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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 952966.

A Digital Twin-based Structural Health Monitoring for Offshore Wind Platforms

Joint Research Unit: CIMNE-UPM

Borja Serván Camas
Julio García Espinosa

Industrial day
Madrid, 18/05/2024

Joint Research Unit CIMNE-UPM

CEHINAV UPM — CIMNE EXCELENCIA SEVERO OCHOA — in cooperation with COMPASS

- Created on 3/8/2021 (strategic collaboration agreement ETSIN-UPM and CIMNE)
- One of the main research groups in naval and offshore engineering in Spain:
  - Team of 23 researchers (naval, civil & offshore engineers, including 4 full professors).
  - Large research experience (more than 25 national, European and international projects and 60 contracts with industry in the last 10 years).
  - CEHINAV Experimental facilities (model basin, dynamics in waves lab, anti-roll lab …).
- Capabilities / Experience:
  - Hydrodynamics tests (towing, decay, anti-roll, heave plates, …) + CFD.
  - Structural design and assessment + innovative materials solutions.
  - Development of innovative computational analysis tools.
  - Development of digital twins.
  - Model and design of marine operations.
  - Internet of Things (IoT) for the naval & offshore industry.
  - Data-management and prediction with ML and AI techniques.

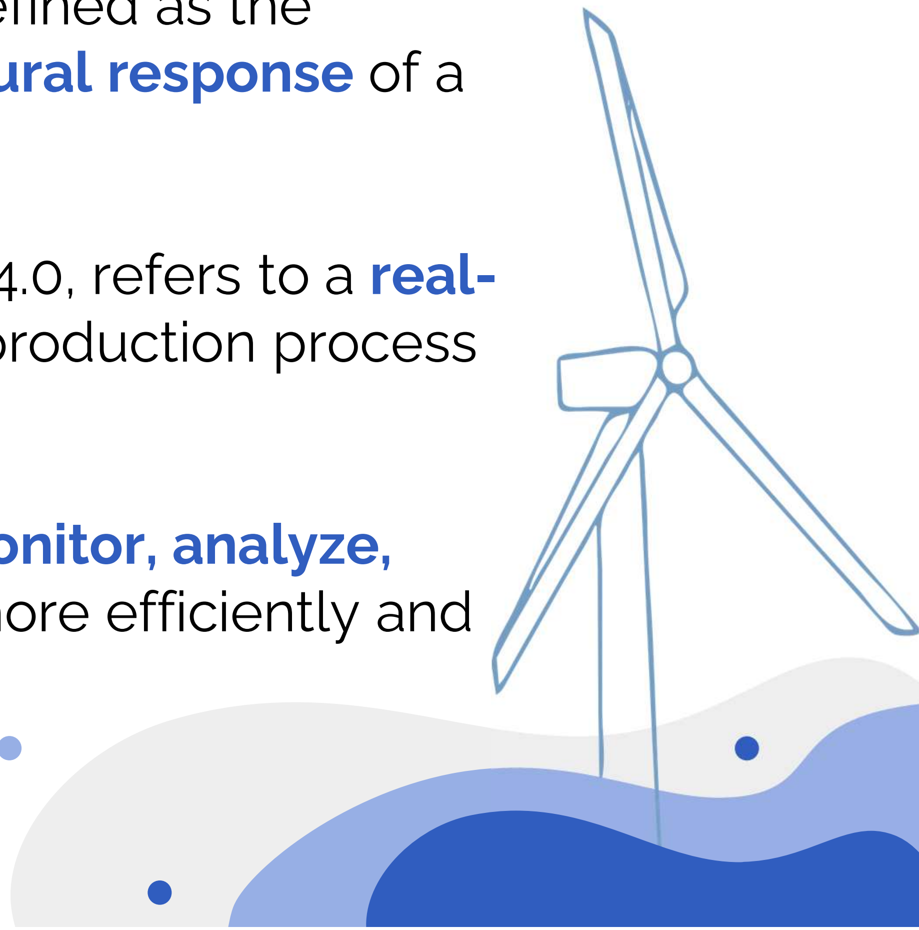
Table of contents

Why digital twin-based SHM?

- Structural Health Monitoring (**SHM**) can be defined as the periodical **monitoring and analysis of structural response** of a structure.

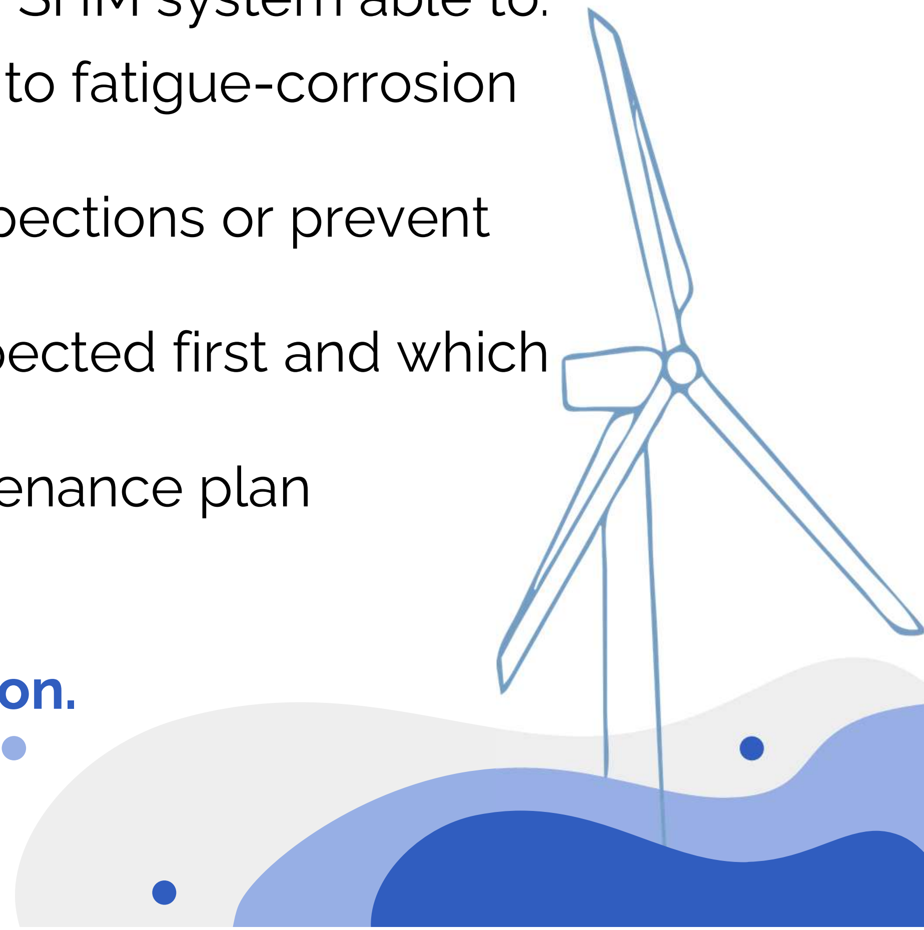
- A digital twin (**DT**) , in the context of Industry 4.0, refers to a **real-time virtual replica** of an object, system, or production process from the physical world.

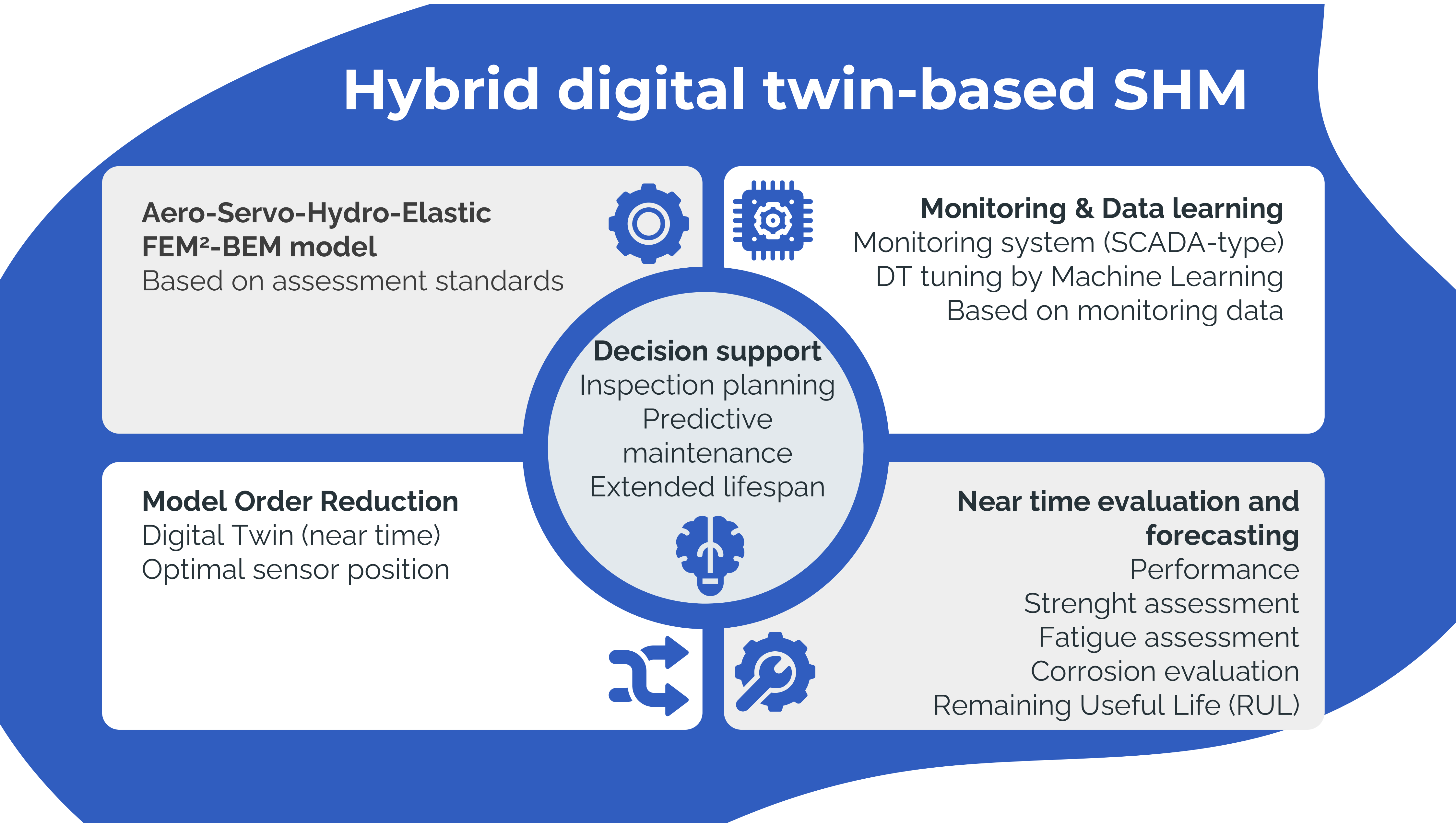
- The **primary purpose** of a digital twin is to **monitor, analyze, and optimize** its operations and processes more efficiently and effectively.



Why digital twin-based SHM?

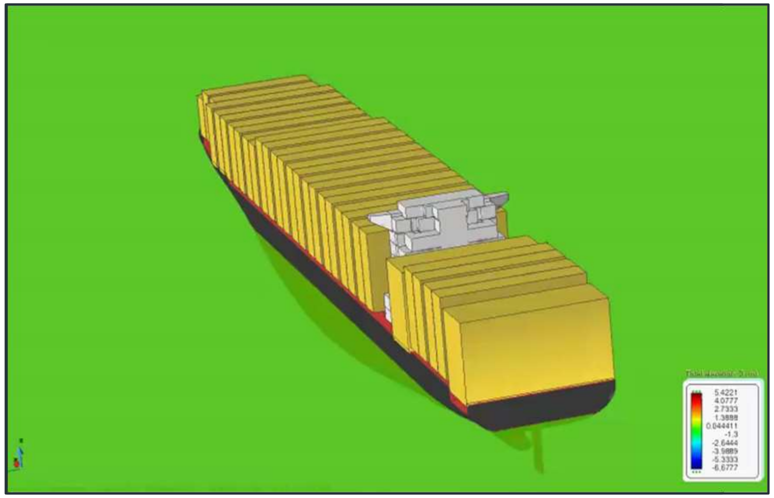
- We aimed at developing a digital twin-based SHM system able to:
  - evaluate remaining useful life (**RUL**) due to fatigue-corrosion of the structural components.
  - **prevent** expensive and unnecessary inspections or prevent too long inspection interval.
  - better **plan** which assets need to be inspected first and which can wait.
  - dynamically **adapt the inspection** maintenance plan (predictive maintenance).
  - support the **response** to severe events.
  - offer a reliable basis for **lifespan extension.**



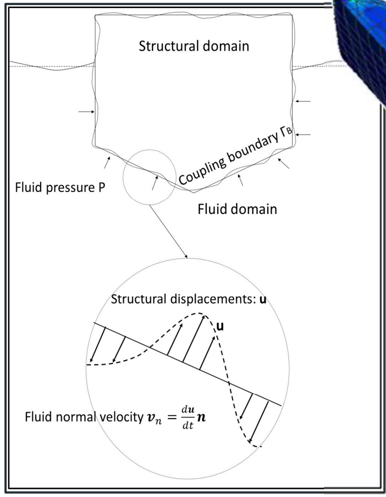

Hybrid digital twin-based SHM
Aero-Servo-Hydro-Elastic FEM²-BEM model
Based on assessment standards
Monitoring & Data learning
Monitoring system (SCADA-type)
DT tuning by Machine Learning
Based on monitoring data
Decision support
Inspection planning
Predictive maintenance
Extended lifespan
Model Order Reduction
Digital Twin (near time)
Optimal sensor position
Near time evaluation and forecasting
Performance
Strenght assessment
Fatigue assessment
Corrosion evaluation
Remaining Useful Life (RUL)

3D FEM Hydro-elastic model

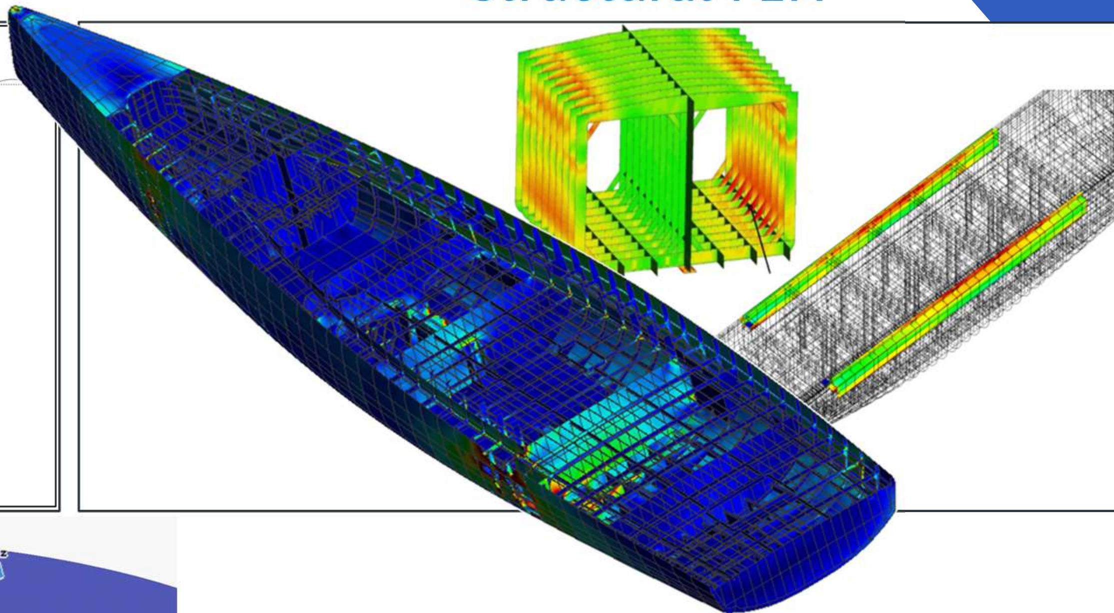
Seakeeping hydrodynamics

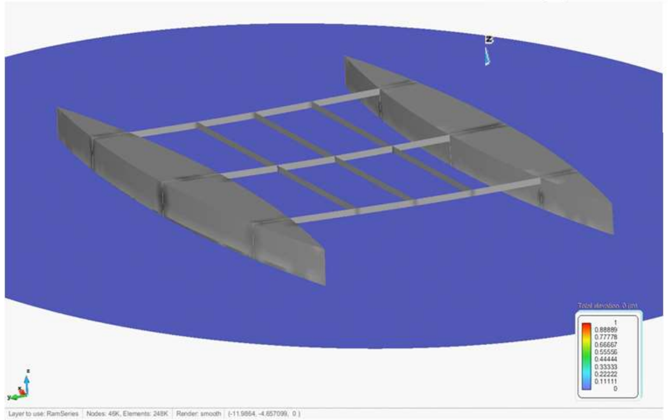


Coupling



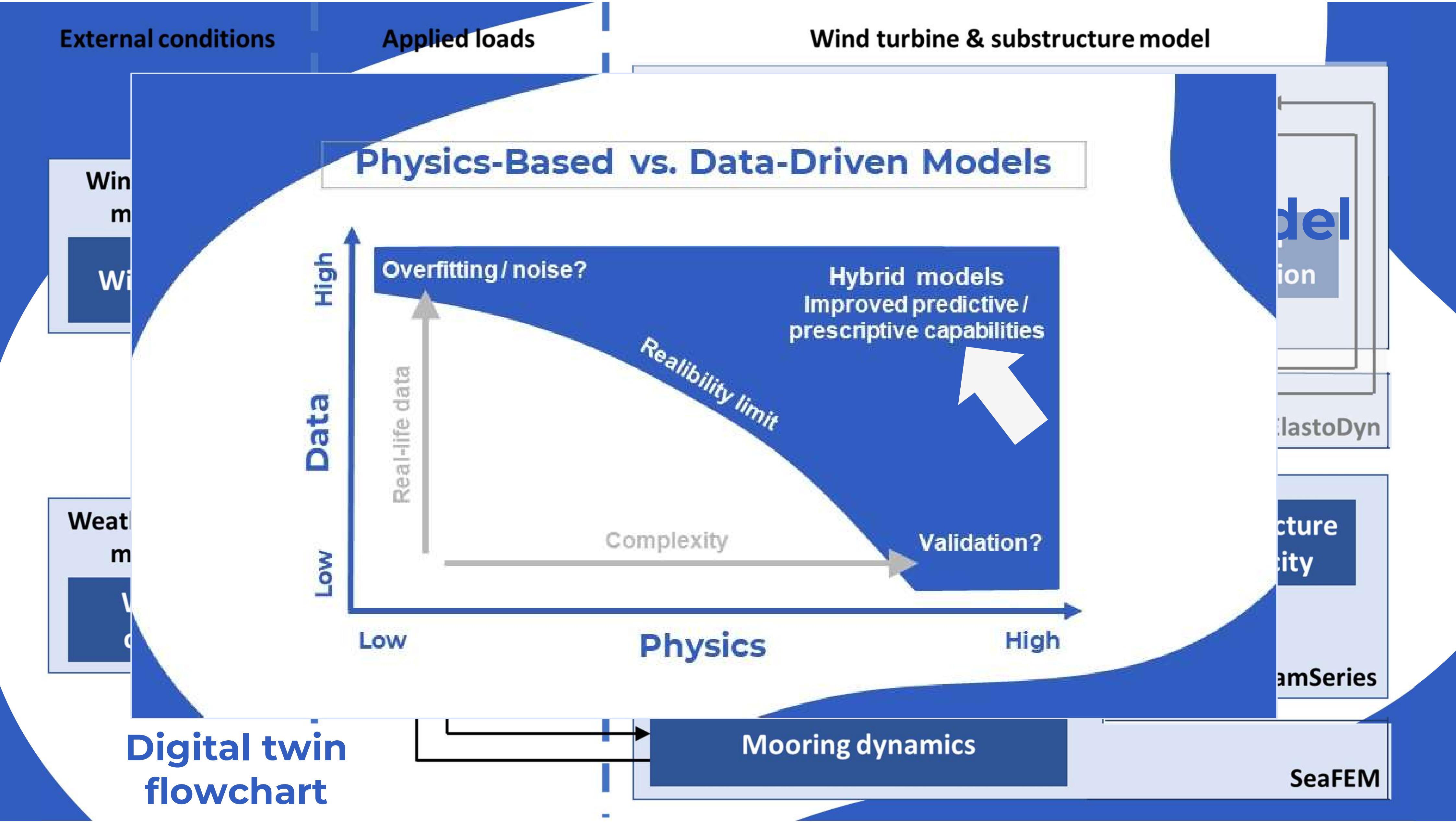
Structural FEM





Some 90% of computational time can be taken by solving the structural dynamics!!

Reference: *Servan-Camas et al. Fully 3D ship hydroelasticity: Monolithic versus partitioned strategies for tight coupling. Marine Structures 80 (2021) 103098*


External conditions
Applied loads
Wind turbine & substructure model
Physics-Based vs. Data-Driven Models
Overfitting / noise?
Hybrid models
Improved predictive / prescriptive capabilities
Realibility limit
Real-life data
Complexity
Validation?
High
Data
Low
Low
Physics
High
ElastoDyn
amSeries
Mooring dynamics
SeaFEM
Digital twin flowchart

Aero-servo-hydro-elastic ROM

COMPLEXITY AND CHALLENGES OF THE COMPUTATIONAL MODEL

- Multiphysics coupling among hydrodynamics, aerodynamics, mooring and structural dynamics.
- Requires time-domain dynamic analysis.
- Long computational times (not suitable for digital twin applications).
- Bottle neck: dynamic structural analysis.

STRUCTURAL REDUCED ORDER MODEL (ROM)

- Objective: Drastically reduce CPU times for dynamic structural analysis.
- Purpose: To be used for: digital twin, during structural design, and fatigue damage assessment.
- ROM: Projecting onto the modal base: Modal Matrix Reduction (MMR)

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{K}\mathbf{u} = 0 \equiv \left\{\boldsymbol{u}(t) = \boldsymbol{a}\,\mathrm{e}^{i\omega t}\right\} \equiv \left(\mathbf{M}^{-1}\mathbf{K}\right)\mathbf{a} = \omega^2\mathbf{a}$$

$$\boldsymbol{u}(\boldsymbol{x},t) = \sum_{i=1}^{m} q_{\mathrm{i}}(t)\cdot\boldsymbol{a}_{\mathrm{i}}(\boldsymbol{x}) \equiv \mathbf{u} = \mathbf{A}\mathbf{q}$$

$$\ddot{q}_i + 2\xi\omega_i\dot{q}_i + \omega_i^2 q_i = \frac{\boldsymbol{a}_{\mathrm{i}}(\boldsymbol{x})}{m_i}\mathbf{f}(x,t)$$

Reference: *García-Espinosa, J.; Serván-Camas, B.; Calpe-Linares, M. High Fidelity Hydroelastic Analysis Using Modal Matrix Reduction. J. Mar. Sci. Eng. 2023, 11, 1168. https://doi.org/10.3390/jmse11061168*

Aero-servo-hydro-elastic ROM

ADVANTAGES OF STRUCTURAL REDUCED ORDER MODEL (ROM)

1. Modal base is orthogonal: $\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\boldsymbol{u}} + \mathbf{Ku}$=F(t) $\quad \ddot{q}_i + 2\xi\omega_i\dot{q}_i + \omega_i^2 q_i = \frac{\mathbf{a}_i}{m_i}\mathbf{f}(t)$

Highly reduce the cost of solving the structural system of equations.

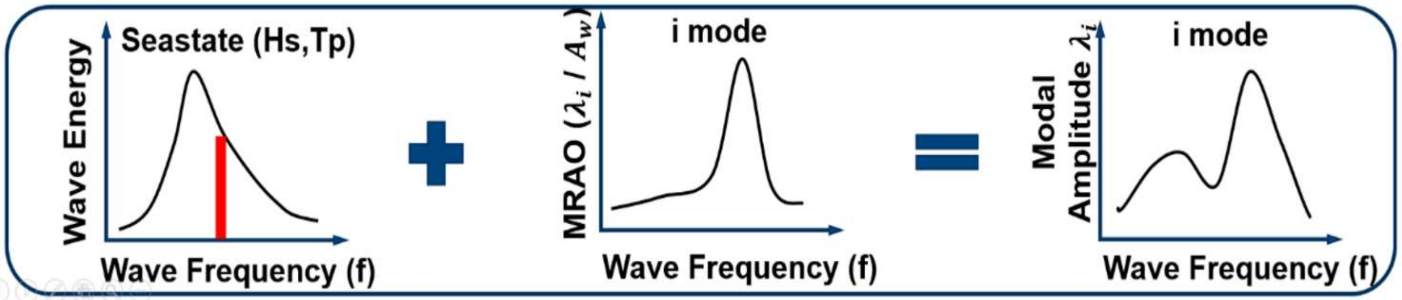
2. Neglect low energy modes: $\boldsymbol{u}(\boldsymbol{x},t) = \sum_{i=1}^{m} q_{\mathrm{i}}(t) \cdot \boldsymbol{a}_{\mathrm{i}}(\boldsymbol{x})$

Drastic reduction of degrees of freedom m<<N (O(100)-O(1000)).

Drastic reduction of computational cost (O(100)-O(1000)).

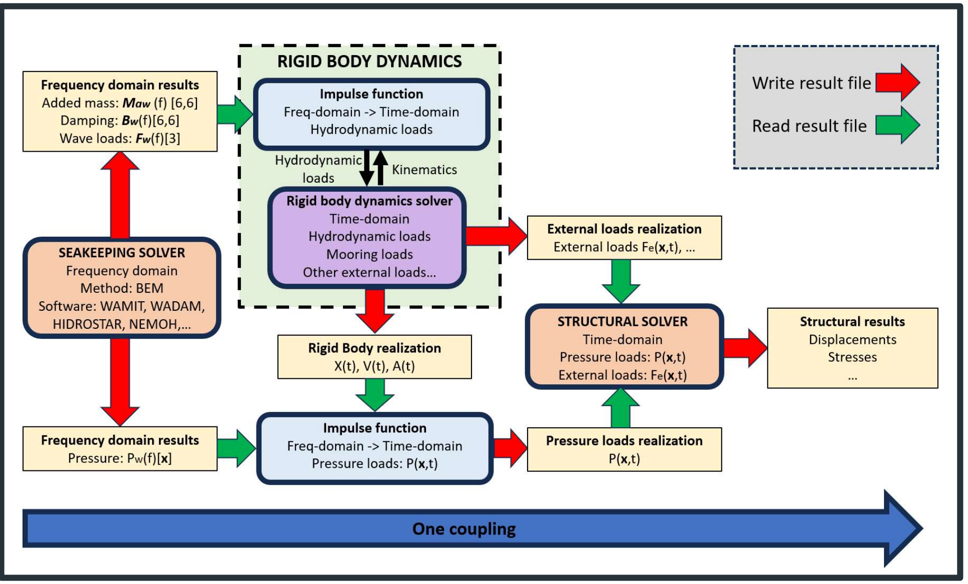
3. If external loads F(t) are linear (mooring, linear waves, …), then compute Modal Response Amplitude Operators (MRAOs).

- Offline MRAOs for single wind and wave loads.
- Fast reconstruction of dynamic analysis under irregular loads.
- Allows to compute a large number of loadcases: fatigue damage assessment, structural design optimization.
- Use in operational conditions: digital twin

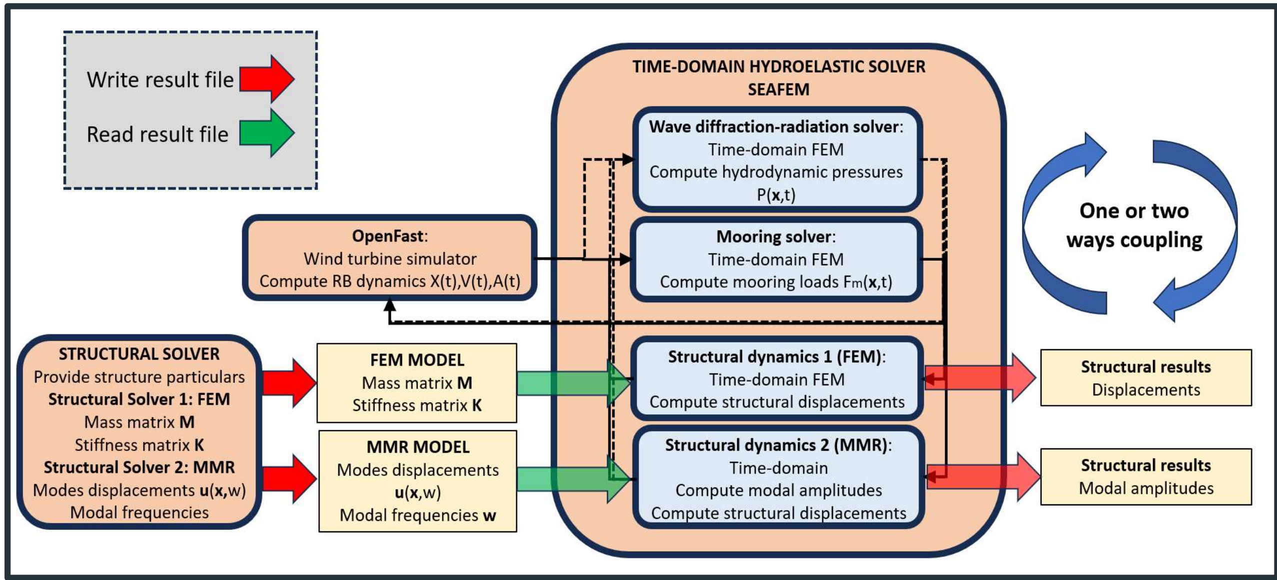


Aero-servo-hydro-elastic model

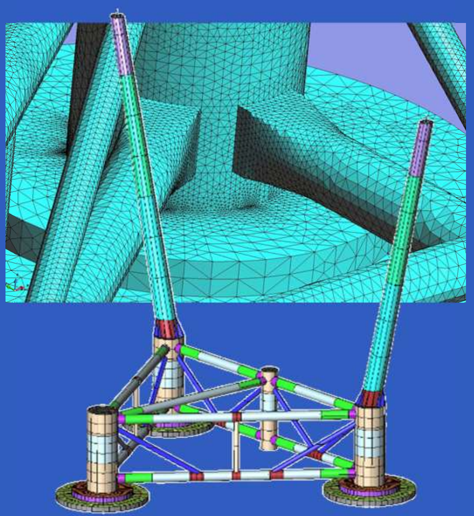
Coupling using conventional frequency domain seakeeping hydrodynamics



Coupling using SeaFEM framework



Aero-servo-hydro-elastic ROM



AERO-SERVO-HYDRO-ELASTIC FEM^2-BEM MODEL

X >1000
SIZE REDUCTION

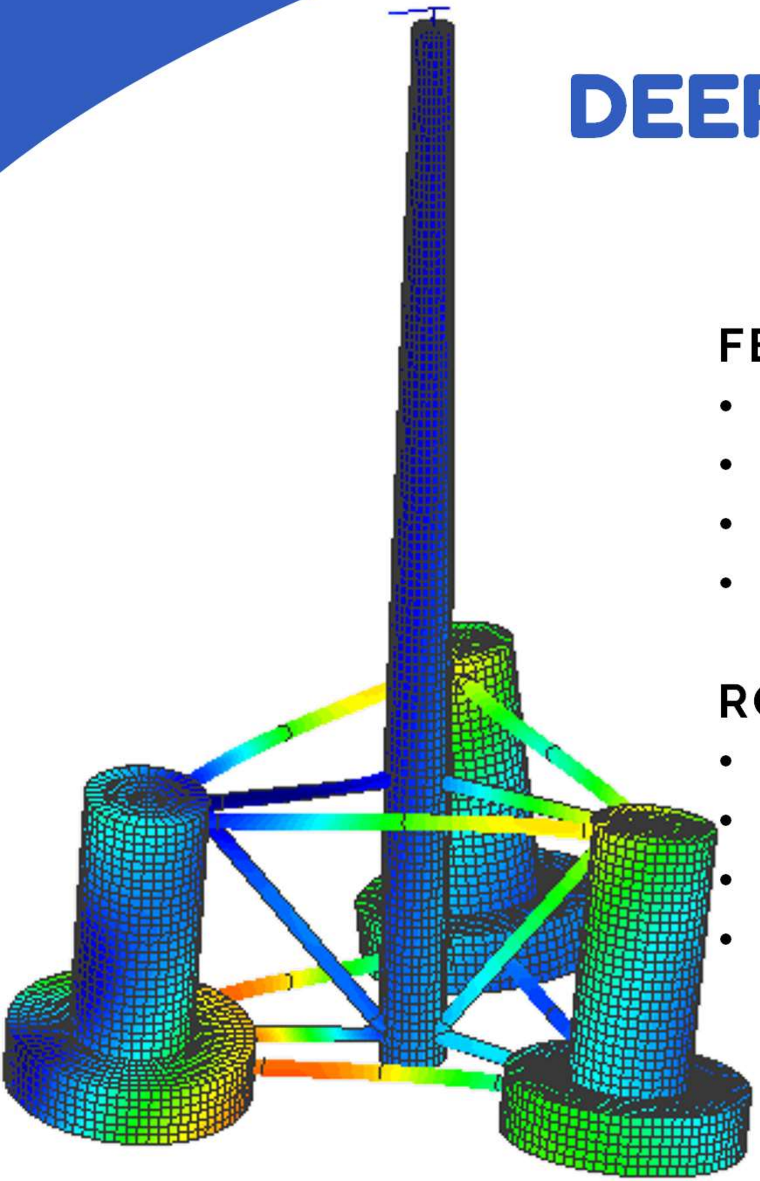
X >300
CPU TIME ACC.

10^{-4}
ACCURACY

MODEL ORDER REDUCTION (EMMR)

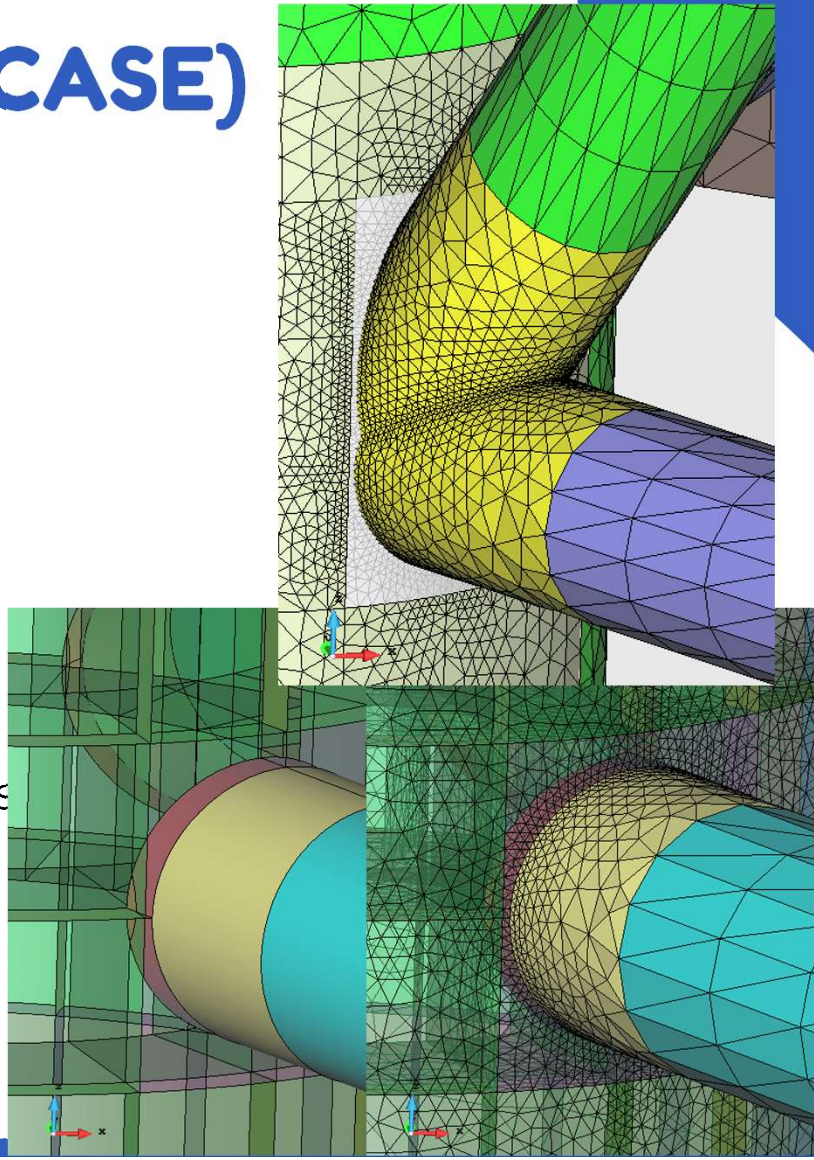
- Based on detailed 3D FEM model (2.5-5.0M dofs)
- Leading edge fully coupled hydro-elastic technology
- Linear and non-linear approach
- Near-real time for design & operation
- Structural and fatigue assessment (based on standards)
- Remaning Useful Life (evaluation and forecasting)

DEEPCWIND (SHOWCASE)

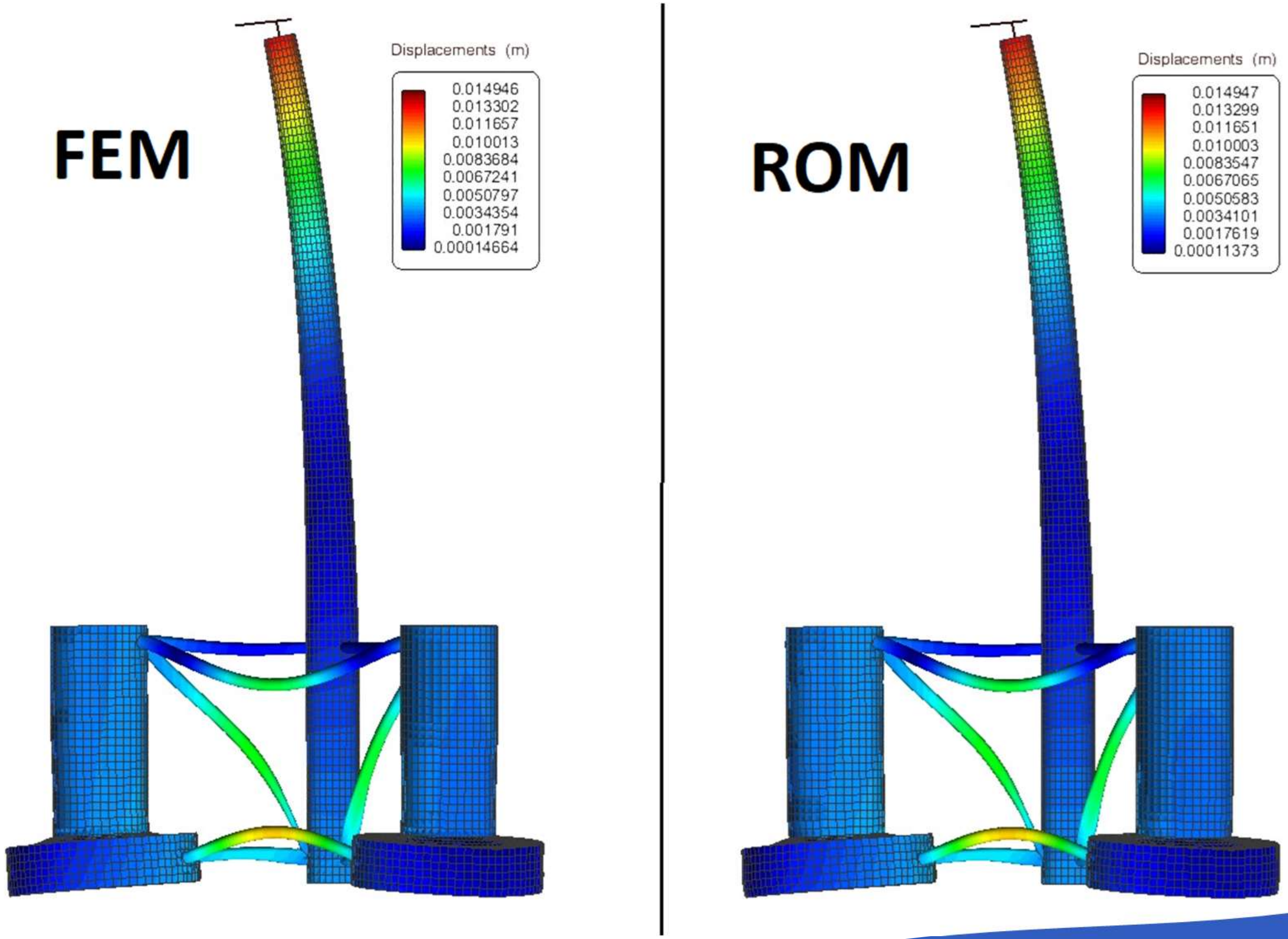


FEM Model:
- 0.72 M shell elements
- 1.2 M dofs
- 0.1s time step
- Computation time: 90s/s

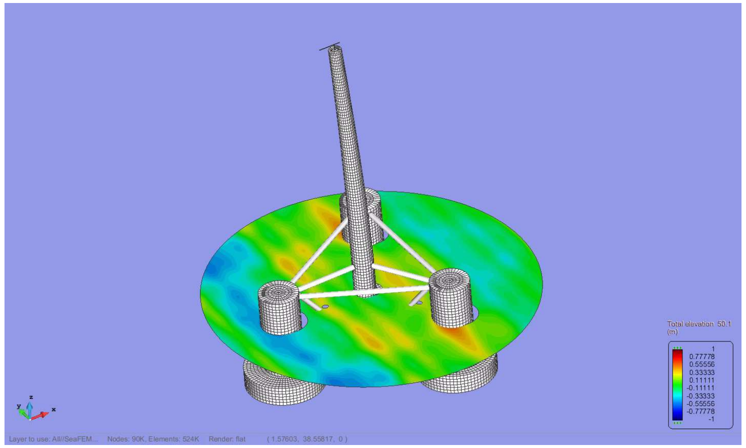
ROM Model:
- 1000 modes (dofs)
- 0.26Hz - 79Hz modal freqs
- 0.1s time step
- Computation time: 0.2s/s

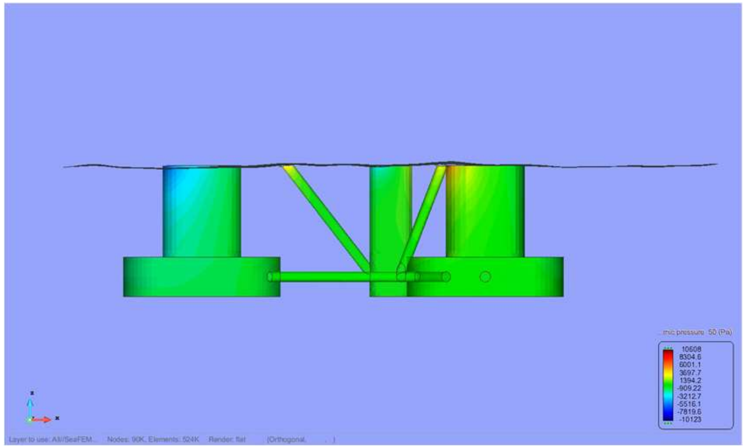


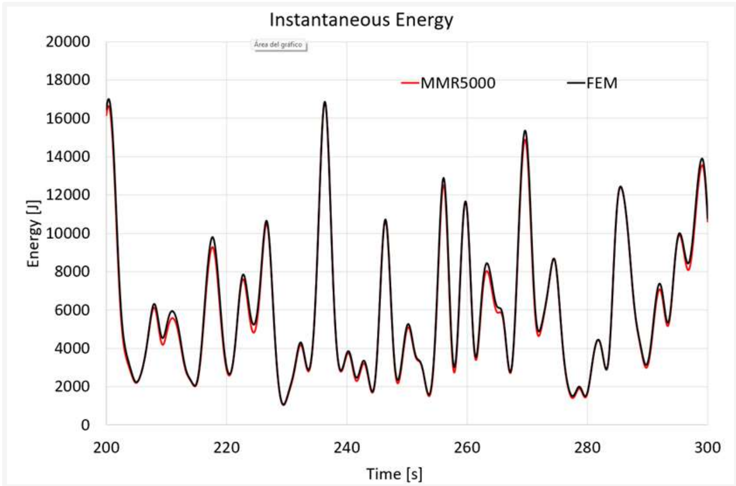
DEEPCWIND (SHOWCASE)

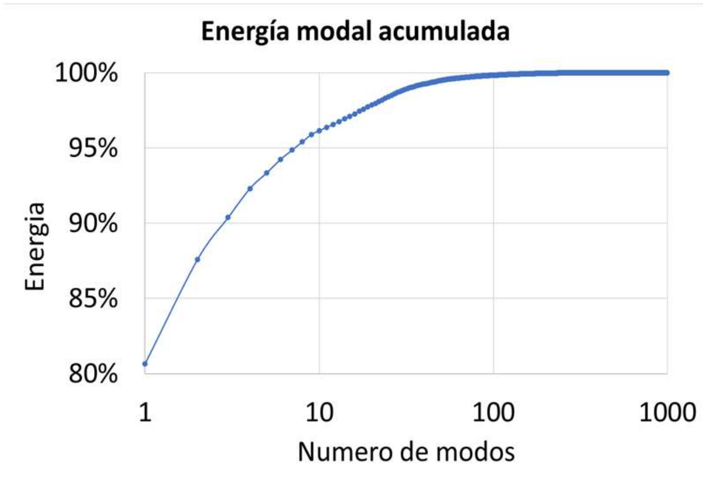


DEEPCWIND (SHOWCASE)

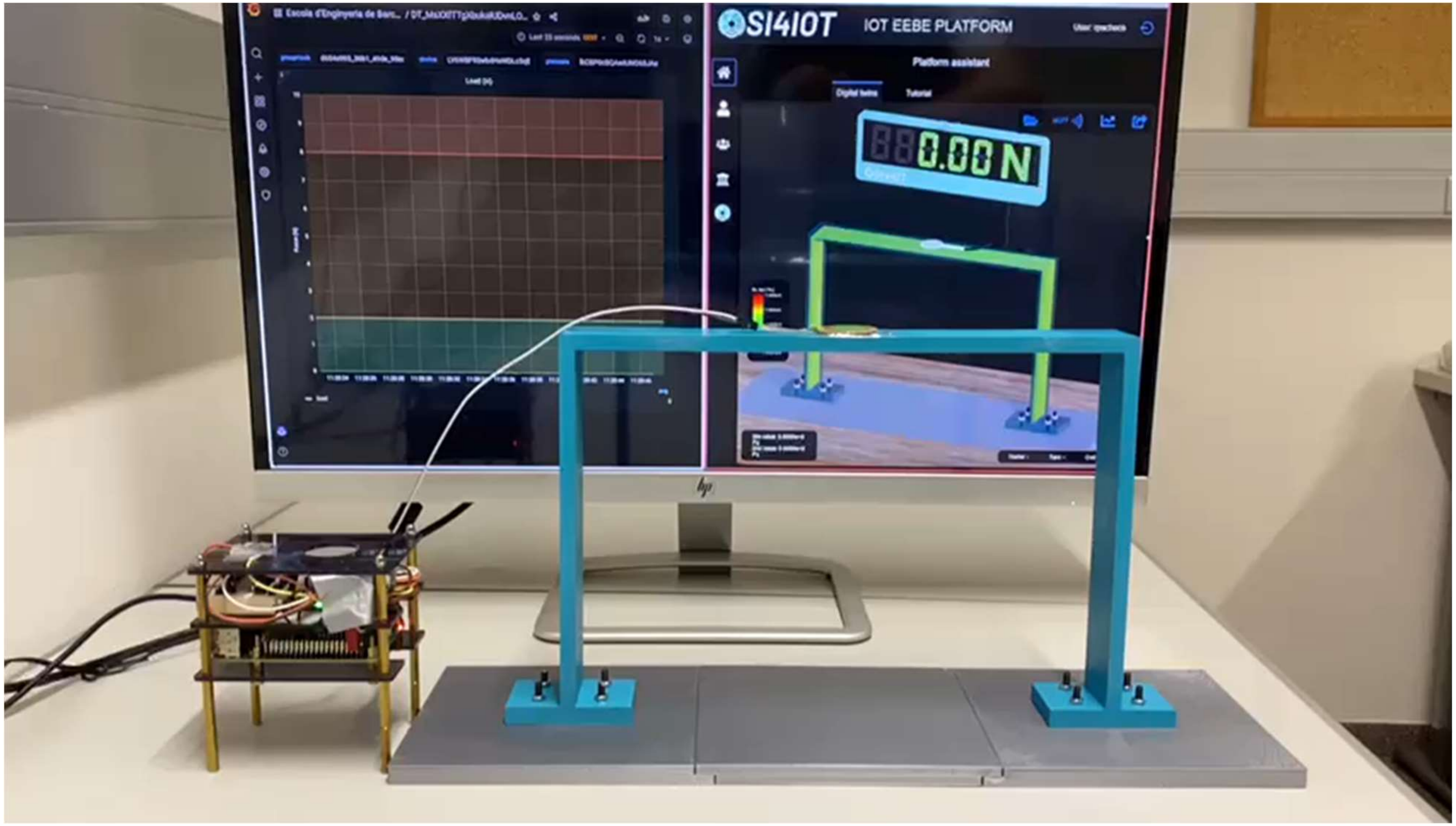








Digital Twin-based SHM Concept



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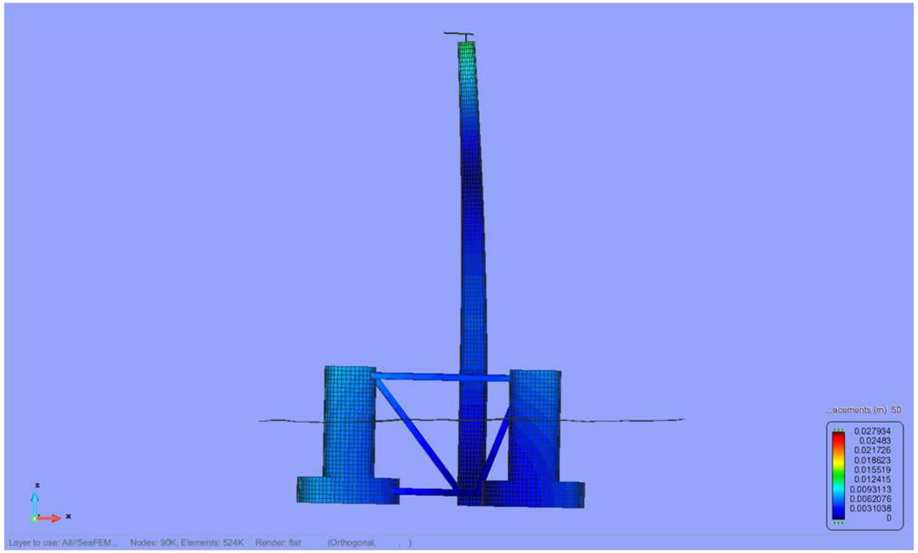
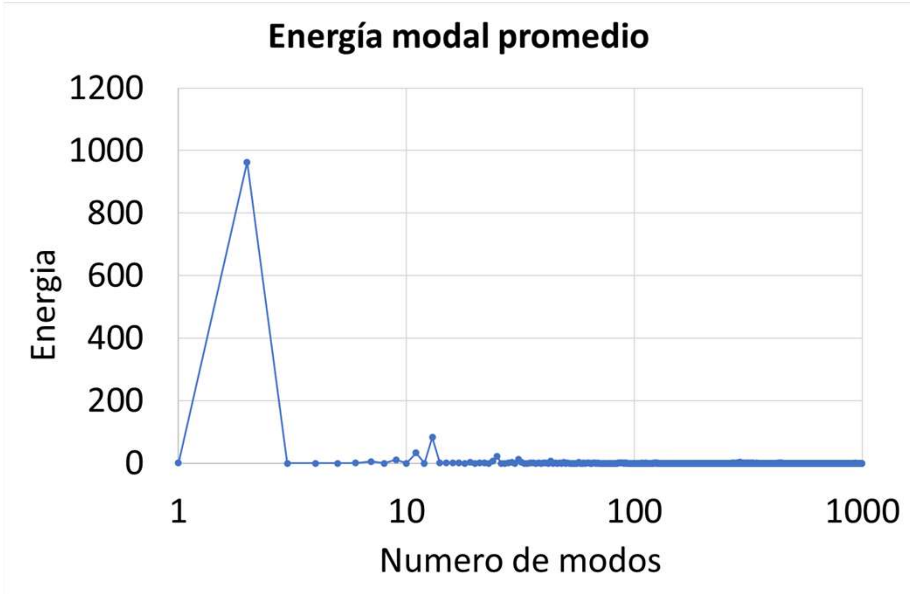
Structure assessment procedure

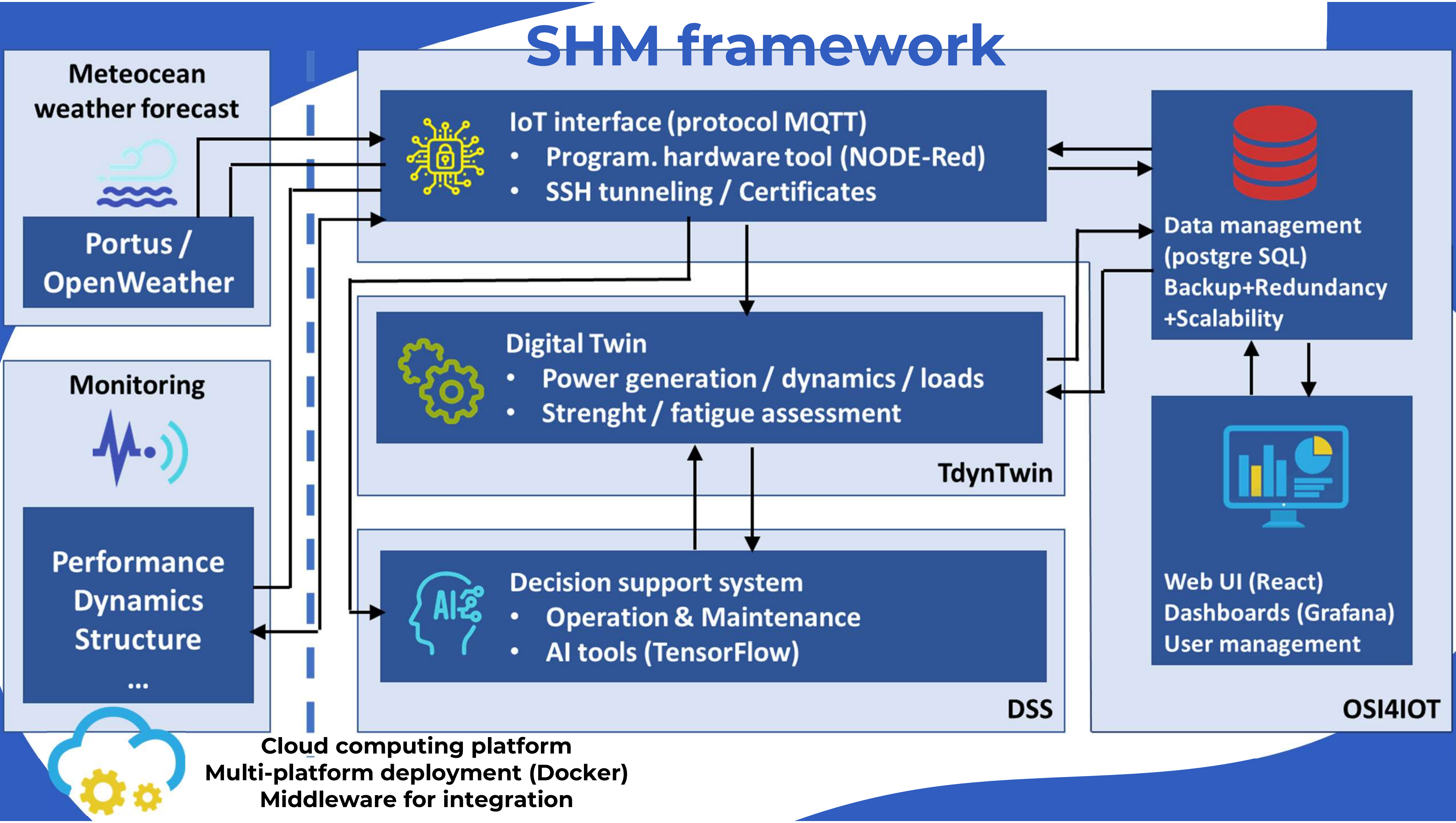
- The underlaying 3D FEM structural model is generated following the **main standards for assessment / certification** of structures
- The near-time structural strength analyses are continuously performed following the standards for the measured (or forecasted) operating conditions.
- The near-time fatigue evaluation / forecasting on hot-spots is continuously performed following the standards for the measured (or forecasted) operating conditions.
- The reduction in thickness due to corrosion is estimated / forecasted using empirical curves defined in industry standards.
- Ensure a reliable RUL / lifespan extension evaluation.

Optimum sensor placement

- Minimum number of sensors for higher accuracy -optimum sensor placement-, with practical restrictions:
  - based on the analysis of the DT.
  - best approximation to the modal coordinates for the most energetic modes
  - GA optimization algorithm.
- Additional focused sensors:
  - based on the analysis of the DT.
  - local peaks of elastic energy.
  - selection of critical hot-spots.
- Sensor system:
  - Based on low cost sensors, but reliable -sensor fault tolerant-.
  - ‘No’ maintenance required -hybrid approach-.







SHM framework
Meteocean weather forecast
Portus / OpenWeather
Monitoring
Performance
Dynamics
Structure
...
IoT interface (protocol MQTT)
• Program. hardware tool (NODE-Red)
• SSH tunneling / Certificates
Digital Twin
• Power generation / dynamics / loads
• Strenght / fatigue assessment
TdynTwin
Decision support system
• Operation & Maintenance
• AI tools (TensorFlow)
DSS
Data management (postgre SQL)
Backup+Redundancy
+Scalability
Web UI (React)
Dashboards (Grafana)
User management
OSI4IOT
Cloud computing platform
Multi-platform deployment (Docker)
Middleware for integration

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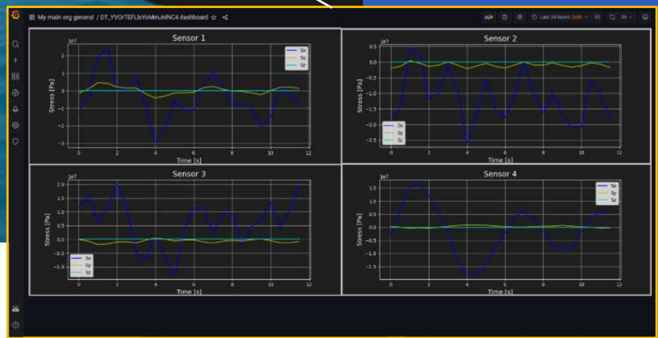
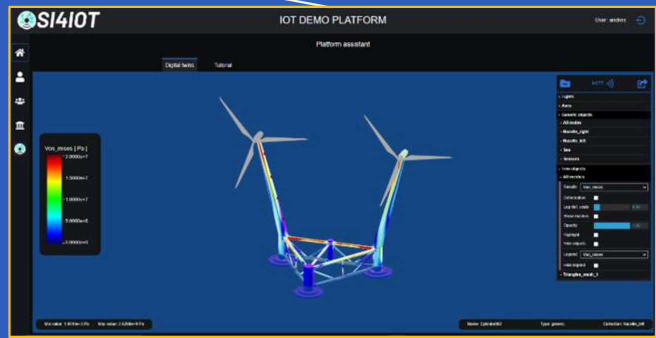
W2POWER's demonstrator + Sea trials

- Digital twin based on aero-servo-hydro-elastic model
  - Rotor + power generation (linear quasi-static)
  - Mooring (linear)
  - Tower (elastic + fatigue)
  - Substructure (hydro-elastic + fatigue) **+ 1.1M DOF reduced to 5000 modes** (2.77Hz-406.76Hz)
  - Seakeeping (radiation-diffraction) + dynamics (SeaFEM)
- Open IoT platform (OSI4IOT) integrating digital twin + monitoring data + weather monitoring / forecast
- Sea-trials ongoing





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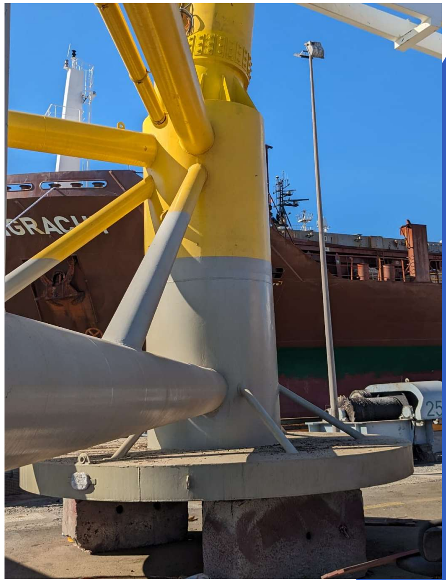
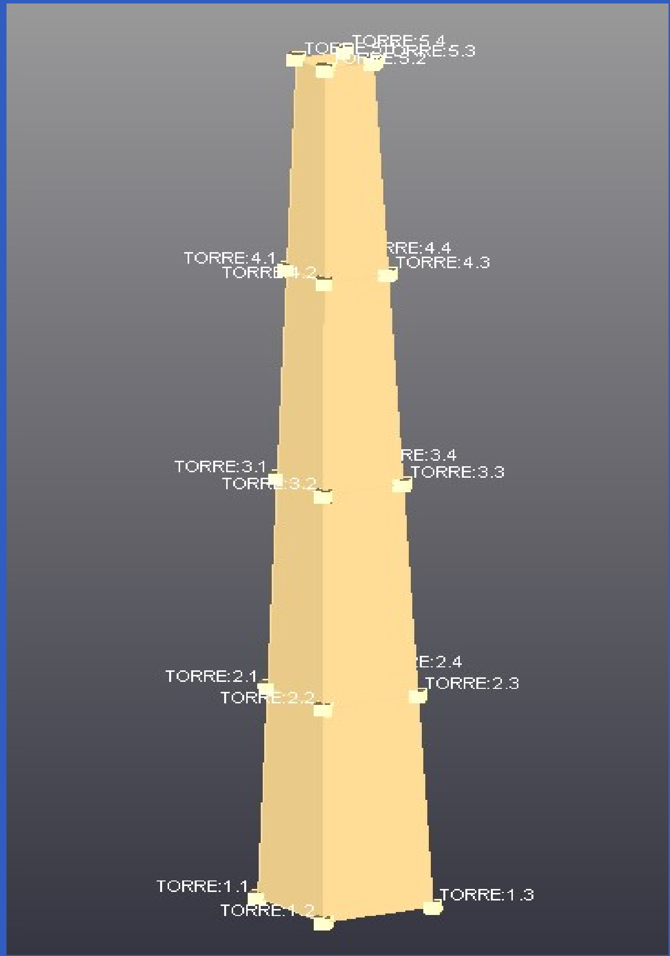
W2POWER's demonstrator + Dry tests



Mode	Frequency ratio	Damping
1 – Radial mode	1.00	1,6
2	1.36	1,17
3 – Torsional mode	1.59	301,2
4 – Bending mode	1.83	3,86
5	1.89	2,16
6	2.21	39,5
7	2.46	3,01
8	2.53	1,23

First modal frequencies and damping for the tower.



Due to confidentiality reasons only non-representative data is shown

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W2POWER's demonstrator + Sea trials

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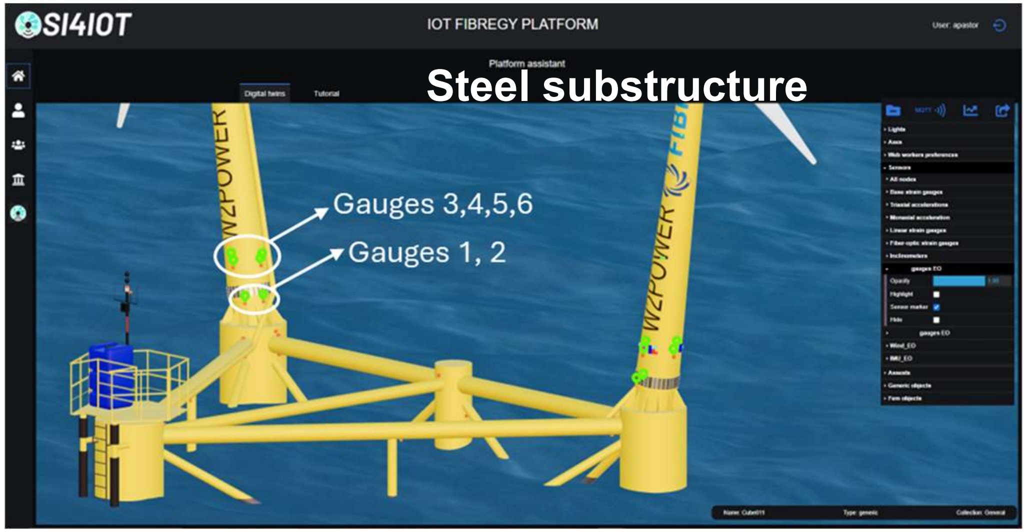
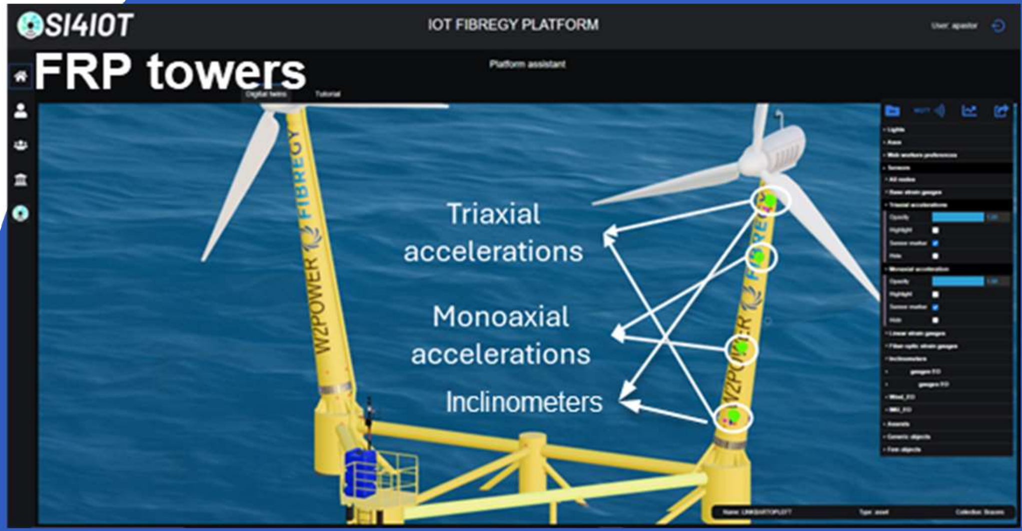
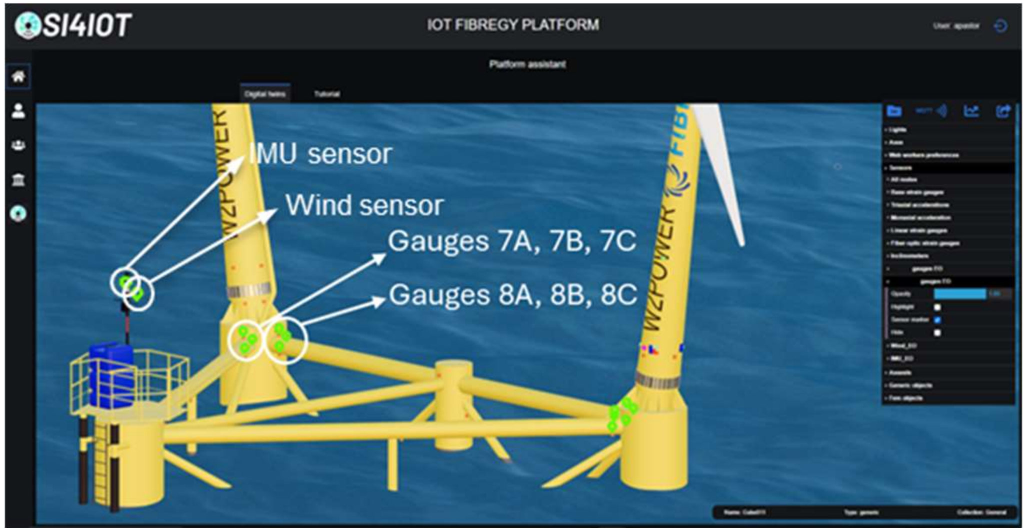
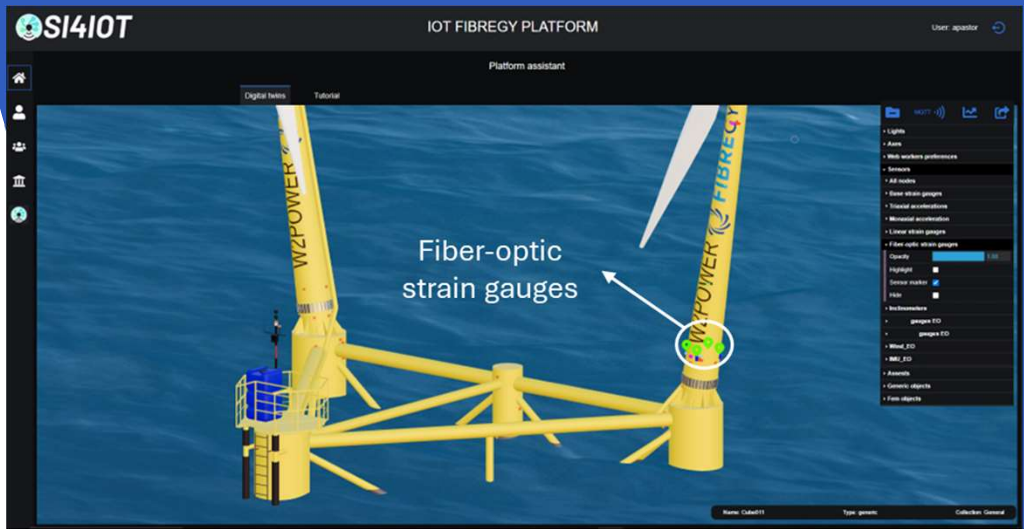
W2POWER's monitoring platform









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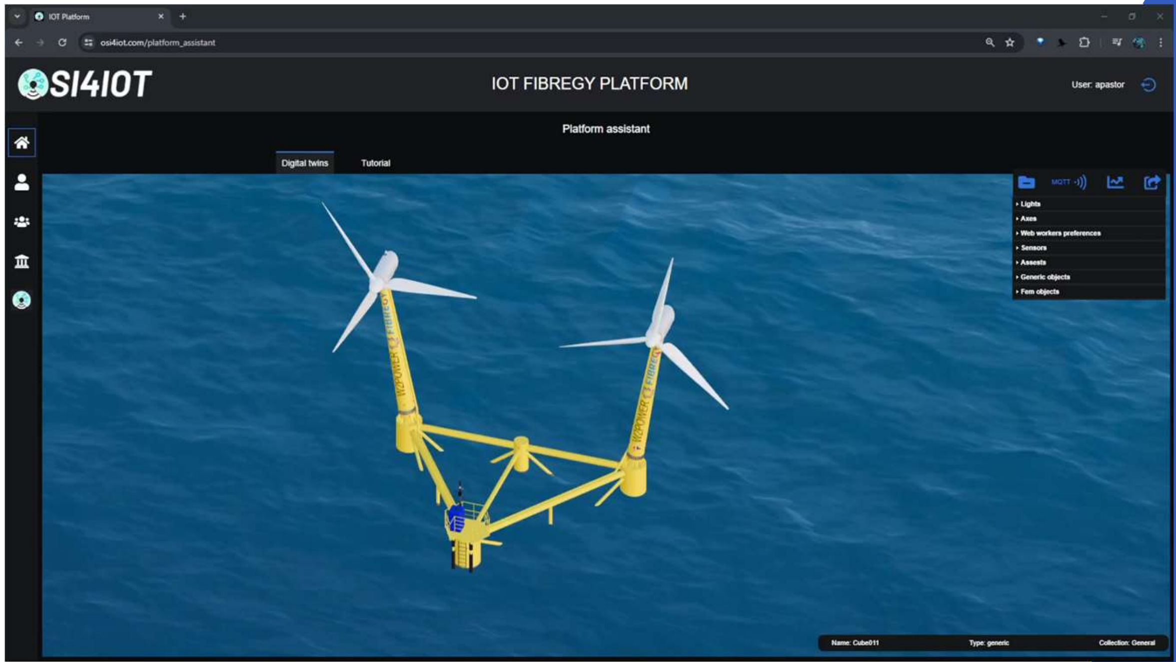

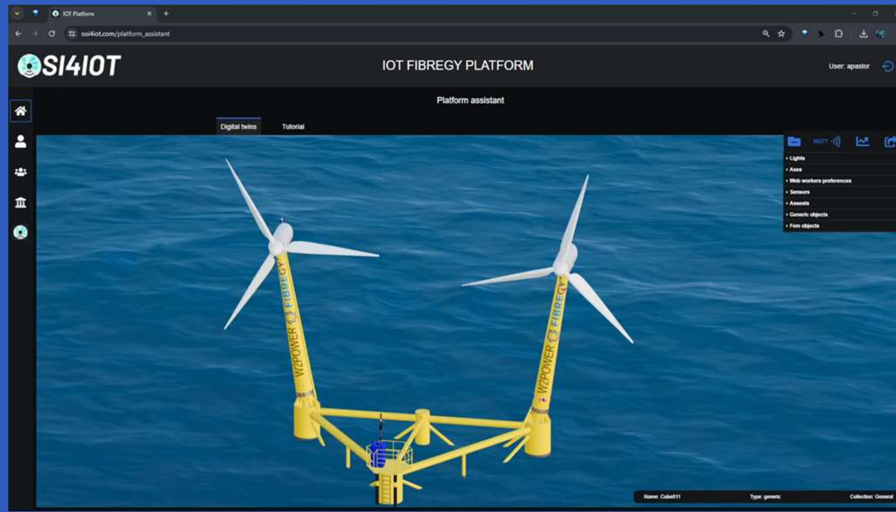

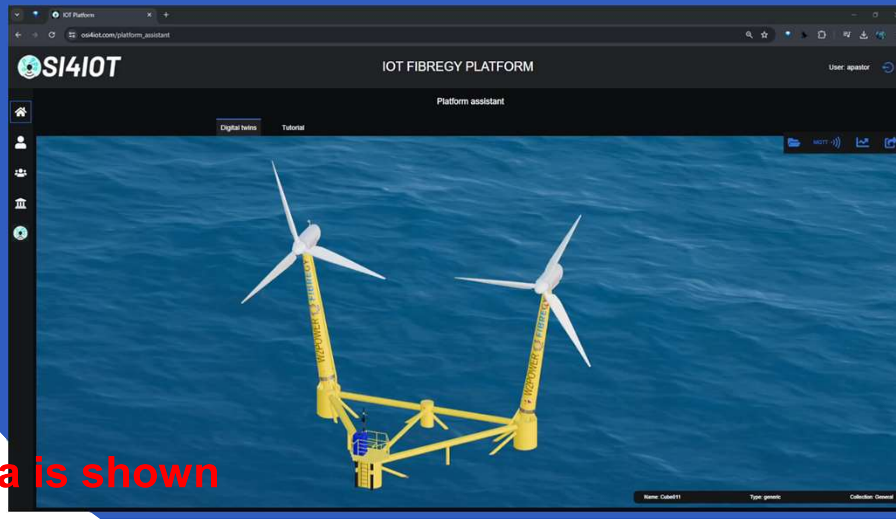

Monitoring data is inmediatly available on the SHM platform

DT's computed data is updated every 8h (forecasting and current)

Due to confidentiality reasons only non-representative data is shown

Conclusions

- **Robust digital twin-based SHM** + physics-based / data tuned approach
- **Optimum sensor system** + sensor fault tolerant (hybrid approach).
- Near time analyses and forecasting based on **assessment (certification) standards**
- **Strenght + RUL evaluation** (enable predictive maintenance and life extension support)
- **Applications**: offshore wind –floating and fixed-, floating PV, floating tidal, oil & gas … and ships.

Tests & Validation

Dry tests
- Gauges testing
- Data transfer testing
- FRP towers' modes validation

Sea trials (static)
- Gauges calibration
- SHM system testing
- SHM uncertainty assessment

Sea trials
- DT+SHM testing
- Data análisis + DT validation
  - FRP towers
  - Substructure
  - Hot spots

Data learning
- ML tools
- DSS + DT 'fine tuning'

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