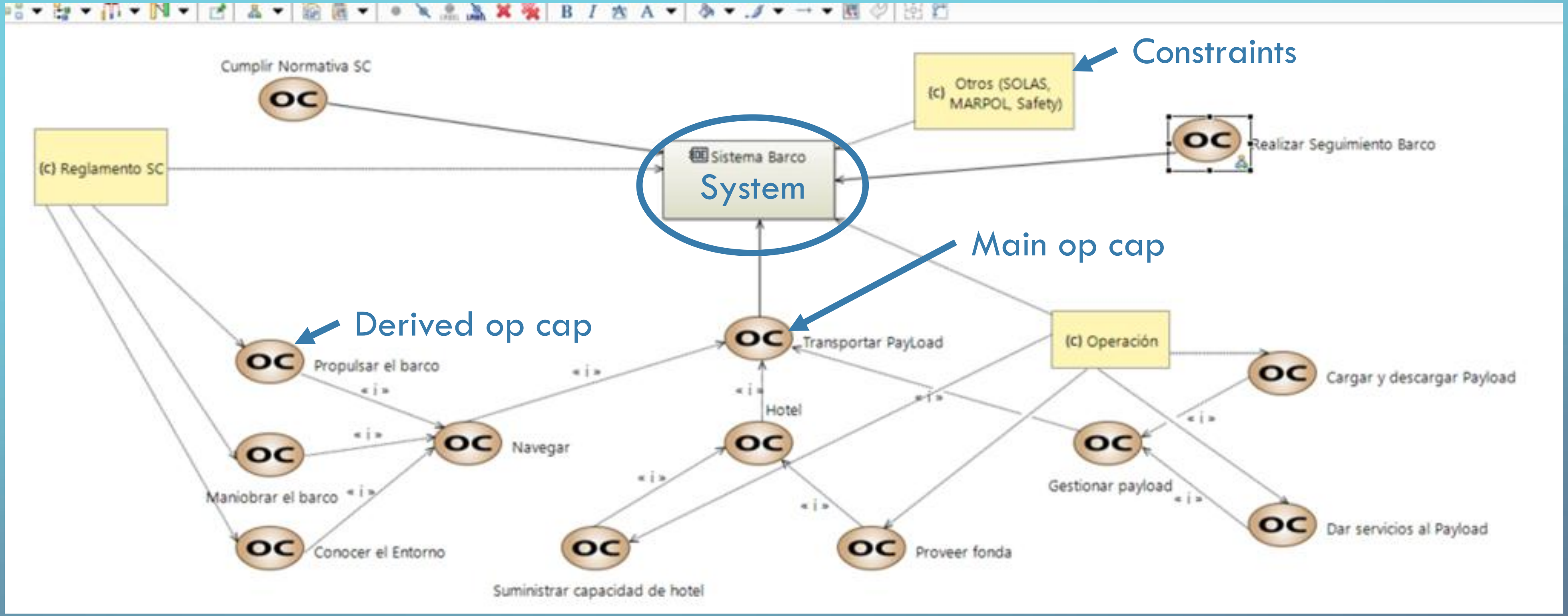
- Users and stakeholders needs
- System constraints

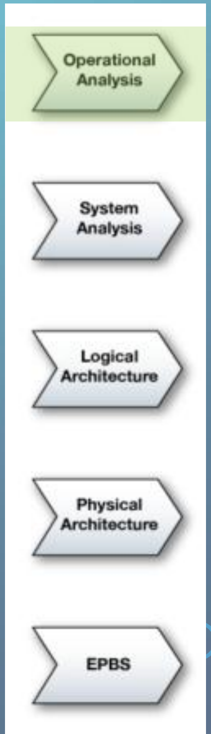
Outputs:

- Missions and its targets
- Operational capabilities that the system must fulfill to reach the targets of the missions
- Users and stakeholders needs



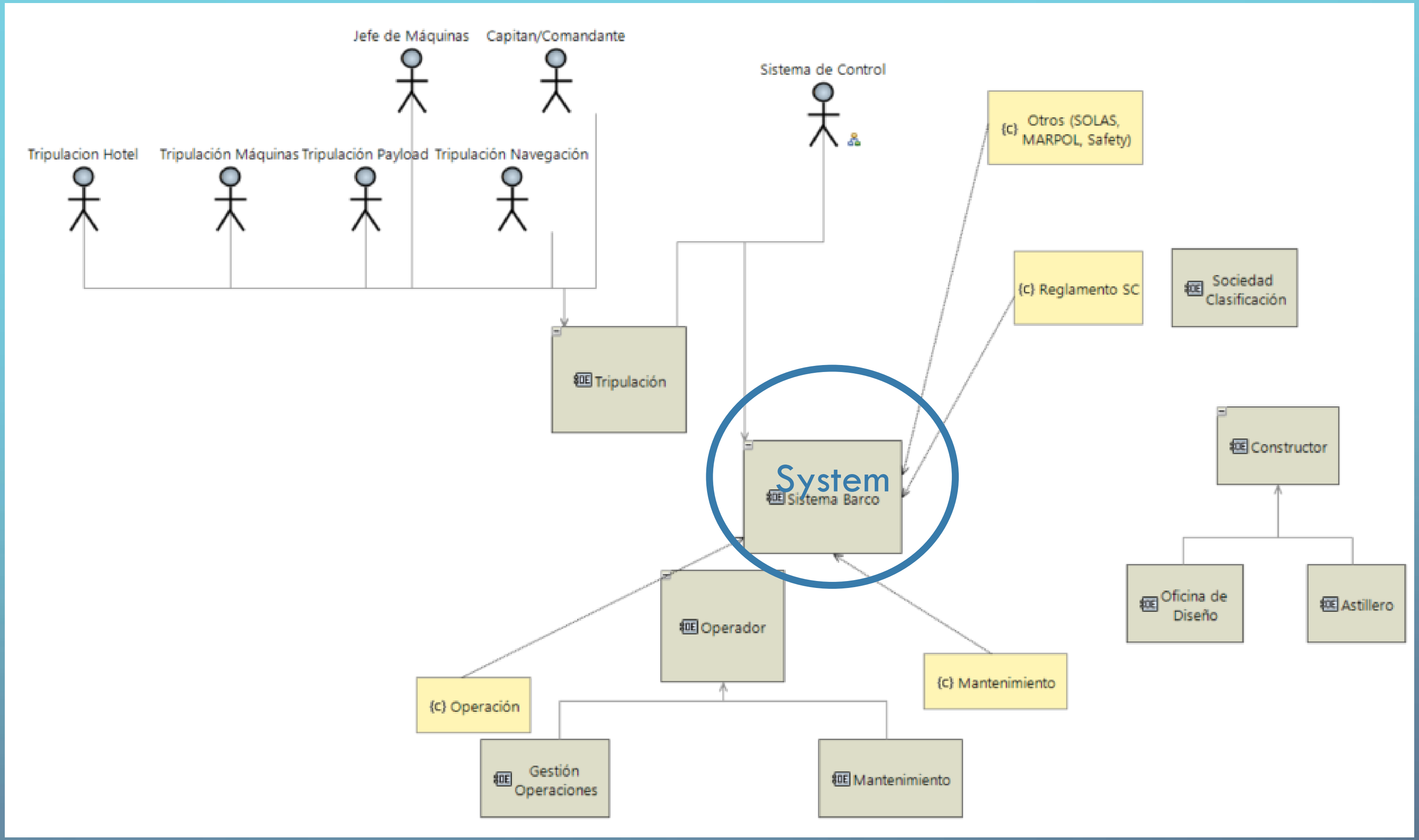
DESIGN. SHIP OPERATIONAL ANALYSIS

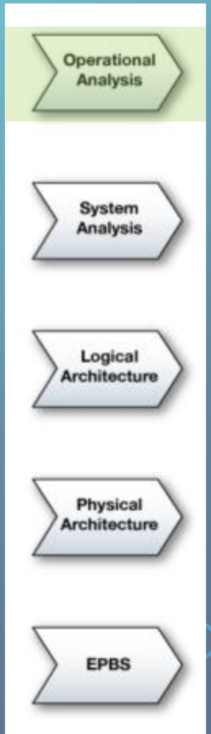




The breakdown of the main operational capabilities is shown in an operational capabilities' architecture diagram

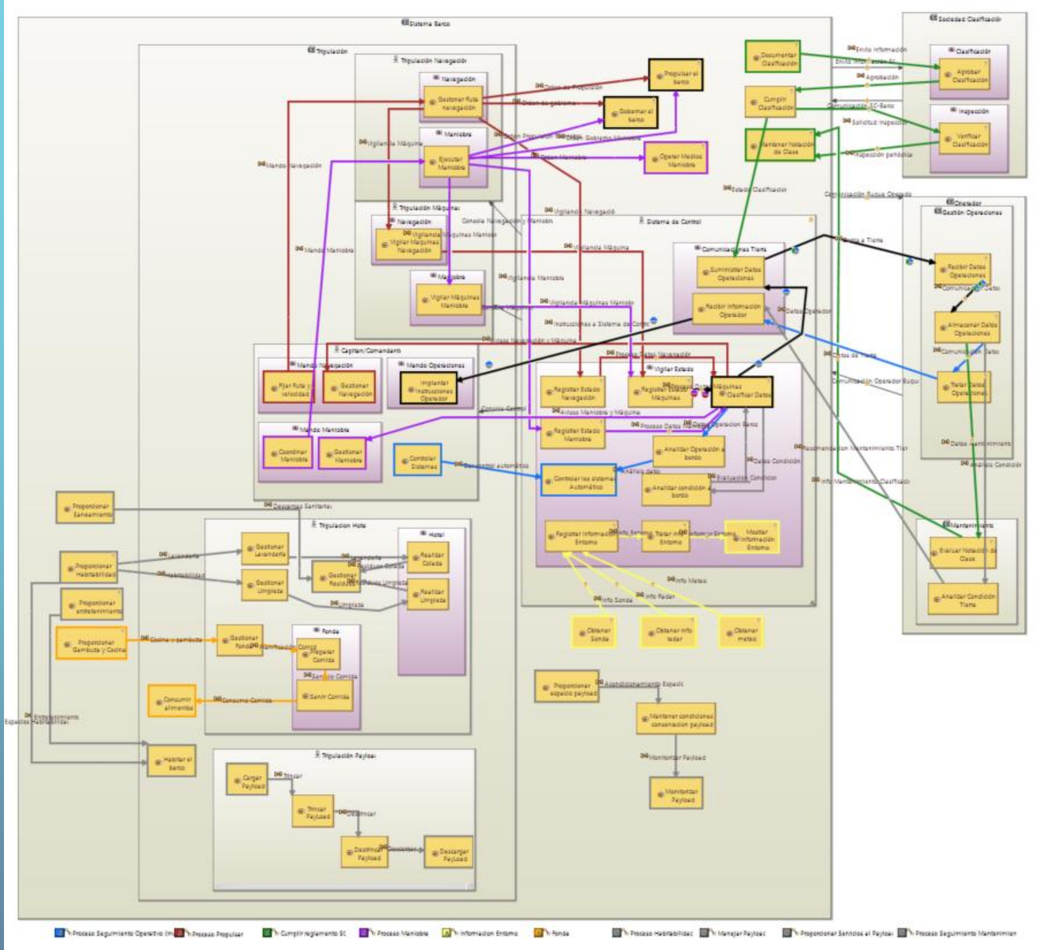
DESIGN. SHIP OPERATIONAL ANALYSIS

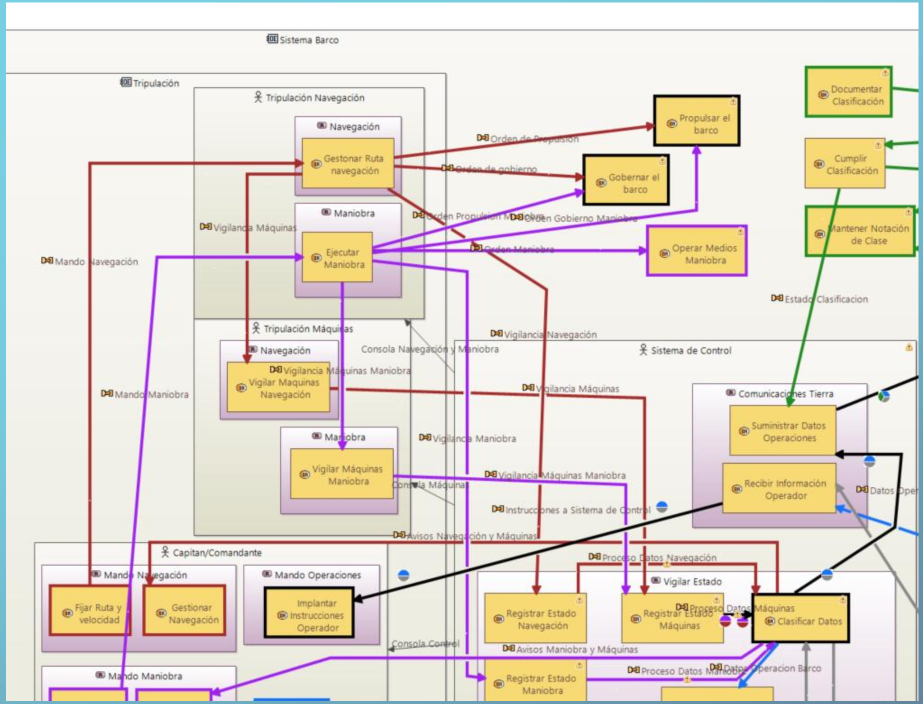


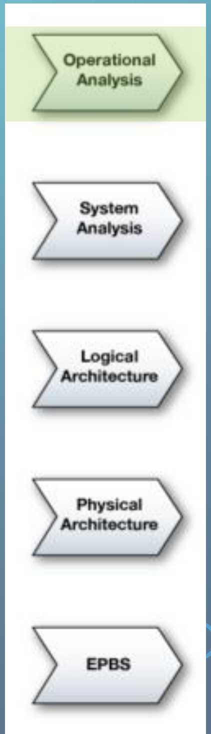


The operational entities breakdown diagram shows how the different actors and operational entities are related.

DESIGN. SHIP OPERATIONAL ANALYSIS

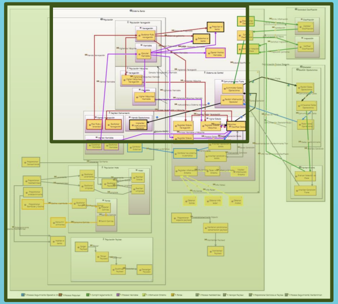


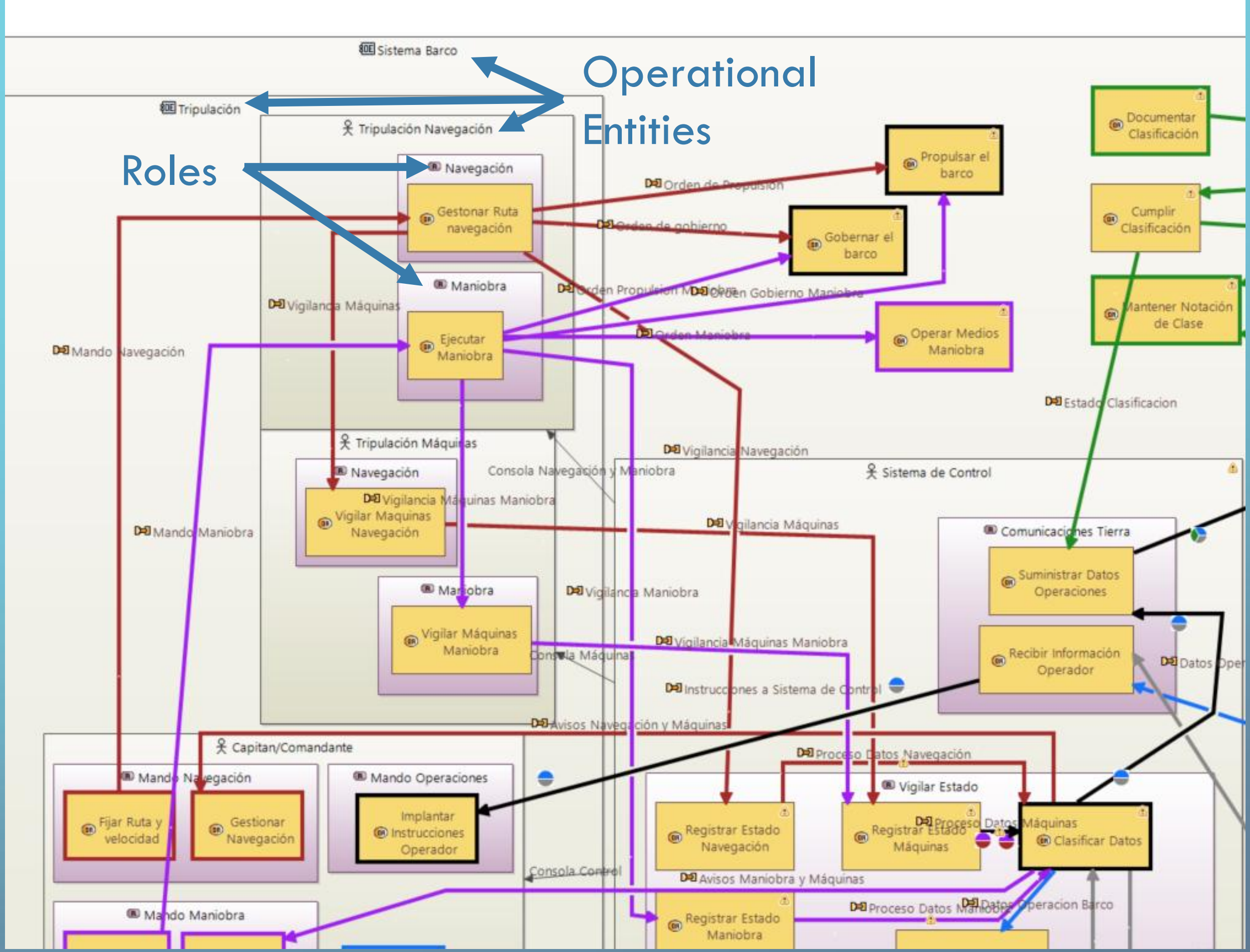


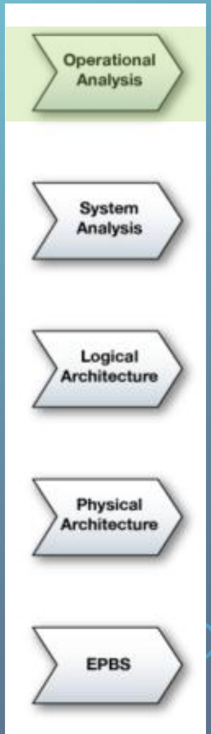


The operational capabilities are structured in operational processes that are sequences of operational activities and exchanges between them, all those features are represented in an Operational Architecture Diagram.

DESIGN. SHIP OPERATIONAL ANALYSIS

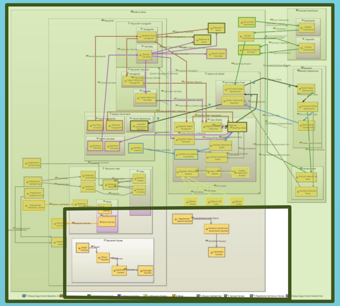


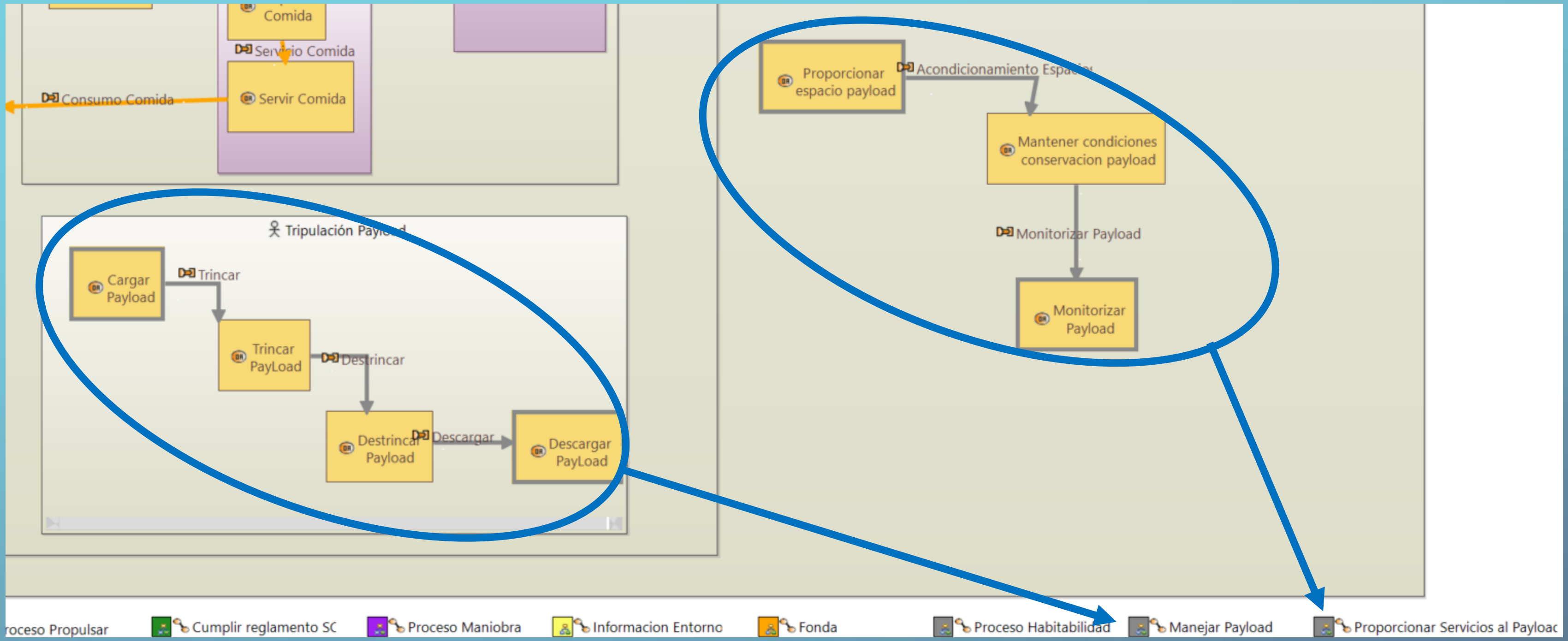


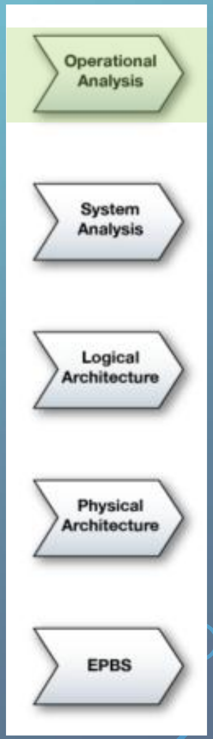


The “contained in” relationship of operational entities is shown by upper-level entities containing in the figure lower-level entities, at any level, different roles for the same actor can be allocated.

DESIGN. SHIP OPERATIONAL ANALYSIS







The operational architecture includes the operational processes, who does what with in and out interchanges.

SHIP DESIGN. SYSTEM ANALYSIS

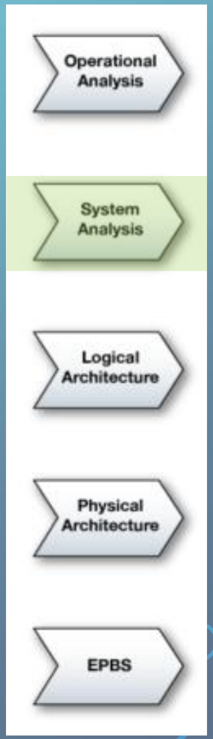
What the system has to accomplish for the users?

Inputs:

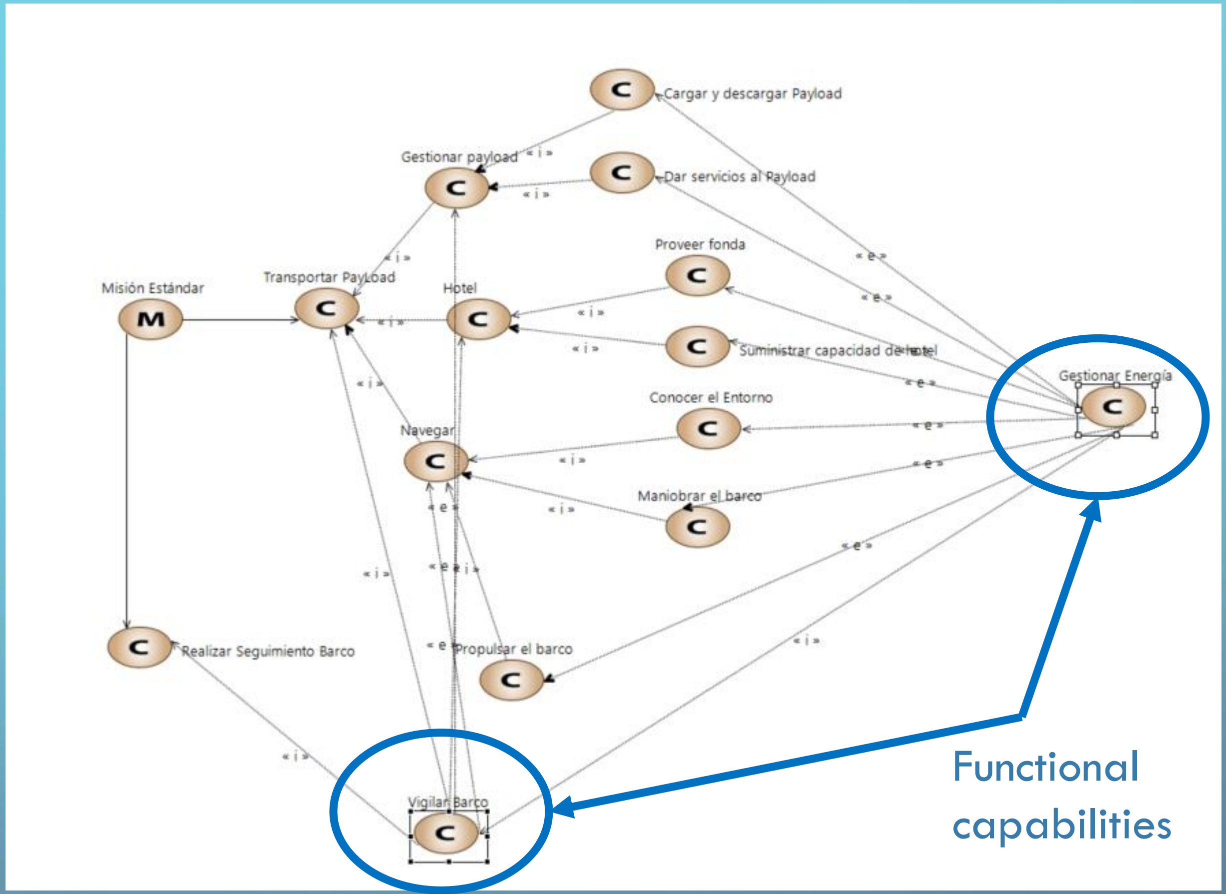
- Operational Analysis
- Design Standards

Outputs:

- Functions to be executed by the system
- Requirements that define the operation of the system and its evaluation from the feasibility, existing solutions and cost point of views

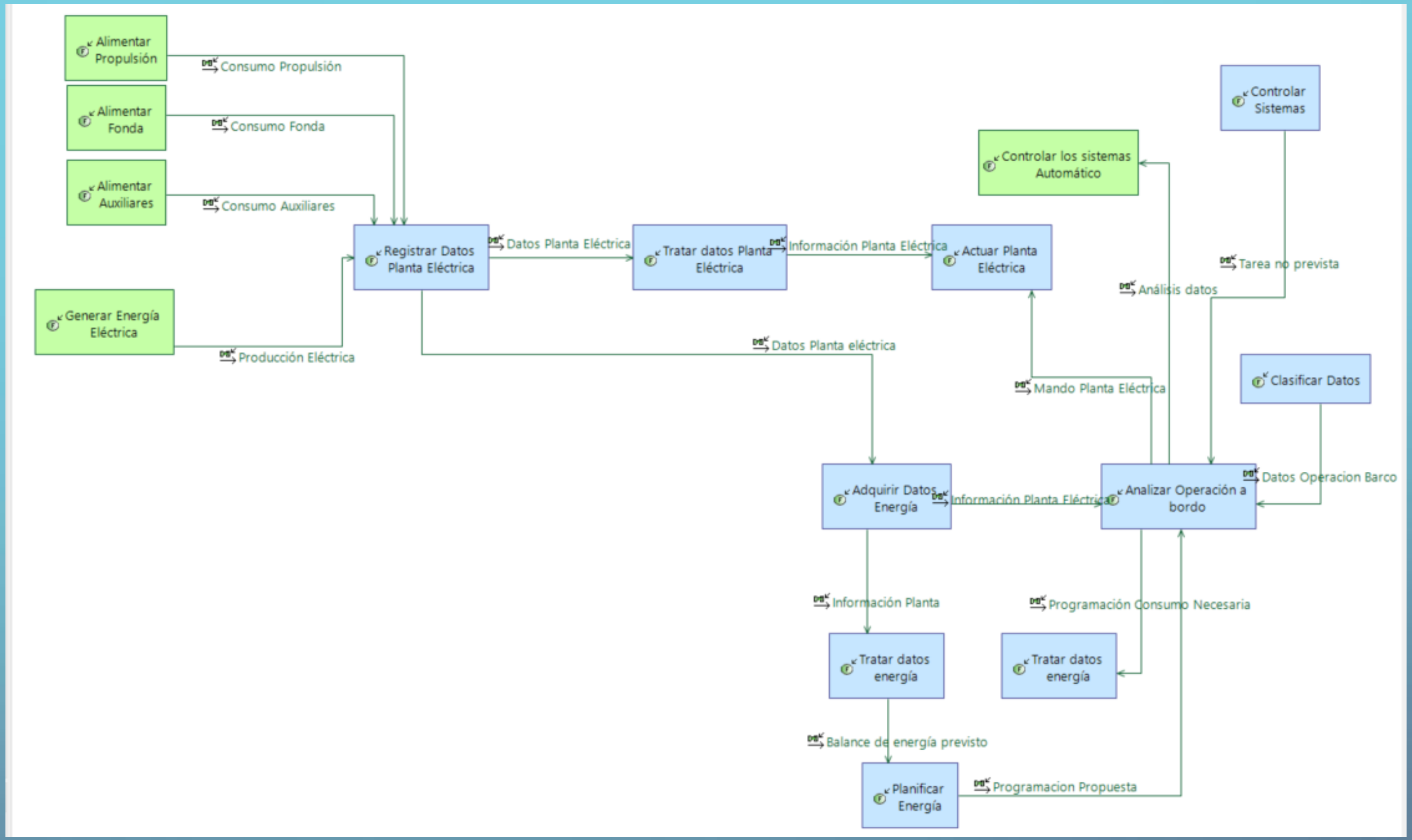


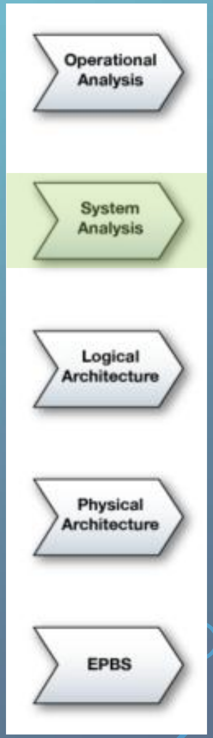
SHIP DESIGN. SYSTEM ANALYSIS



The system analysis starts designing the missions which are dimensioned by defining the parameters of the different capabilities, those capabilities are inherited from the operational analysis or new to cover design needs

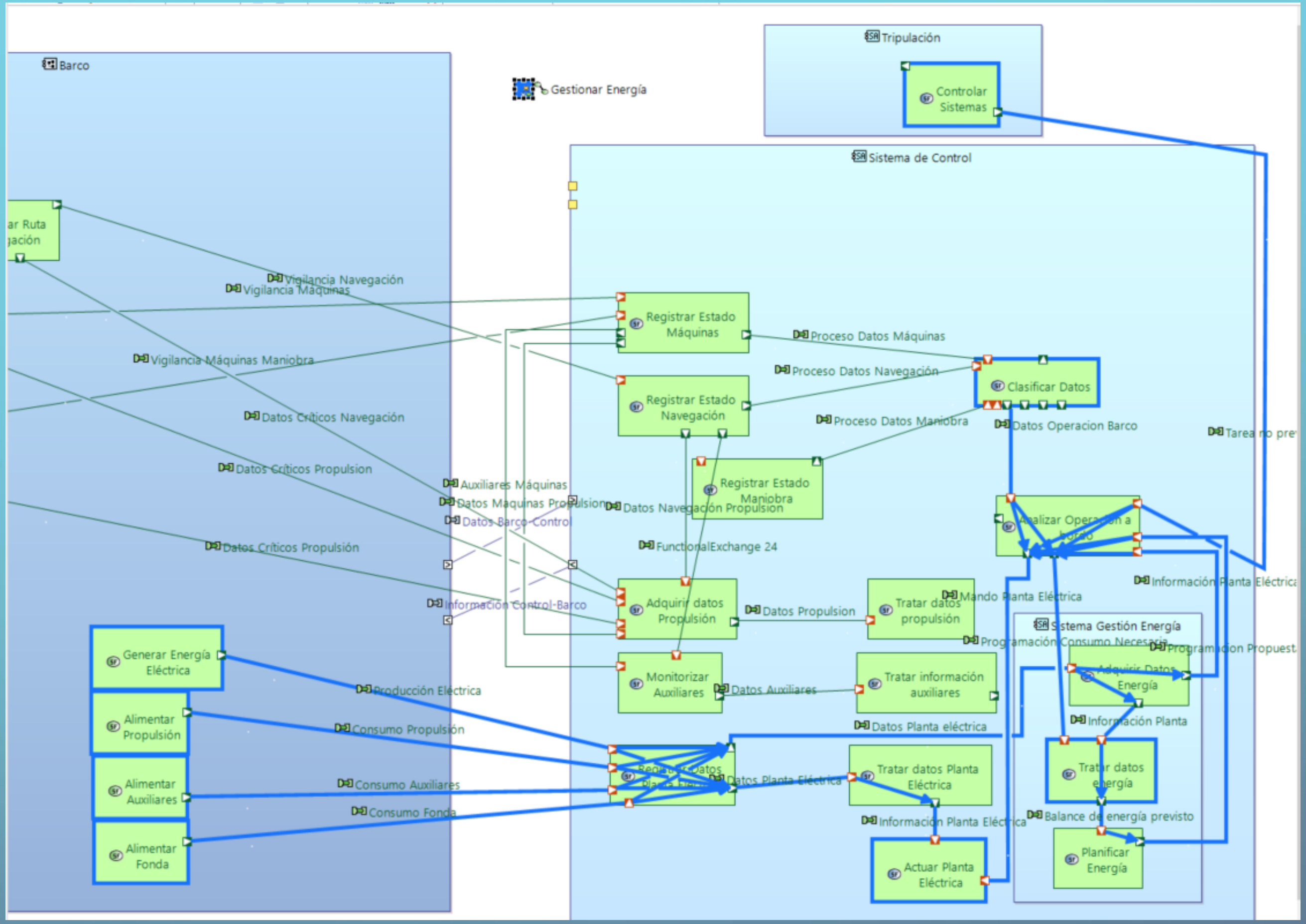
SHIP DESIGN. SYSTEM ANALYSIS

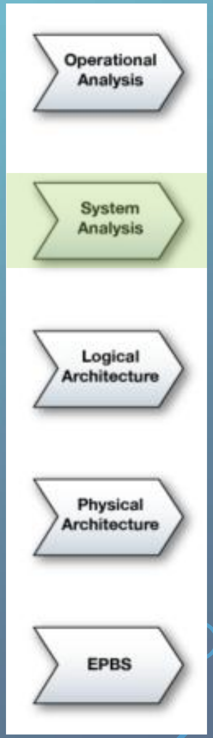




Each capability is broken down in functions and functional interchanges creating a functional chains that represents functional processes

SHIP DESIGN. SYSTEM ANALYSIS





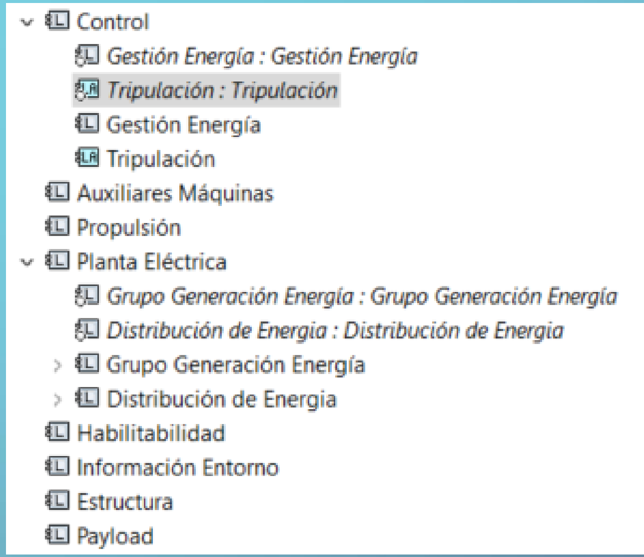
The functional chain is represented in a Functional Architecture Diagram including the functions, its interchanges and different actors involved.

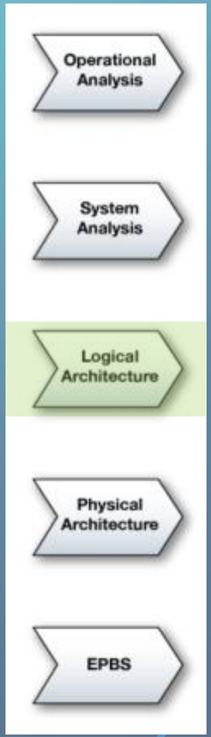
SHIP DESIGN. LOGICAL ARCHITECTURE

How will the system work to fulfill expectations?

Inputs:

- Functional Analysis
- Design domains
- Organizational, cost and other restrictions

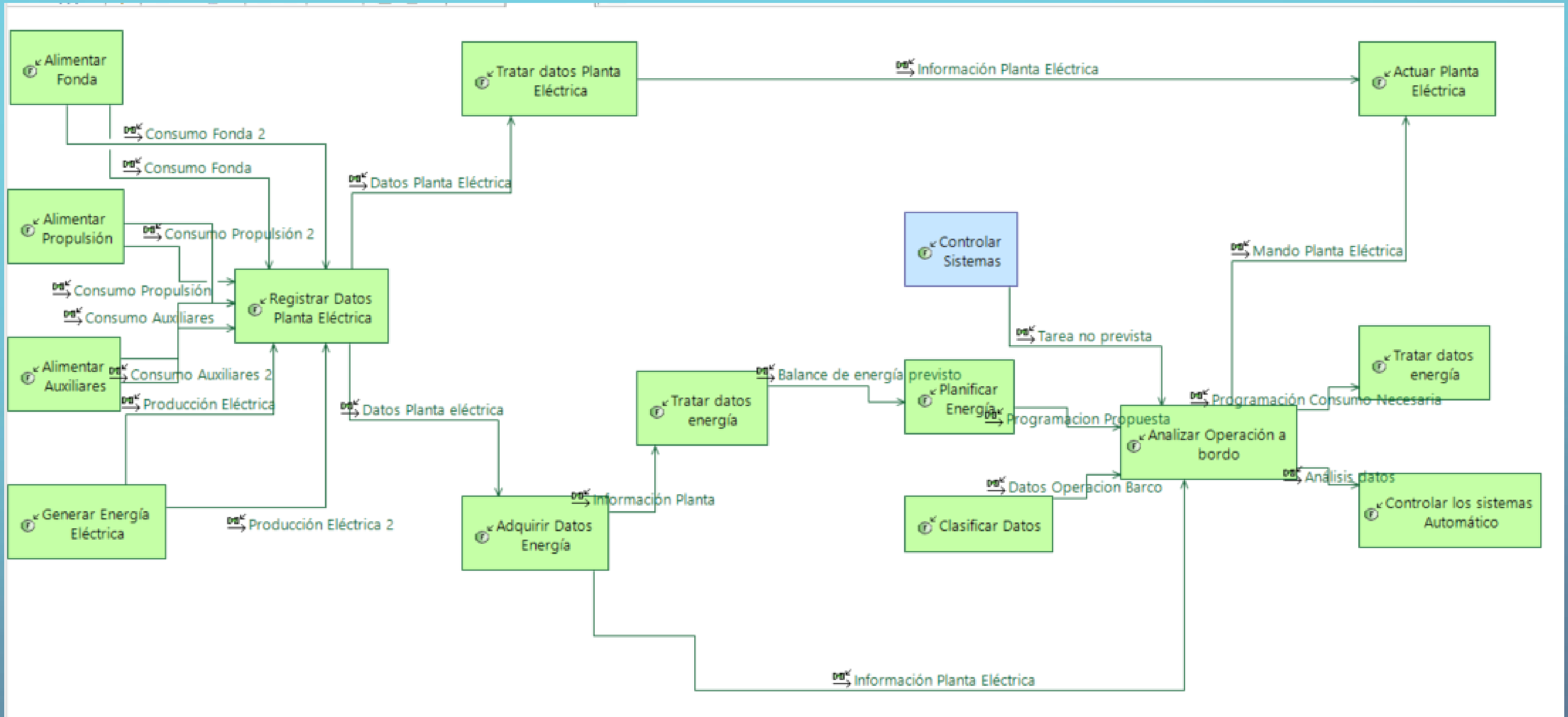


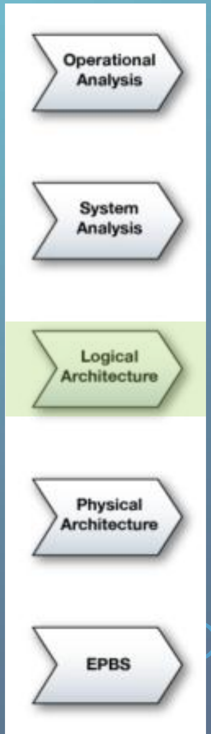


Outputs:

- High level breakdown of the system to allocate the functions of the system to manage its complexity (risks, engineering, design and development)
- Architecture and system preliminary validation against non-functional restrictions

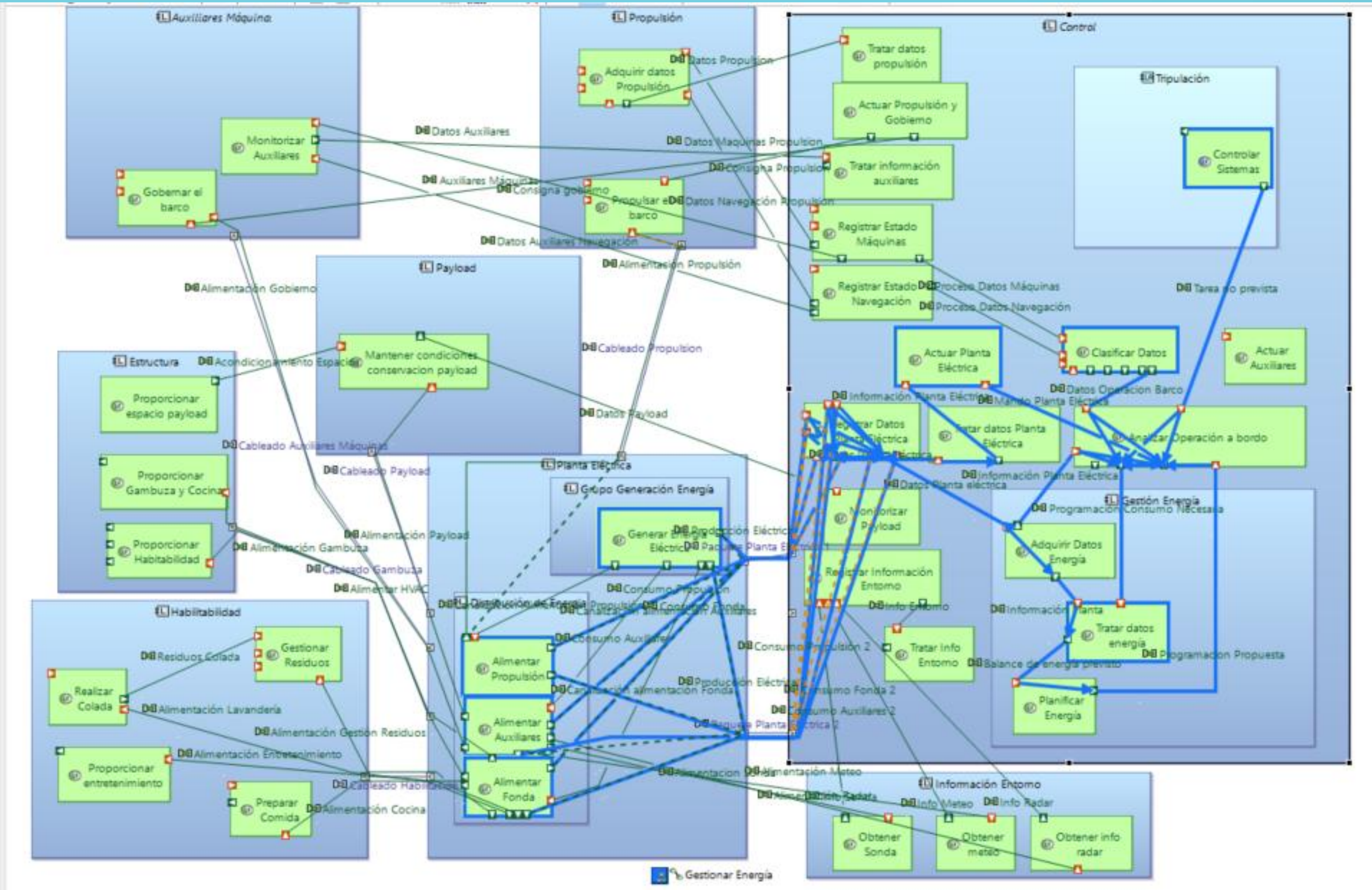
SHIP DESIGN. LOGICAL ARCHITECTURE

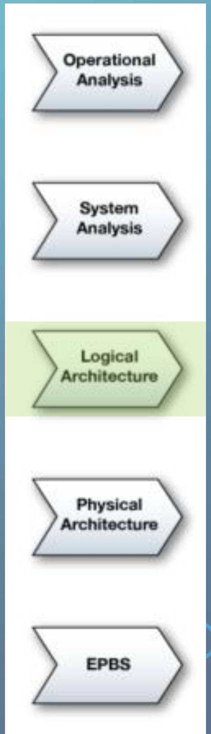




The functional process is represented in a Logical Functional Chain Description including the functions and its interchanges.

SHIP DESIGN. LOGICAL ARCHITECTURE





The functional chain is represented in a Logical Architecture Diagram including the functions, its interchanges, physical ports and different logical parts and actors involved.

SHIP DESIGN. PHYSICAL ARCHITECTURE

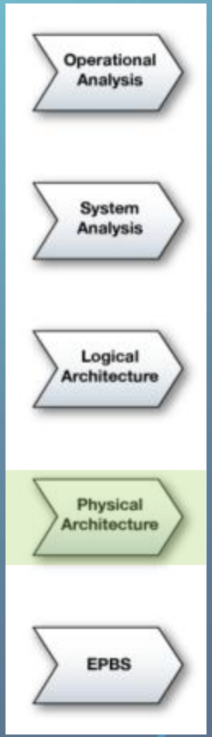
How will the system be developed and built?

Inputs:

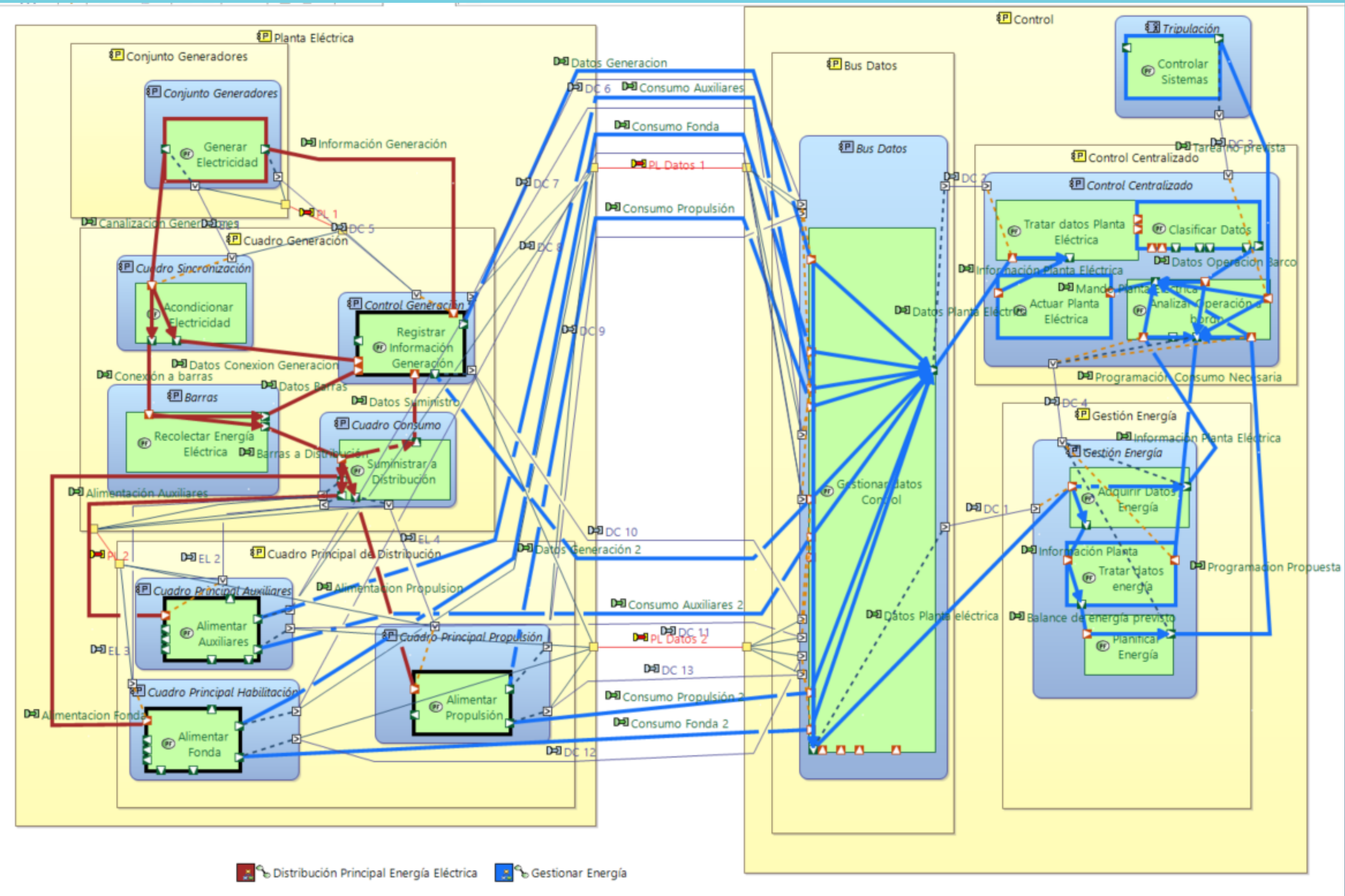
- Logical Architecture
- Existing designs
- Technical risks

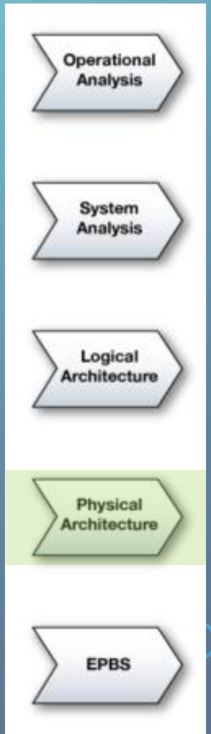
Outputs:

- Low level system breakdown to manage complexity, isolate risks and component development, and ease integration, verification and validation of the system
- Reuse of designs, products and assets
- Early design validation



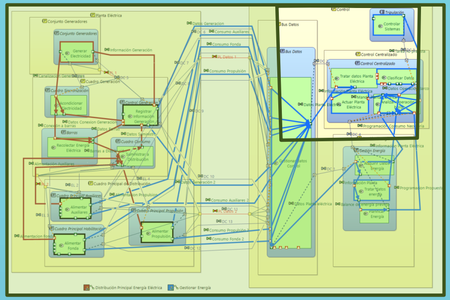
SHIP DESIGN. PHYSICAL ARCHITECTURE

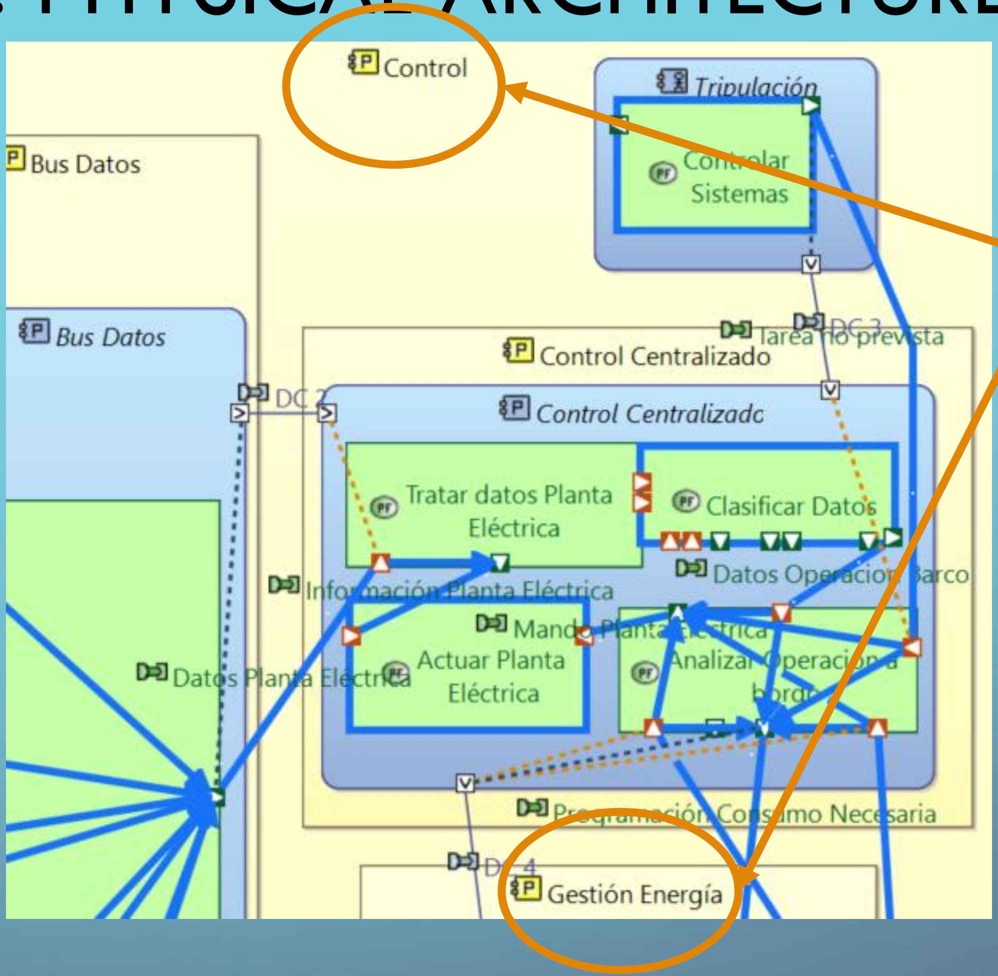




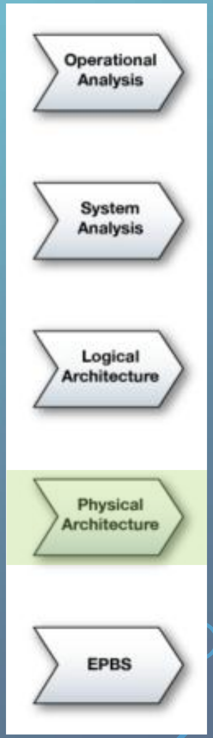
The functional process is represented in the Physical architecture by a Physical Functional Chain including the functions and its interchanges allocated to behavioral components and physical components.

SHIP DESIGN. PHYSICAL ARCHITECTURE



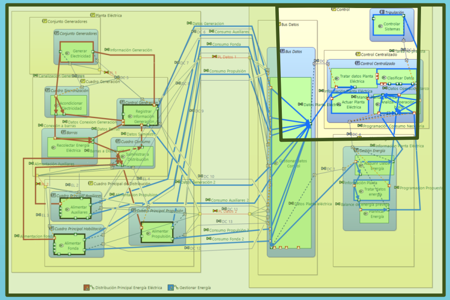


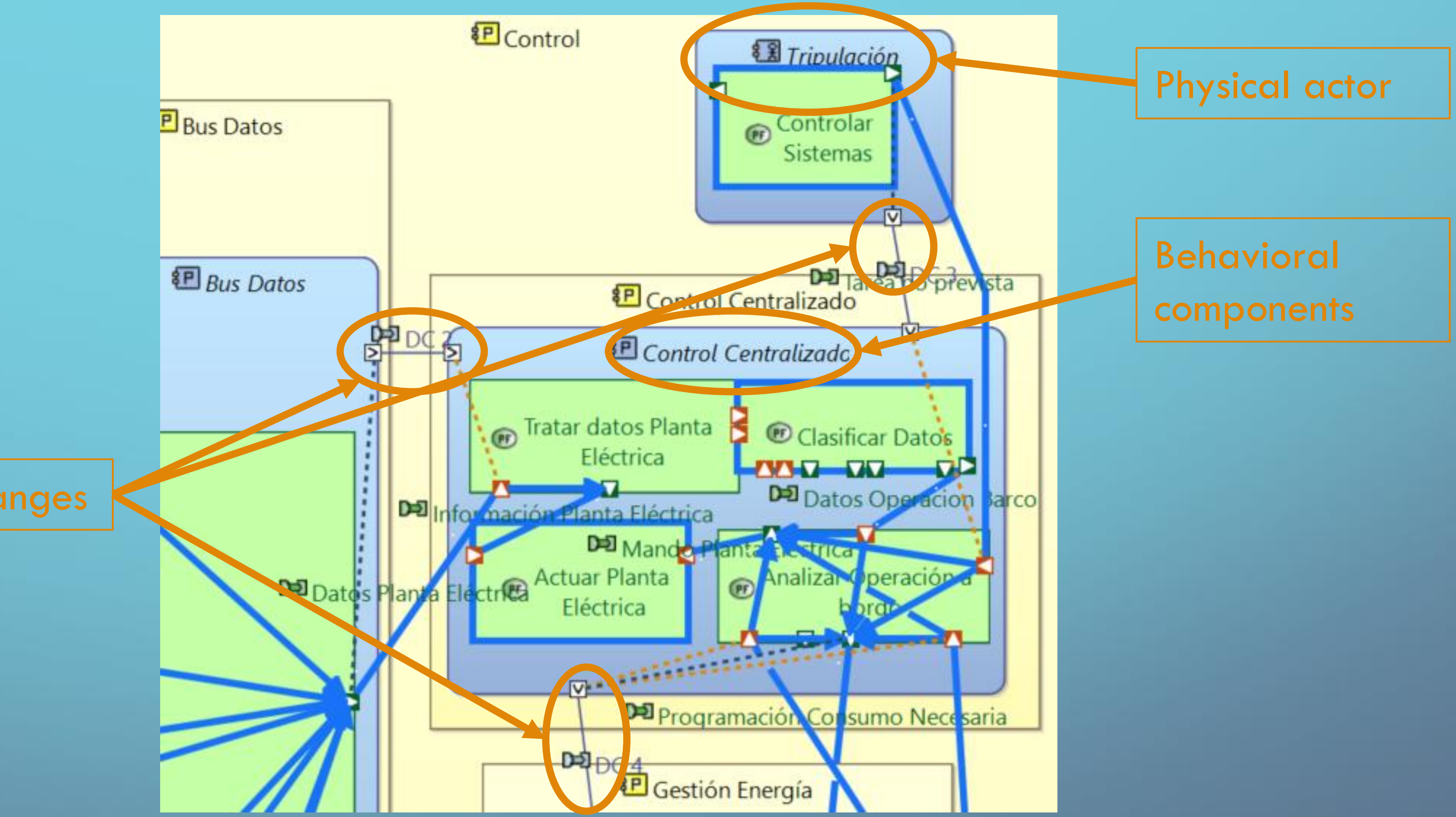
Physical components

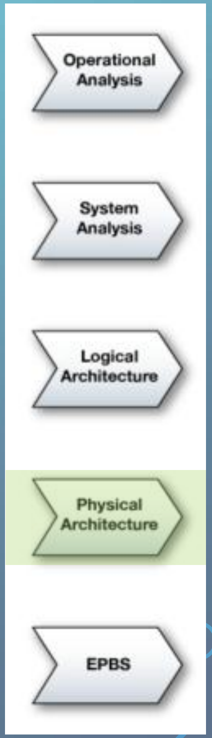


The physical components can be nested showing their integration in more complex components.

SHIP DESIGN. PHYSICAL ARCHITECTURE

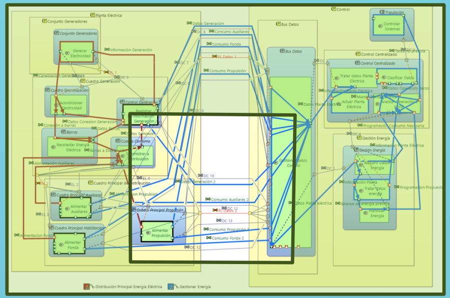


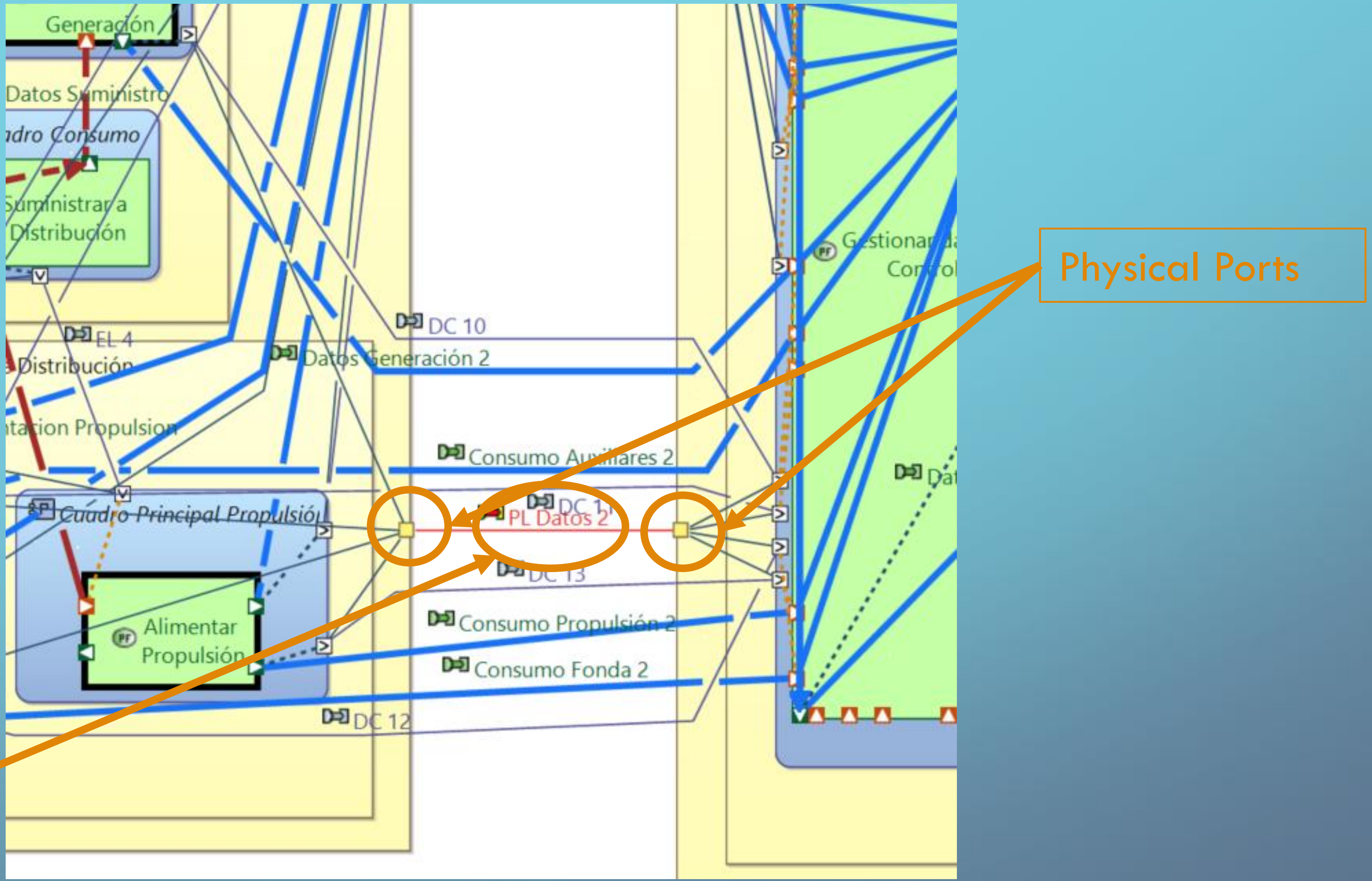


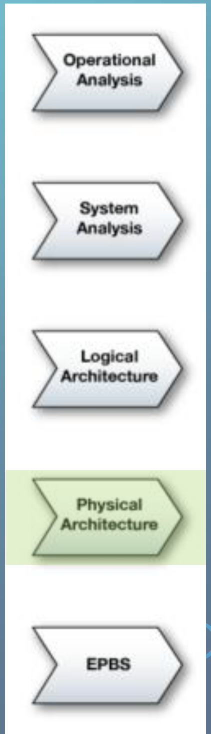


The physical actors and behavioral components will be the simulation components to be created, to deliver the required output from the allocated functions through the functional exchanges, the functional exchanges are gathered in component exchanges which are the interfaces collection between components.

SHIP DESIGN. PHYSICAL ARCHITECTURE







The physical ports allocated to physical components are the representation of the physical interfaces of the components, the connections between physical ports are the components that transfer the allocated interchanges between the components (piping, cables, mechanical).

SHIP MODEL ARTIFACTS SUMMARY

Arcadia layer	Requirements	Capability	Capability description	Functional	Structure	Modes and States	Data	Interfaces
Operational Analysis	R-OA Capture stakeholder requirements	OA1 Define Operational Capabilities	OA2 Define processes and scenarios	OA3 Define Operational Activities and interactions	OA4 Capture Operational Entities and Actors. Allocate Operational Activities to Operational Actors, Entities	M&S-OA5 Define operational modes and states	D-OA6 Define operational data model	I-OA7 Define interfaces and describe interfaces scenarios
System Analysis	R-SA Derive Stakeholder requirements and capture System requirements	SA1 Define System Missions and System Capabilities	SA2 Define Functional Chains and Scenarios.	SA3 Define System Functions. Define Functional Exchanges and components	SA4 Allocate System Functions to System and Actors	M&S-SA5 Define system modes and states	D-SA6 Define system data model	I-SA7 Define interfaces and describe interfaces scenarios Enrich Logical Scenarios.
Logical Architecture	R-LA Derive system requirements and Capture components requirements	LA1 Transition Capabilities Realization from system layer	LA2 Define Functional Chains and scenarios	LA3 Derive System Functions and define Logical Functions. Define Functional Exchanges and components.	LA4 Allocate Logical Functions to Logical Components	M&S-LA5 Define logical components modes and states	D-LA6 Define logical data model	I-LA7 Delegate System Interfaces and create Logical Interfaces. Enrich Logical Scenarios.
Physical Architecture	R-PA Derive logical requirements and capture physical requirements	PA1 Transition Capabilities Realization from logical layer	PA2 Define Functional Chains, Scenarios, and Physical Path	PA3 Derive Logical Functions and define Physical Functions. Define Functional Exchanges and components.	PA4 Define Physical Nodes and refine Behavioural Physical Components. Allocate Behavioural Components.	M&S-PA5 Define physical nodes modes and states	D-PA6 Define physical data model	I-PA7 Delegate Logical Interfaces and create Physical Interface. Enrich Physical Scenarios.

SHIP DESIGN. EXTENDED PHYSICAL ARCHITECTURE

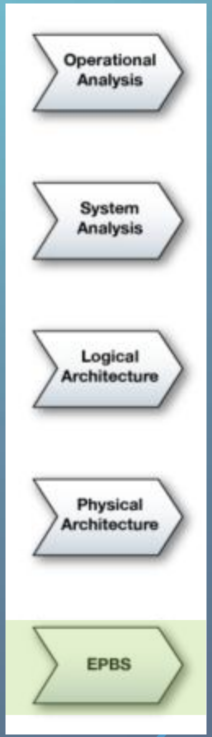
How will the system be procured and assembled?

Inputs:

- Physical Architecture
- Existing components specs (COTS, MOTS, previous developments)
- Technical risks
- Industrial capabilities

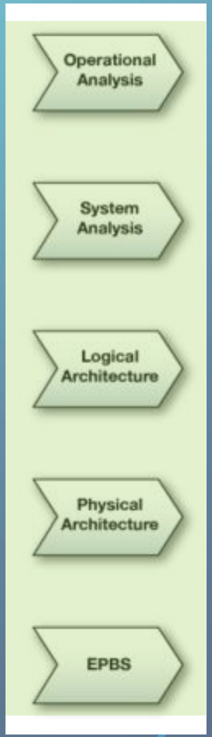
Outputs:

- Material selection to spec for the different components
- System Analysis (purchase specification) for the components to be developed
- Verification, validation and qualification plan
- Building strategy



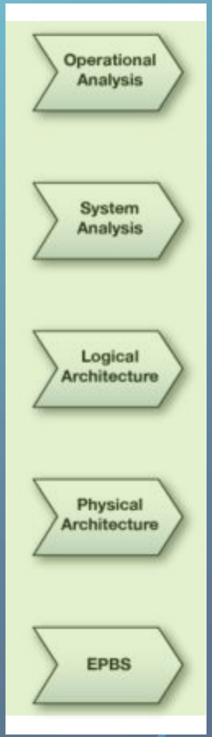
SHIP EXTENDED PHYSICAL ARCHITECTURE FEATURES

- Ship bill of materials
- Ship functions breakdown at component level
- Interfaces between the components and functions trough mass flow, energy flow, command and data interchanges
- Detailed simulation models breakdown through the behavioral components and simulation parameters through the interchange's values
- Traceability to mission capabilities



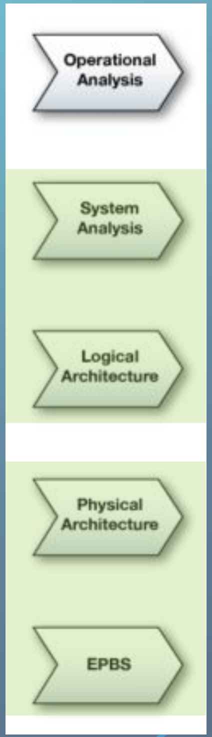
SHIP MODEL USES

- Design verification by simulation ✓
- Reuse of known components (COTS, MOTS, previous developments) ✓
- Design simulation model structure and parameters ✓
- Operation simulation model structure and parameters ✓
- Life cycle support simulation model structure and parameters ✗



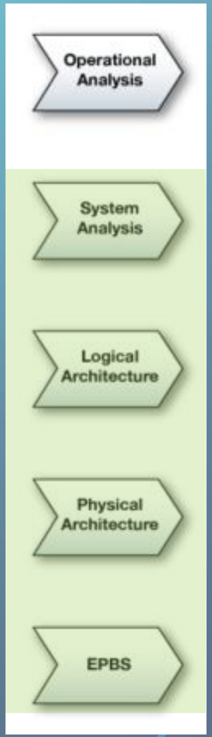
SHIP THROUGH LIFE SUPPORT MODEL

- Life cycle support model structure and parameters
  - The capability of monitoring and assessing the selected assets must be included
  - New functional chains must be included in the analysis
  - New physical components must be included in the system
  - New behavioral components must be included in the system
  - New "Support" Ship Breakdown Structure as a consequence of adding asset monitoring to the Ship Breakdown Structure
  - Reliability can be evaluated for each operational capability



SHIP THROUGH LIFE SUPPORT SIMULATION MODEL

- Life cycle support simulation model structure and parameters
  - Behavioral components are different to the design and operation ones, so simulation models are
  - Input and output parameters are different
  - A completely different simulation model is needed



THE ENERGY MANAGEMENT SYSTEM

DESIGN MODEL

- Operation architecture model (As designed)
- Identify design parameters

- Operation simulation model (As designed)
- Design parameters

OPERATION MODEL

- Operation architecture model (As maintained)
- Identify operation parameters

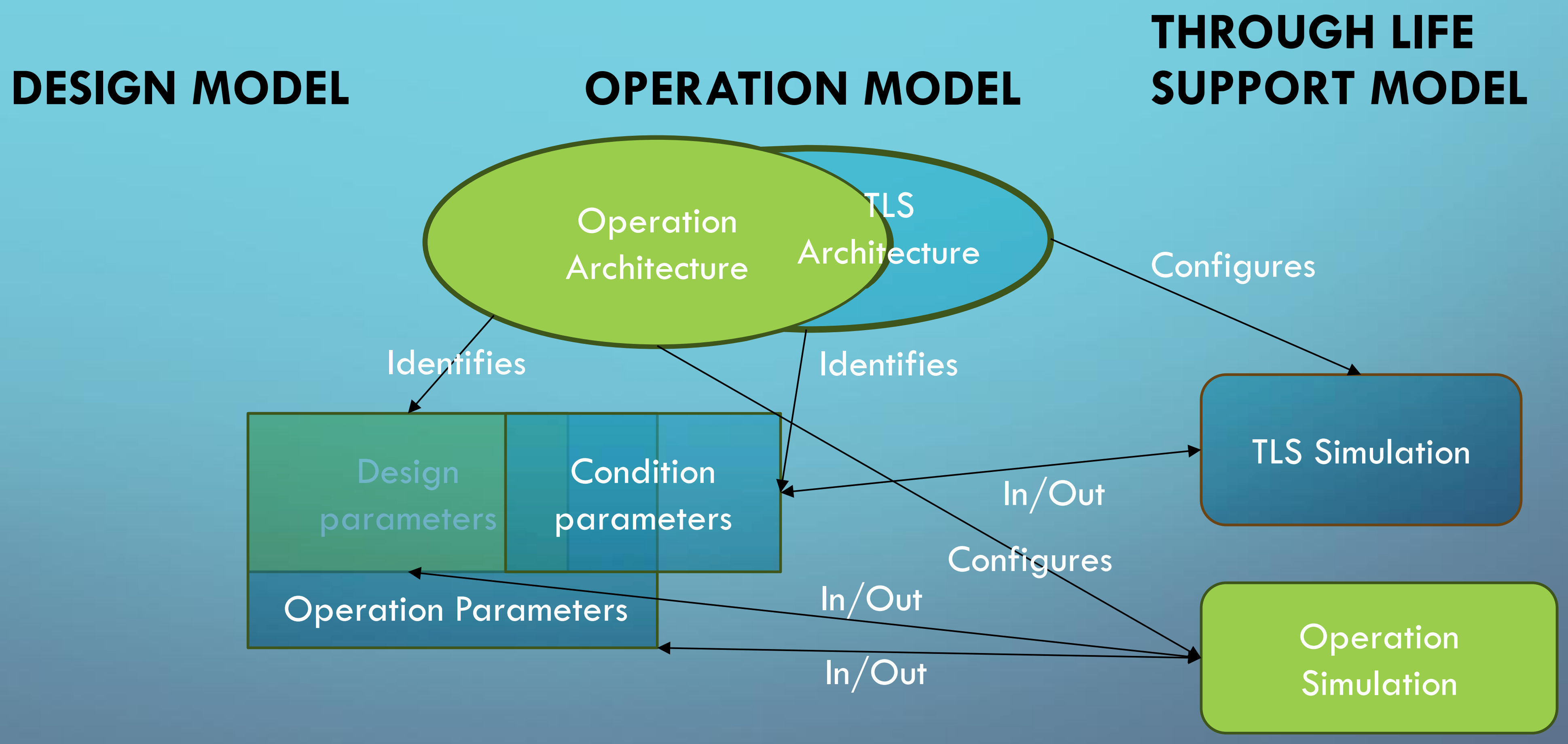
- Operation simulation model (As maintained)
- Operation parameters

THROUGH LIFE SUPPORT MODEL

- TLS architecture model (As maintained) derived from operation architecture model
- Identify operation parameters
- Identify asset condition parameters

- TLS simulation model (As maintained) new, not using operation simulation model
- Operation parameters
- Asset condition parameters

THE ENERGY MANAGEMENT SYSTEM



WHAT IS NEEDED TO USE MBSE?

- **MBSE** as a methodology to specify, design, build and operate ships that returns value by reusing it not only in the design but also in operation
- **Involvement** of all actors
- **Simulation** tools and models
- Dedicated **team** from concept to disposal

WHAT'S THE WAY FORWARD?

- Create a standard **framework** for ship MBSE

- **Involvement** of all parties:
  - Shipowners model specifying
  - Design organizations model engineering and designing
  - Supply chain providing operation and through life support models
  - Shipbuilders by including seamlessly model information

- Sufficient knowledge in components performance as a function of the operation and health parameters to build **model libraries**
- Train and maintain a dedicated **team** to support model from concept to disposal

WHAT'S THE EXPECTED OUTCOME?

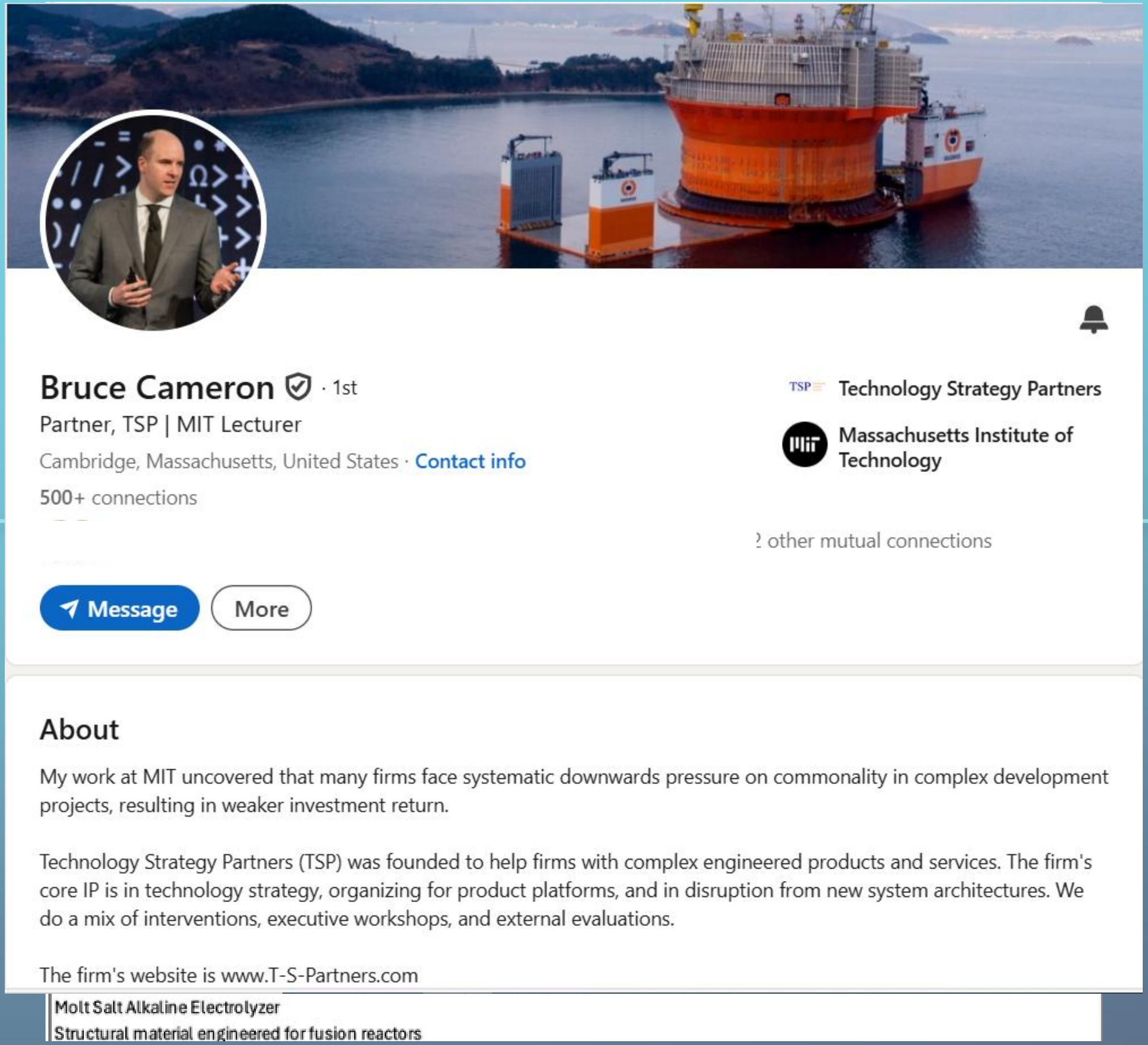
- Single and **shared** source of information

- **Reuse** of previous engineering and design

- More **efficient** acquisition, design, procuring, building and operation of ships

- The real **DIGITAL TWIN**

WHY SHOULD WE BE DEVELOPING MBSE?



WHY SHOULD WE BE DEVELOPING MBSE?

Digital twins and machine learning in nanofabrication	
(CAD) Processes for Modular Construction for Prefabricated Wood Components	
AI and MBSE tools in ship design and build	AI in Design and Fabrication
Nonlinear wave-ice interactions and machine learning (ML) for ship hull design	
Next generation AI models applied to CAD synthesis and optimization	

MBSE FOR SHIP DESIGN AND BUILDING IS IN THE AGENDA OF MIT

Through its SDM Program (Systems Design and Management) the MIT is to develop the MBSE tools for ship design and build as a key feature in 2025.

THANK YOU!!