EPFL

Innovation for construction & the environment

Dr. Dimitrios Terzis

18/11/2025

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Today's class

- Structural Health Monitoring (SHM)
- Digital Twins & semantics
- Cyberphysical systems
- An example from the EPFL Innovation ecosystem

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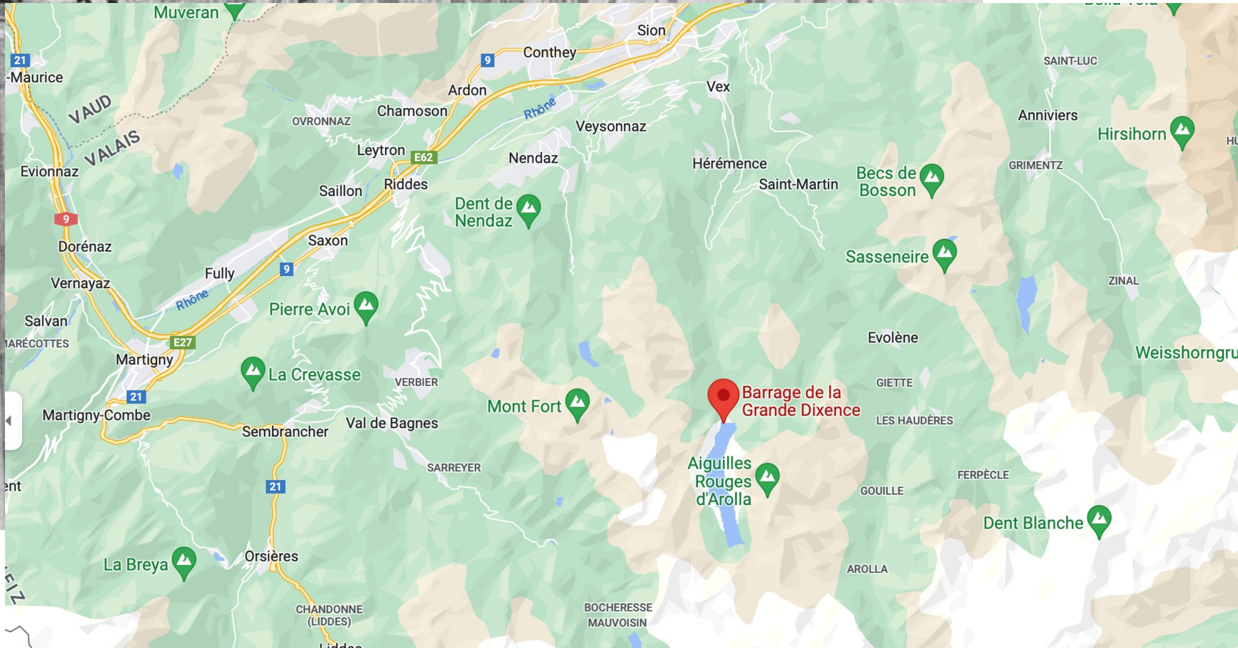
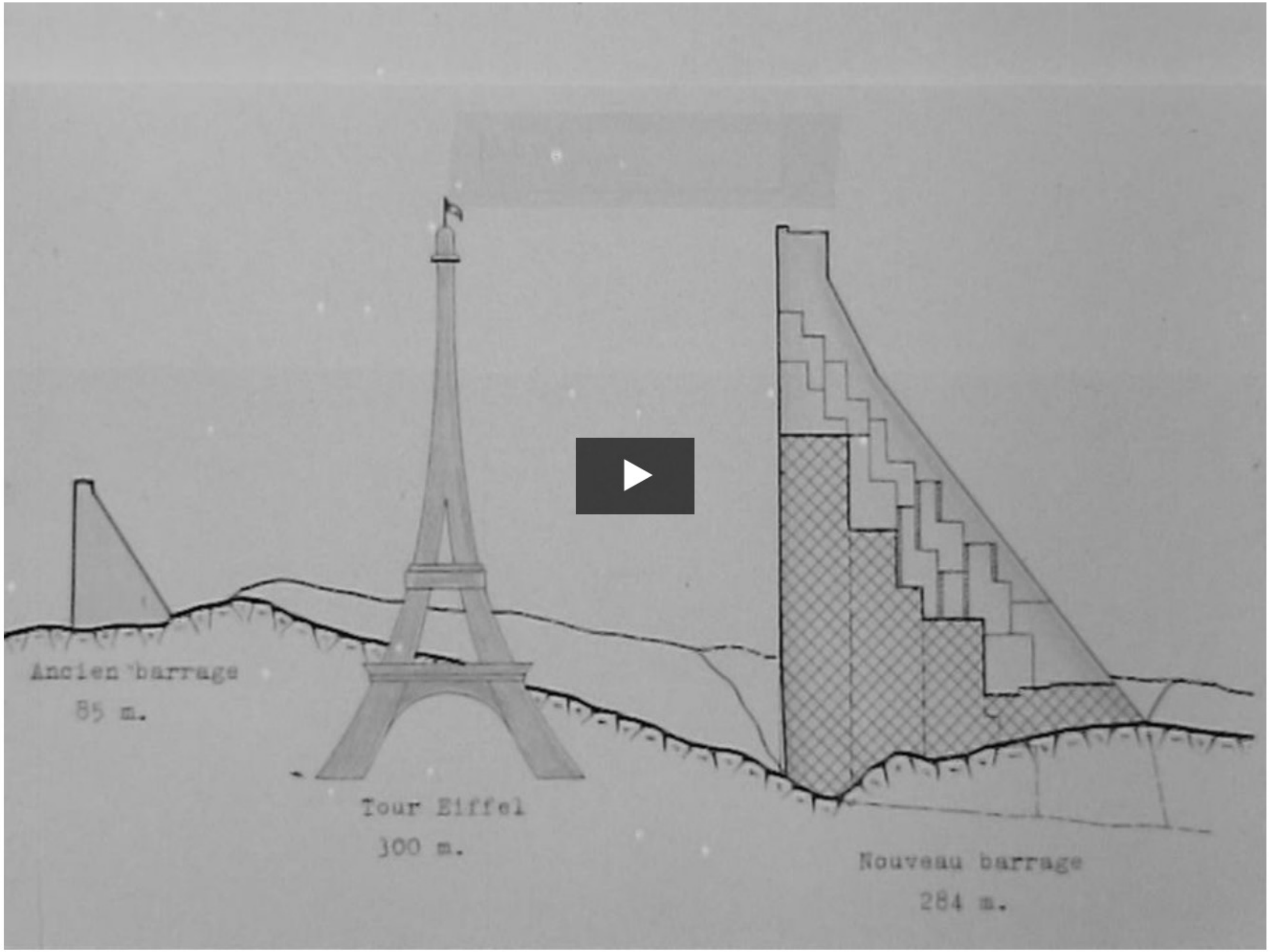
INNOVATION FOR CONSTRUCTION AND THE ENVIRONMENT

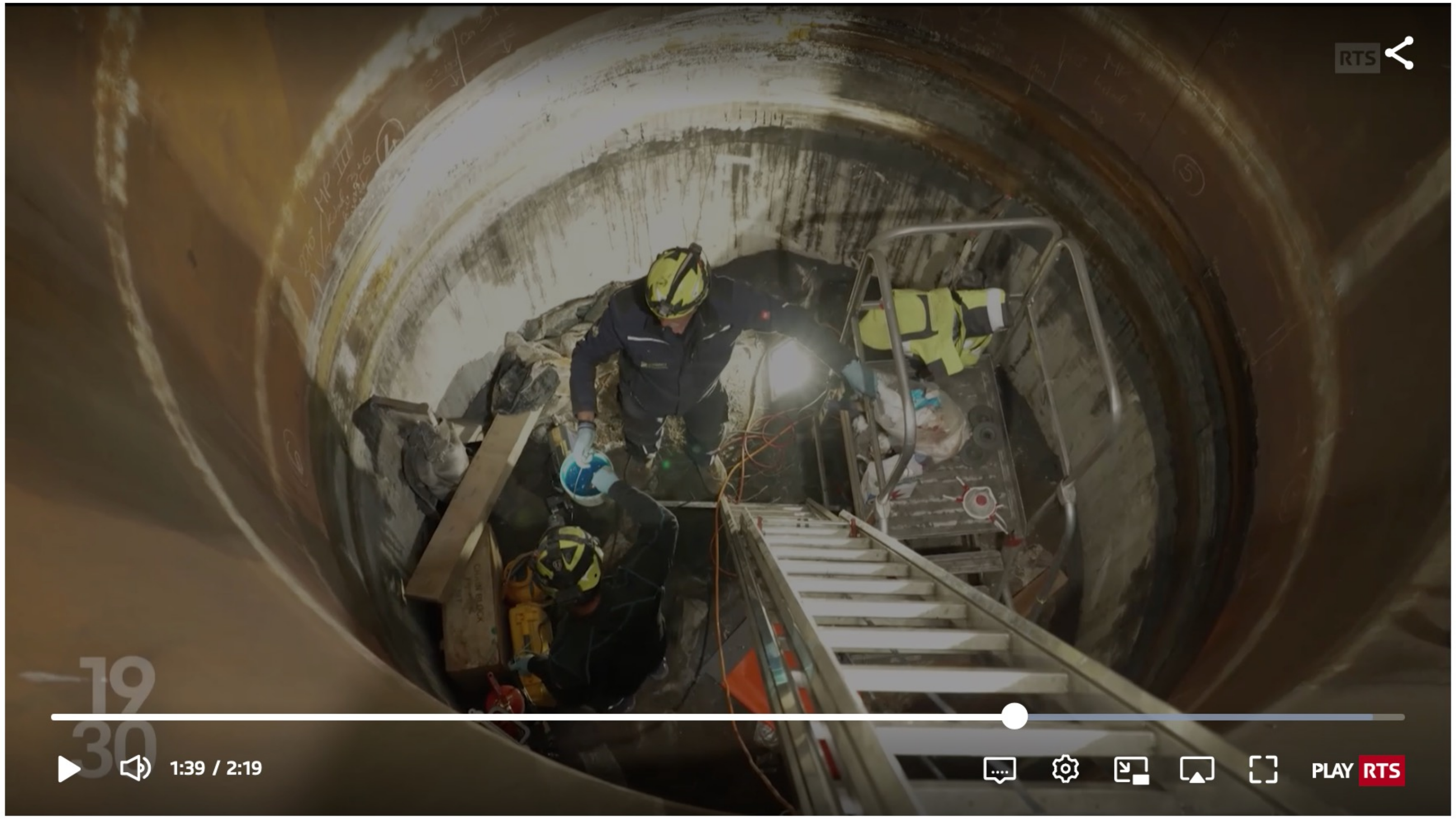




La sécurité du barrage de la Grande Dixence / Le Régional / 5 min. / le 14 octobre 1960

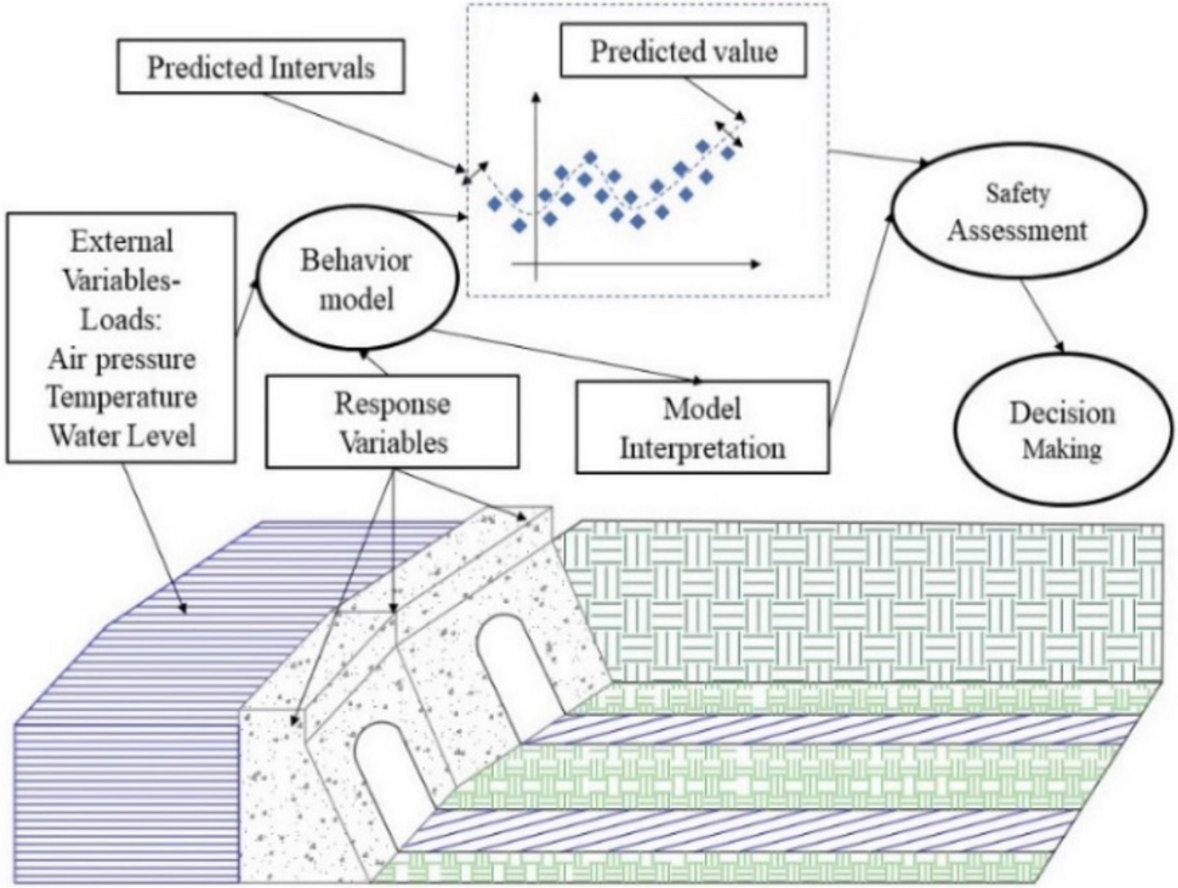
Valais Modifié vendredi à 20:33

Des installations de la Grande Dixence remises à neuf pour 240 millions



Après six ans de travaux, la rénovation de la Grande Dixence touche à sa fin / 19h30 / 2 min. / vendredi à 19:30

On SHM of Dams



Flah, M., Nunez, I., Ben Chaabene, W. and Nehdi, M.L., 2021. Machine learning algorithms in civil structural health monitoring: A systematic review. *Archives of computational methods in engineering*, *28*, pp.2621-2643.

On SHM of critical infrastructure

https://www.chemengonline.com/Assets/whitepapers/Oracle_PPM_US_EN_WP_TheImpactofAgeing.pdf

Ageing infrastructure is a headache for many industries. A substantial majority (87%) of executives report that ageing infrastructure has had an impact on their operations in recent years; one in ten say problems related to ageing infrastructure have caused severe problems in their operations that they are still trying to address successfully.

The current infrastructure upgrade spend will rise. Almost 33% of executives say they plan to increase spending on infrastructure in the coming years, while just 8% plan to decrease spending.

Fully 17% of executives say their companies will spend more than 40% of their operating budget on projects involving ageing infrastructure in the coming five years.

On SHM of bridges

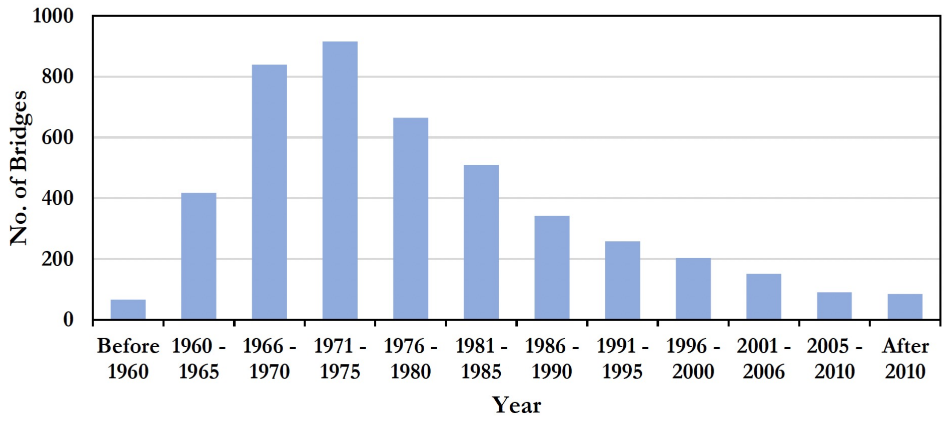


Figure 3: Bridge Construction by Year [Switzerland] **((FEDRO) Office Fédéral des Routes, 2018)**

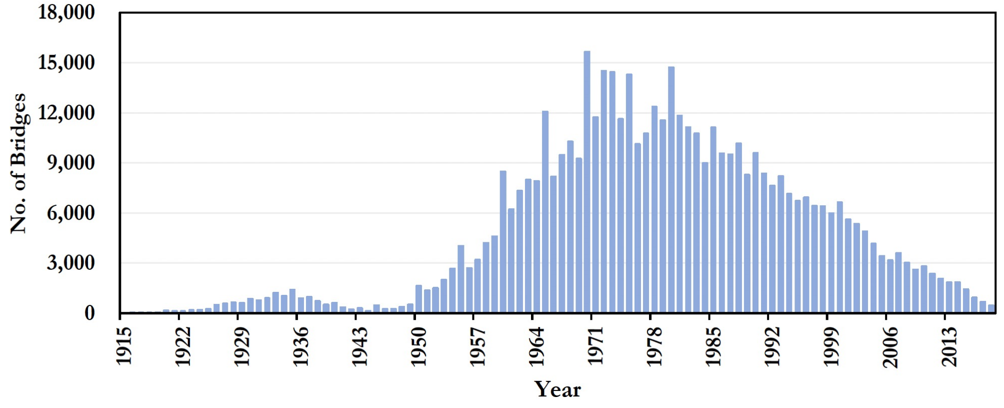


Figure 2: Bridge construction by year [Japan] **(MLIT Ministry of Land, 2019)**

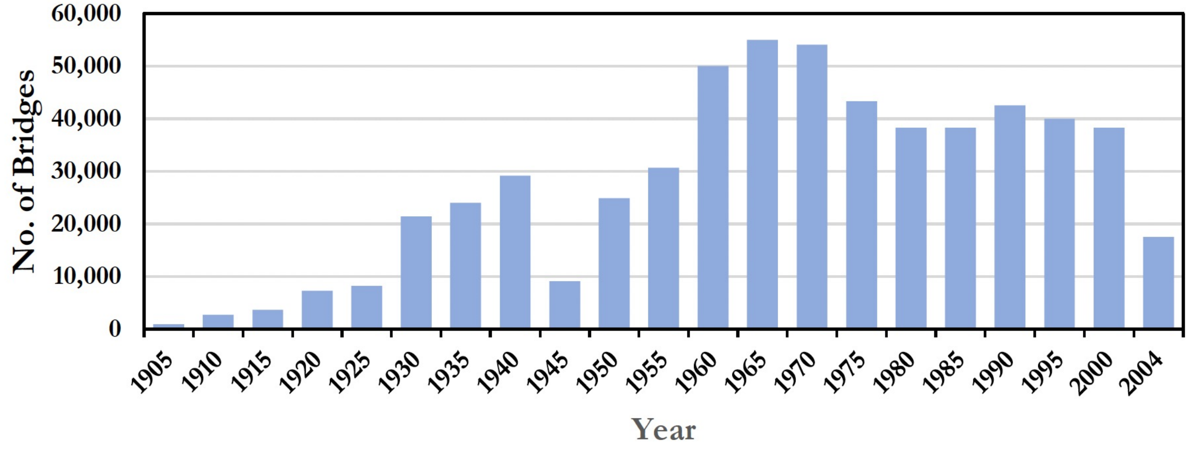


Figure 1: Bridge construction by year [USA] **(Choate & Walter, 1981)**

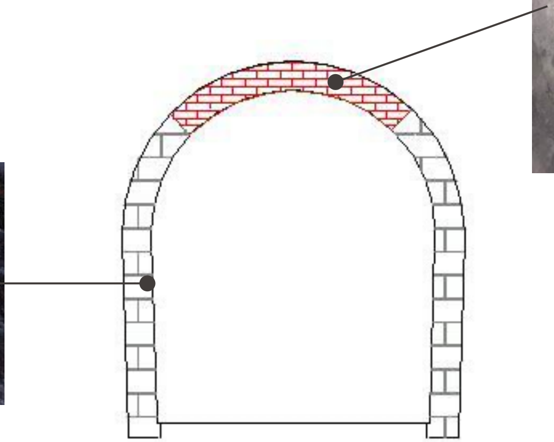
On SHM of tunnels

Case study: Serre de la Voûte tunnel

Horseshoe shaped tunnel

Crown: small cement bricks

Side walls: rock blocs masonry



Sclerometer results	Zone (cm from the surface)	Material
No response	0.5 -1.0	Dust, result of several years of operation
9-13	2	Highly weathered material
26-39	2.5 - 3	Sound material

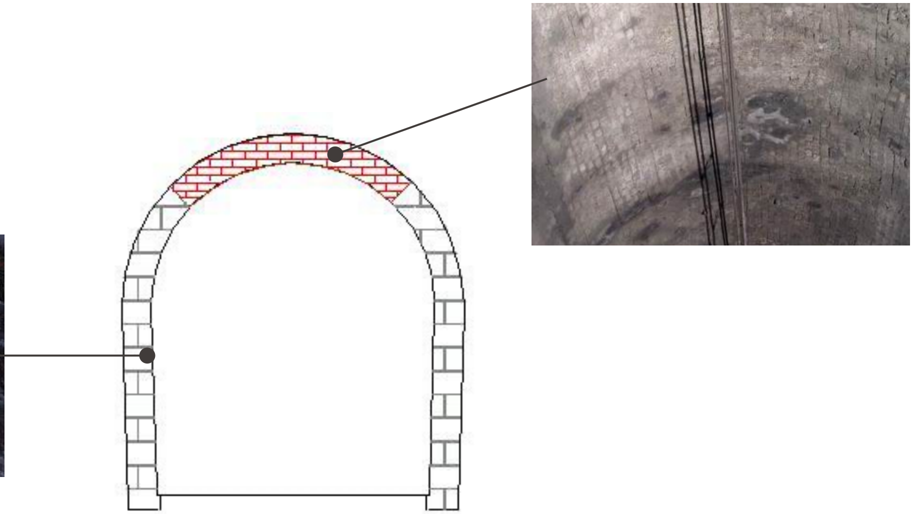
Local hammering for checking the deterioration degree of the rock blocs:

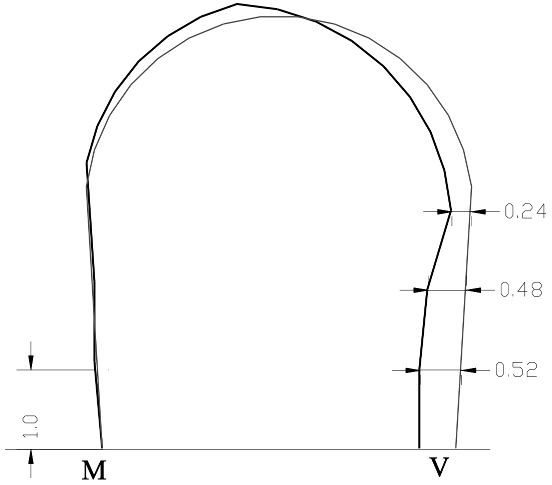
On SHM of tunnels

Dr. Dimitrios Terzis

Case study: Serre de la Voûte tunnel

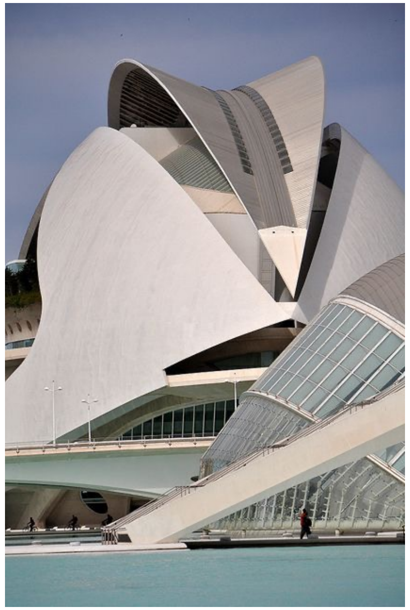
- The majority of the masonry joints is highly weathered
- Dripping points, mainly located on the tunnel crown
- Local deformation of the side wall on a 30 m long zone close to the North portal





On SHM of metallic structures





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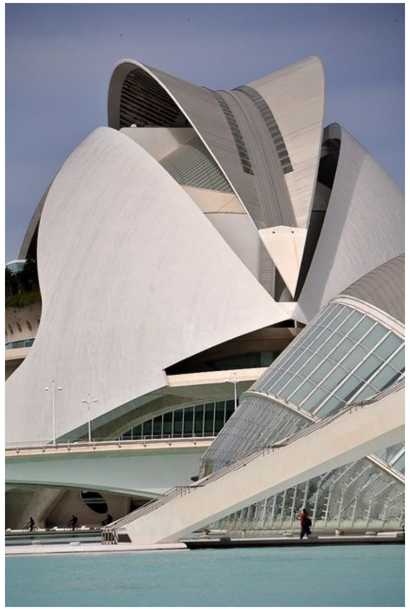
On SHM of metallic structures



On Digital twins

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The digital twin

The "Digital twin" programme is one of the major campaigns launched in-house by the Engineering & Projects (I & P) and Innovation Divisions. The aim is to optimise project design, service portfolio content and production functions.

A technological innovation with multiple applications to enter service by 2024

Like the ghost in video games, a digital twin is the virtual reproduction of a system as it really exists and not as it would be in an ideal world. NASA was the first to apply this principle to its industrial requirements for the Apollo mission. The technique is also widely used in the aerospace industry. SNCF Réseau is aiming to have it in service by 2024.

> **"The (rail) sector has taken inspiration from the aeronautics industry, a precursor in the field, particularly with the digital twins used for reactors to factor in the whole of their lifecycle operating history."**
>
> Pierre Cresci, Cabinet Oliver Wyman

On Digital twins

The construction industry is among the least digitized.

McKinsey Global Institute industry digitization index; 2015 or latest available data

Relatively low digitization — Relatively high digitization

● Digital leaders within relatively undigitized sectors

[1]Based on a set of metrics to assess digitization of assets (8 metrics), usage (11 metrics), and labor (8 metrics).
[2]Information and communications technology.

Source: AppBrain; Bluewolf; Computer Economics; eMarketer; Gartner; IDC Research; LiveChat; US Bureau of Economic Analysis; US Bureau of Labor Statistics; US Census Bureau; McKinsey Global Institute analysis

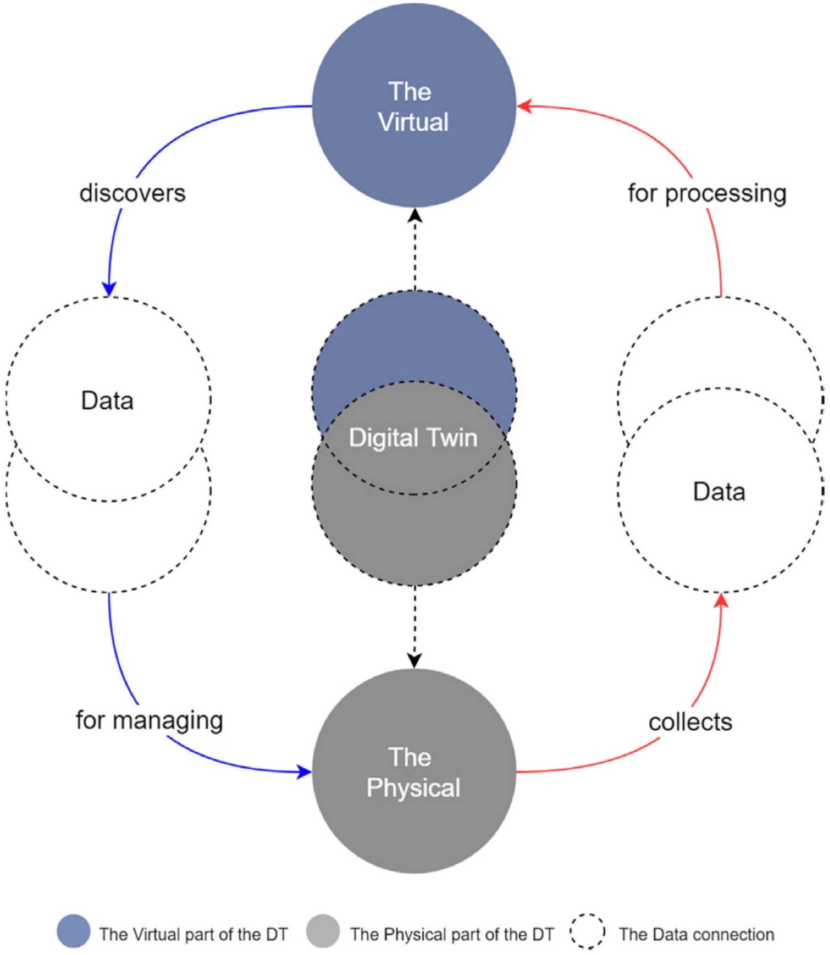

Fig. 1. The Digital Twin paradigm.

Boje, C., Guerriero, A., Kubicki, S. and Rezgui, Y., 2020. Towards a semantic Construction Digital Twin: Directions for future research. *Automation in construction*, *114*, p.103179.

On Digital twins

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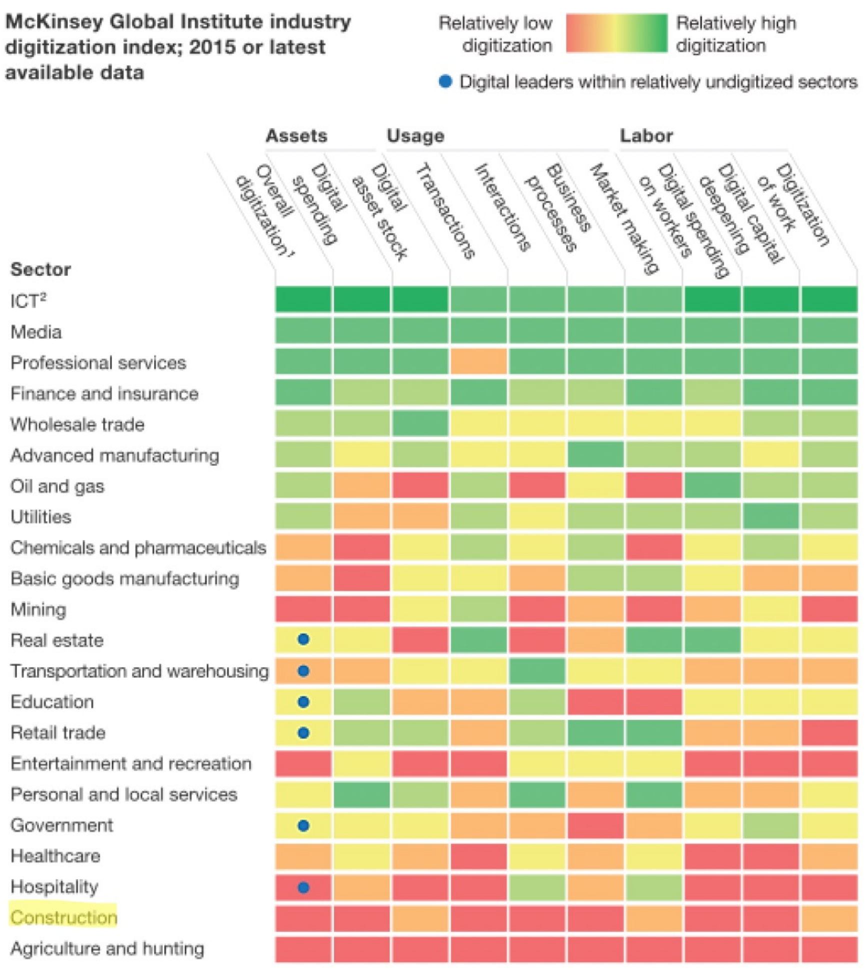

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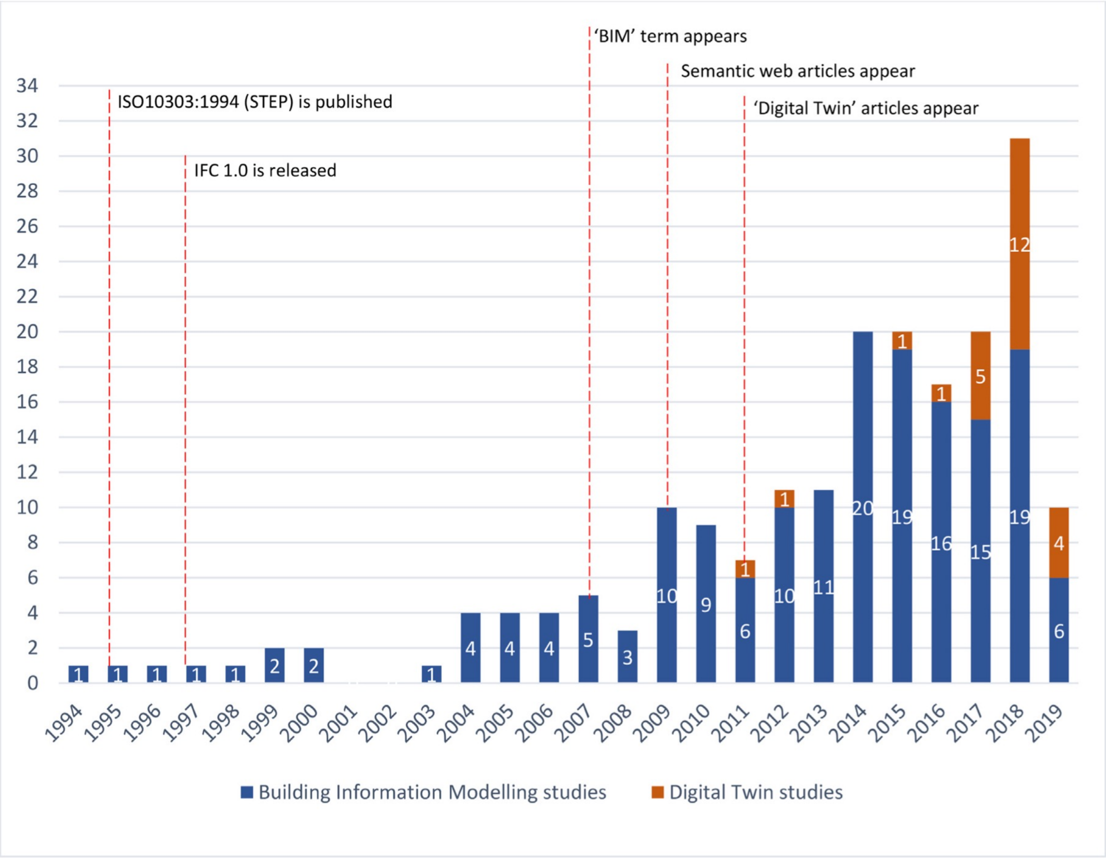
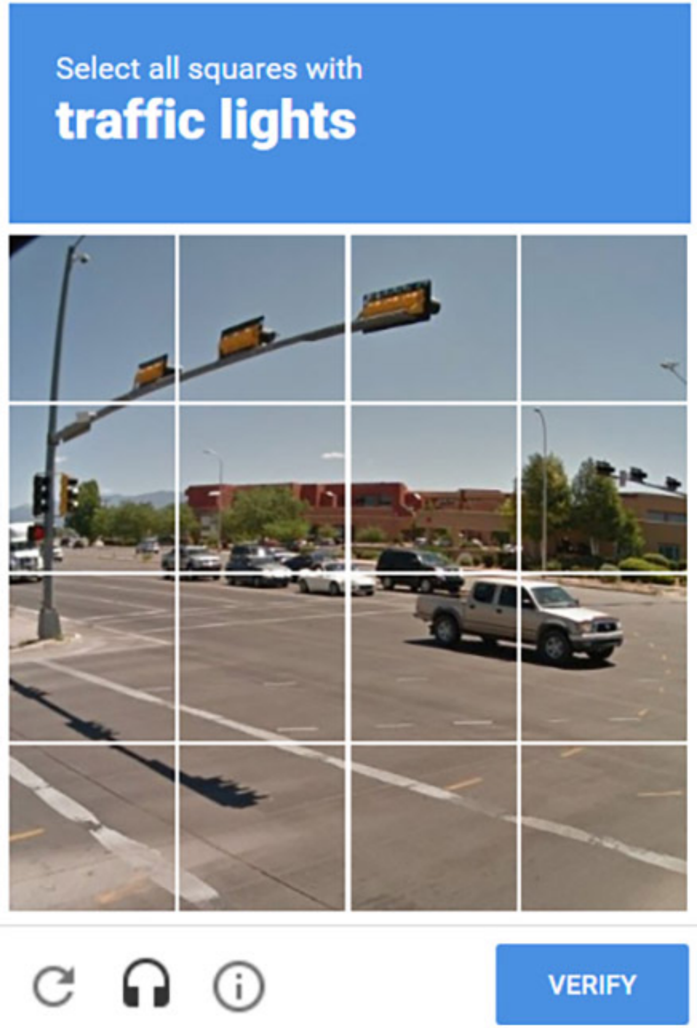


Fig. 3. Distribution of reviewed papers by publication date with important milestones in the construction sector.

Boje, C., Guerriero, A., Kubicki, S. and Rezgui, Y., 2020. Towards a semantic Construction Digital Twin: Directions for future research. *Automation in construction*, *114*, p.103179.

A break to understand semantics



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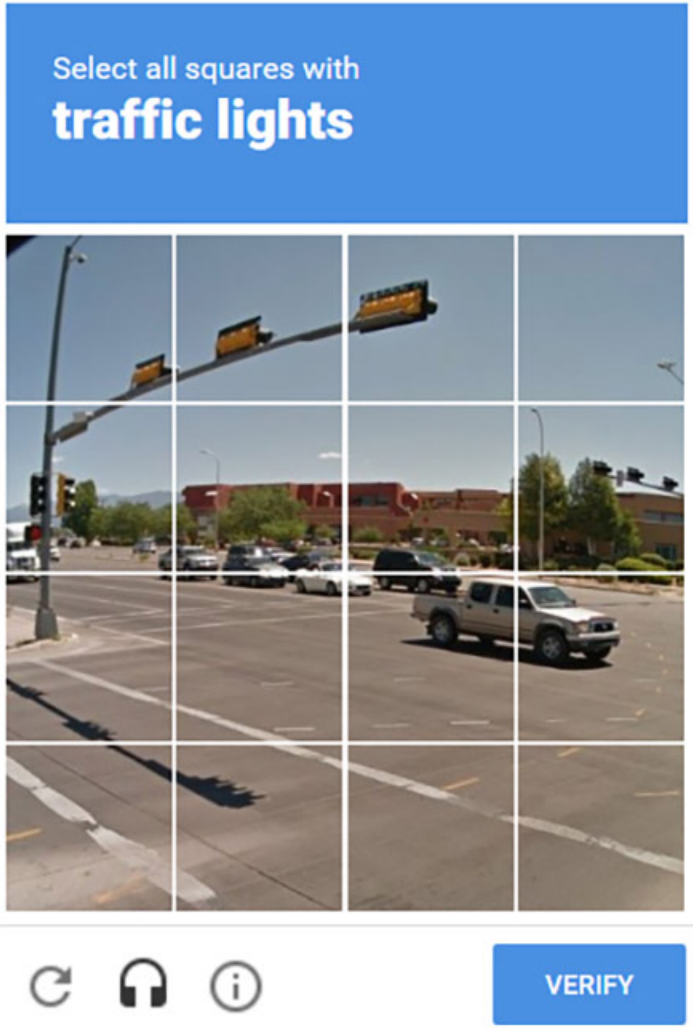
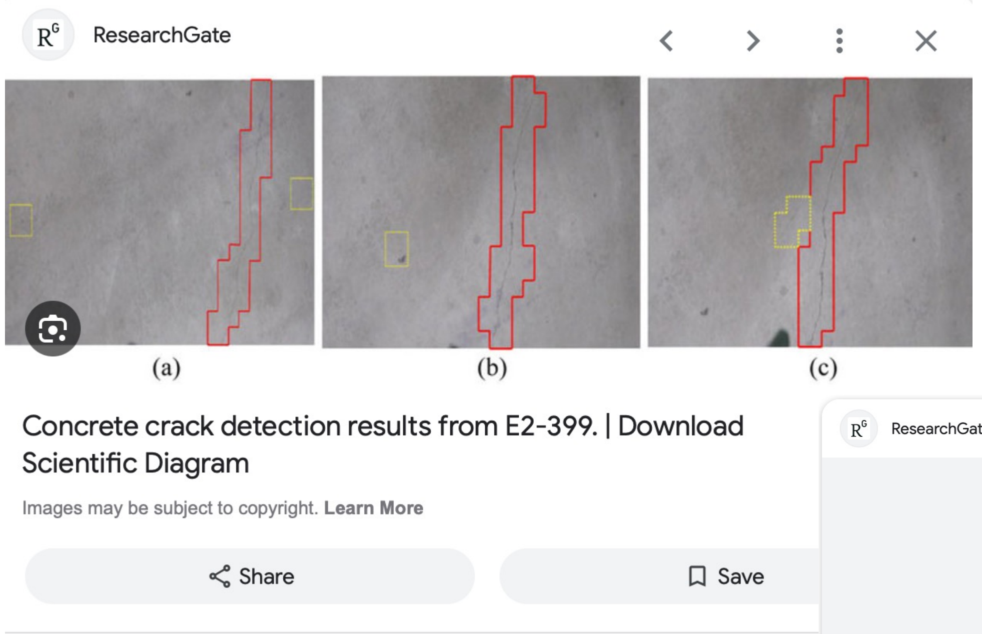
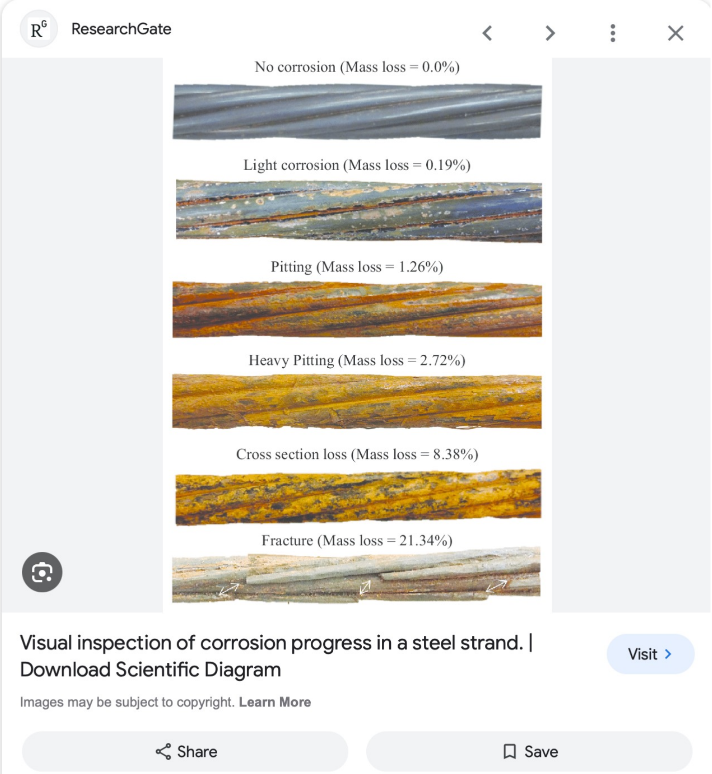
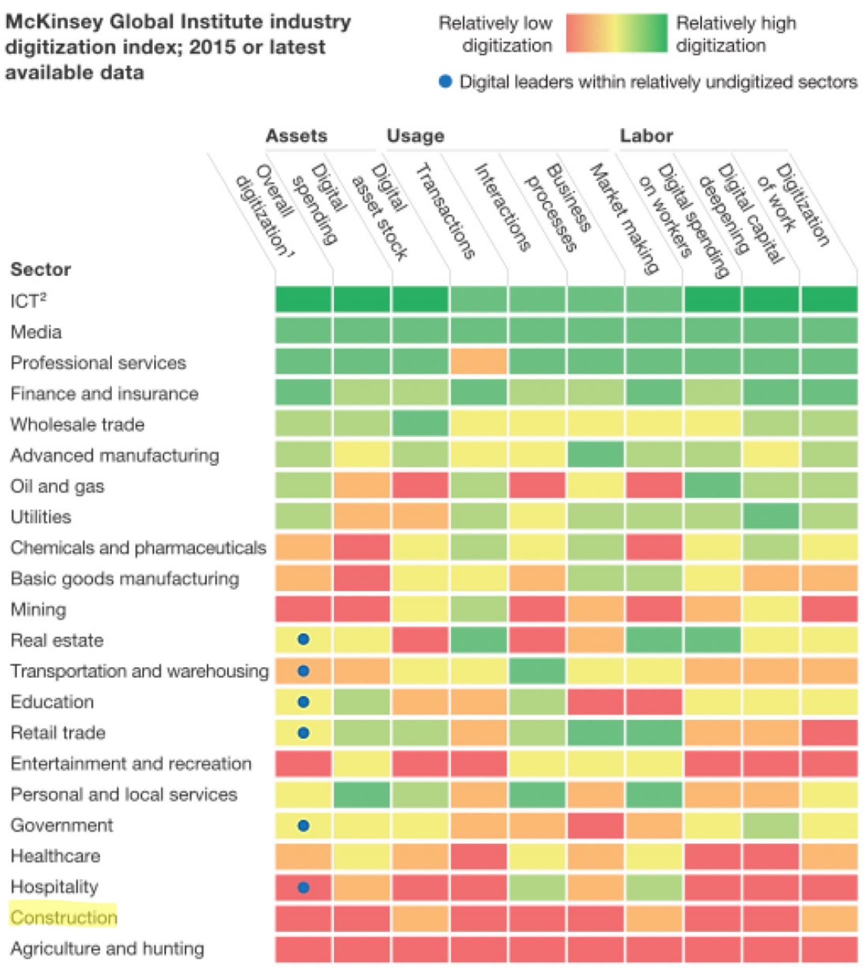






On Digital twins & Cyberphysical systems

The construction industry is among the least digitized.



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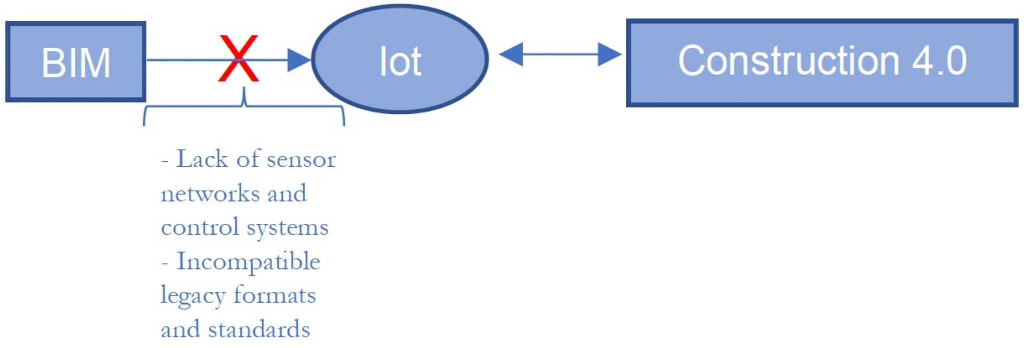

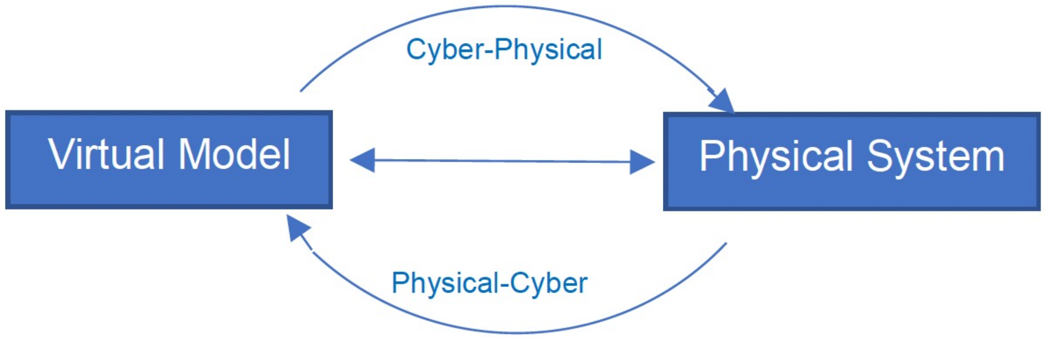

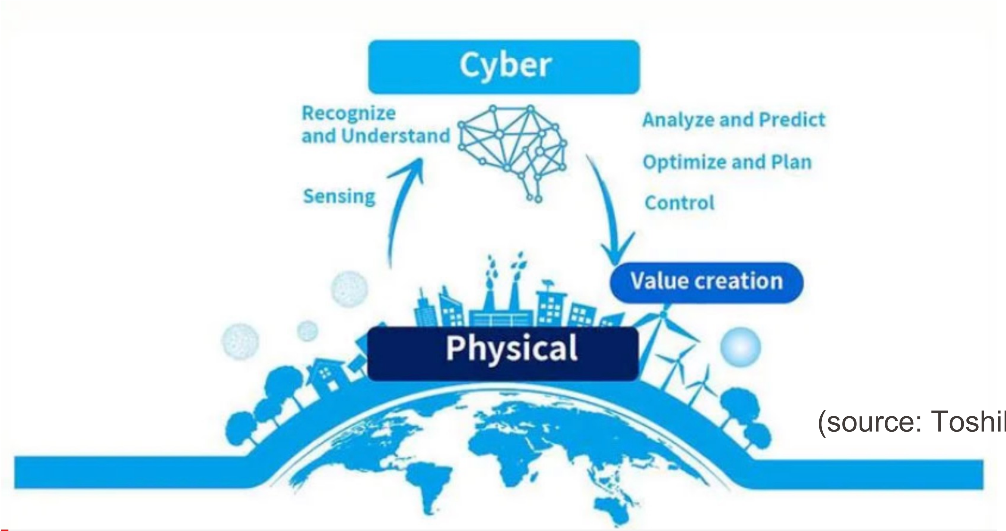

(source: Toshiba)

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On Digital twins & Cyberphysical systems

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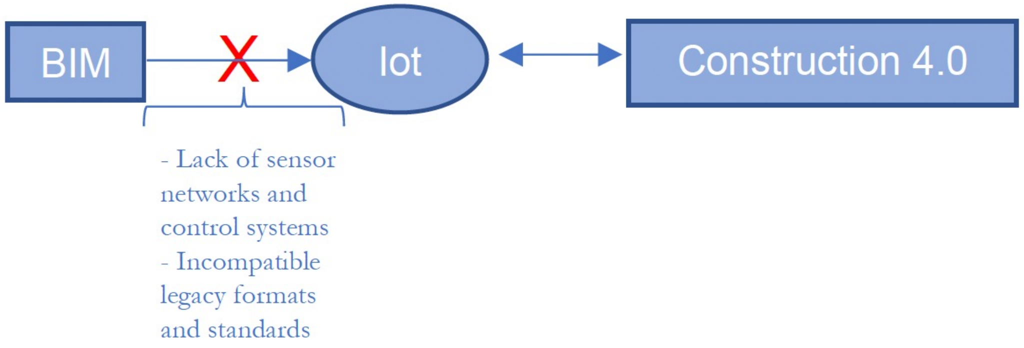

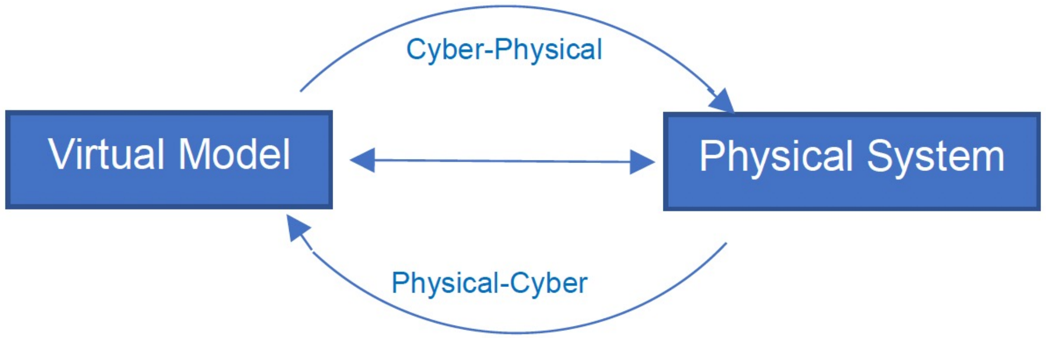

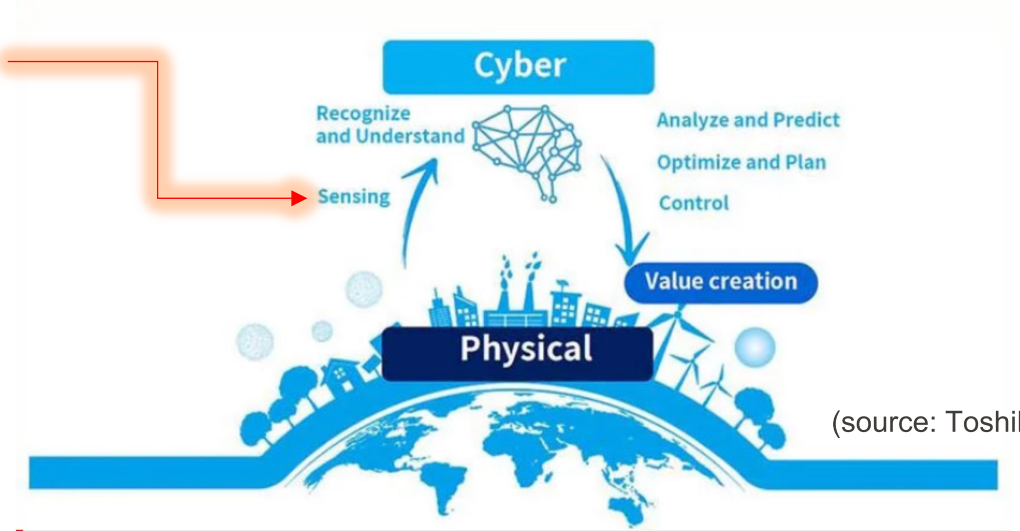

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On Digital twins & Cyberphysical systems

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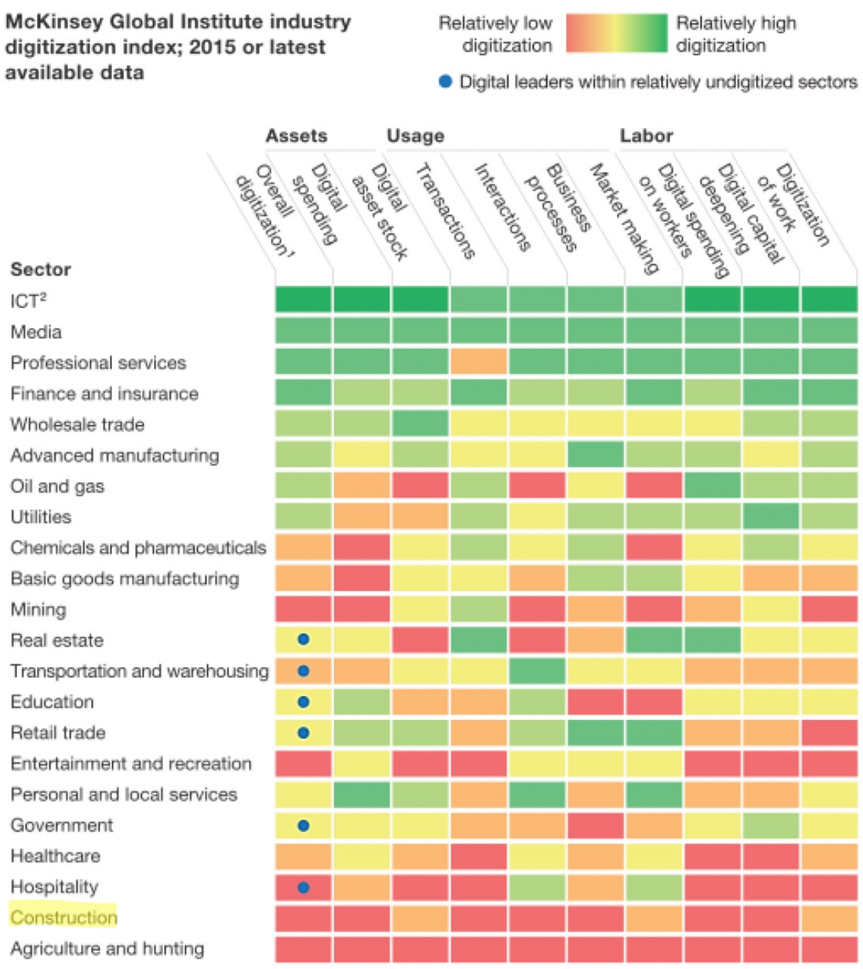

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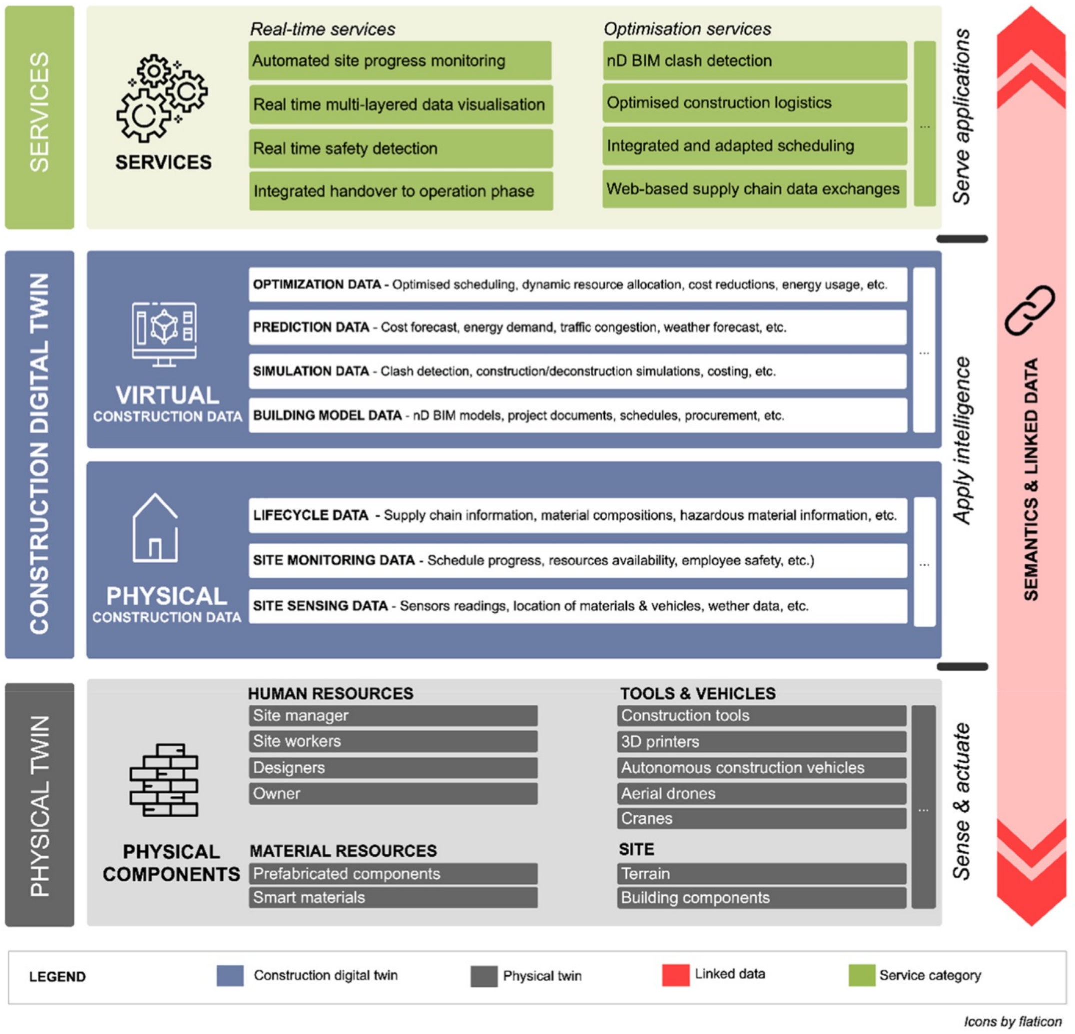

Fig. 5. Construction Digital Twin data usage for facilitating smart construction services (based on Tao et al. [106]).

Boje, C., Guerriero, A., Kubicki, S. and Rezgui, Y., 2020. Towards a semantic Construction Digital Twin: Directions for future research. *Automation in construction*, *114*, p.103179.

DT->CPS and 6-Dimensional modelling

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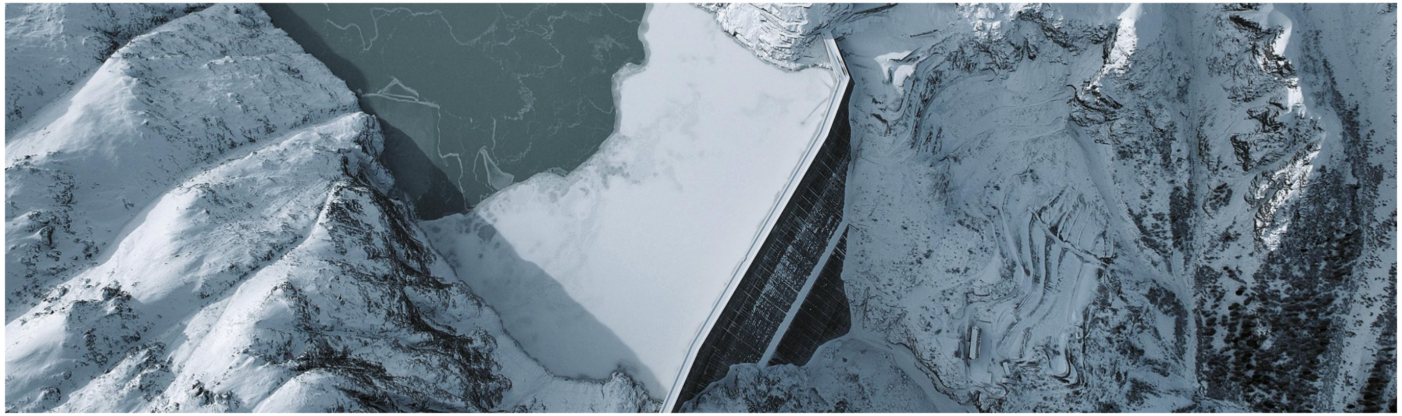
More efficient energy generation and trading thanks to near real-time snow monitoring from space. Committed to Open Source and with a strong partner network, we transparently deliver satellite data power to the Energy industry.



- 3D Space
- Time
- Cost (resources management)
- Environment

Keyword: *Parametric design*

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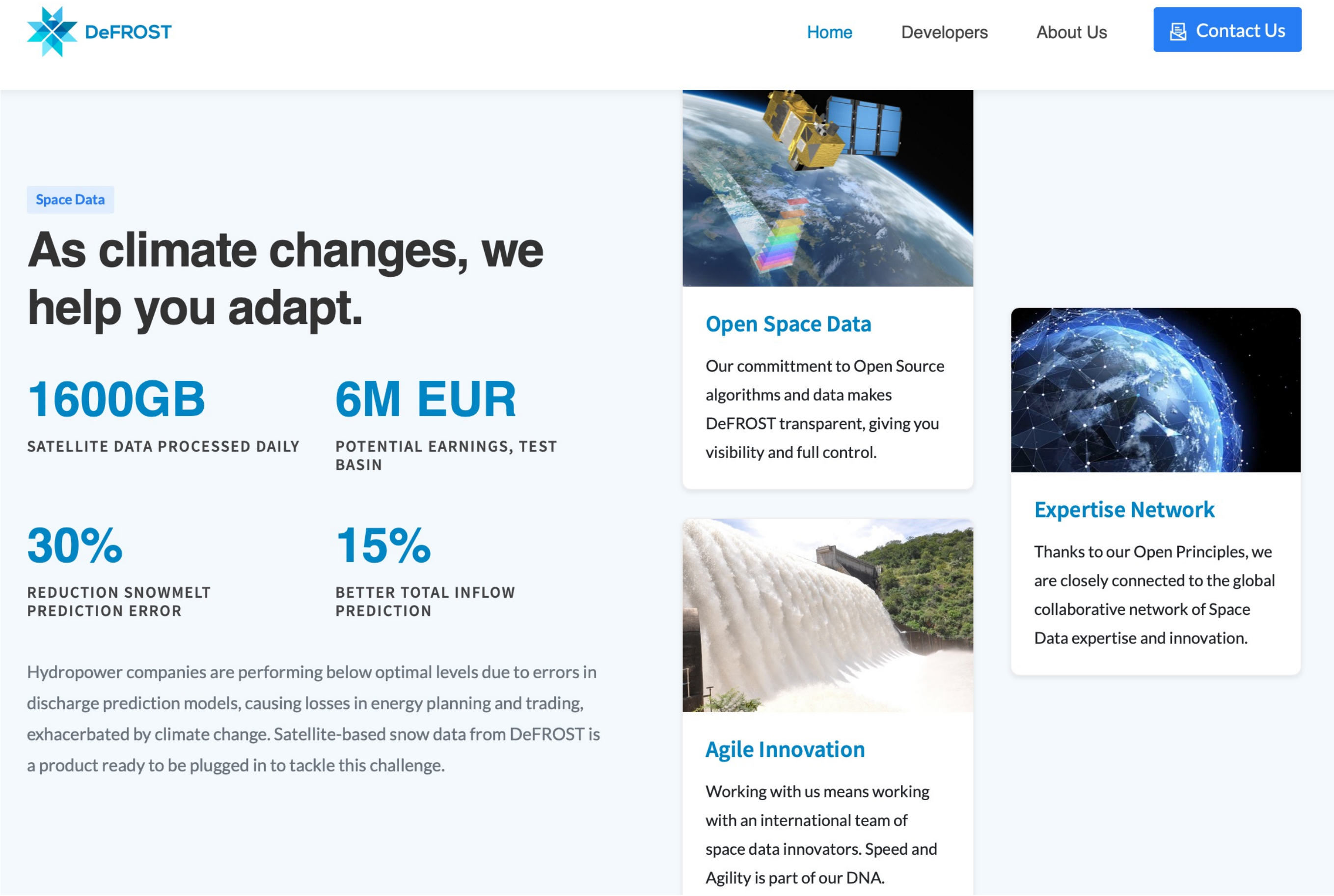
Digital twins and 6-Dimensional modelling



- 3D Space
- Time
- Cost (resources management)
- Environment

Keyword: *Parametric design*

Active players in the field from EPFL

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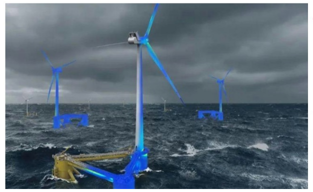
Akselos gets strategic investment from GRO Capital to propel advancements in physics-based digital twins

14.06.2023 10:33, Rita Longobardi

Akselos, the creator of a pioneering engineering simulation technology, announced it has received an investment from GRO to accelerate organizational expansion, global commercial scaling, and product leadership.

Grounded in more than 15 years of advanced academic research at the Massachusetts Institute of Technology (“MIT”), Akselos provides physics-based simulation engineering software, or digital twins, of highly complex mechanical assets. The technology enables customers to reduce risk, increase operational efficiency, and extend the life of their energy infrastructure in operation. The Company is disrupting the industry standard with its solution being 1,000x faster than legacy technology, facilitating real-time condition monitoring and delivering significant customer value.



Akselos’ digital twin technology is currently in use by customers across the energy industry, including upstream and downstream, and renewable energy. It is trusted by clients including Shell, Lamprell, and Pan American Energy. Offshore wind is a key vertical, aligning with the company’s vision of providing technology that enables the green energy transition in line with IEA’s Net Zero 2050 roadmap.

AKSELOS

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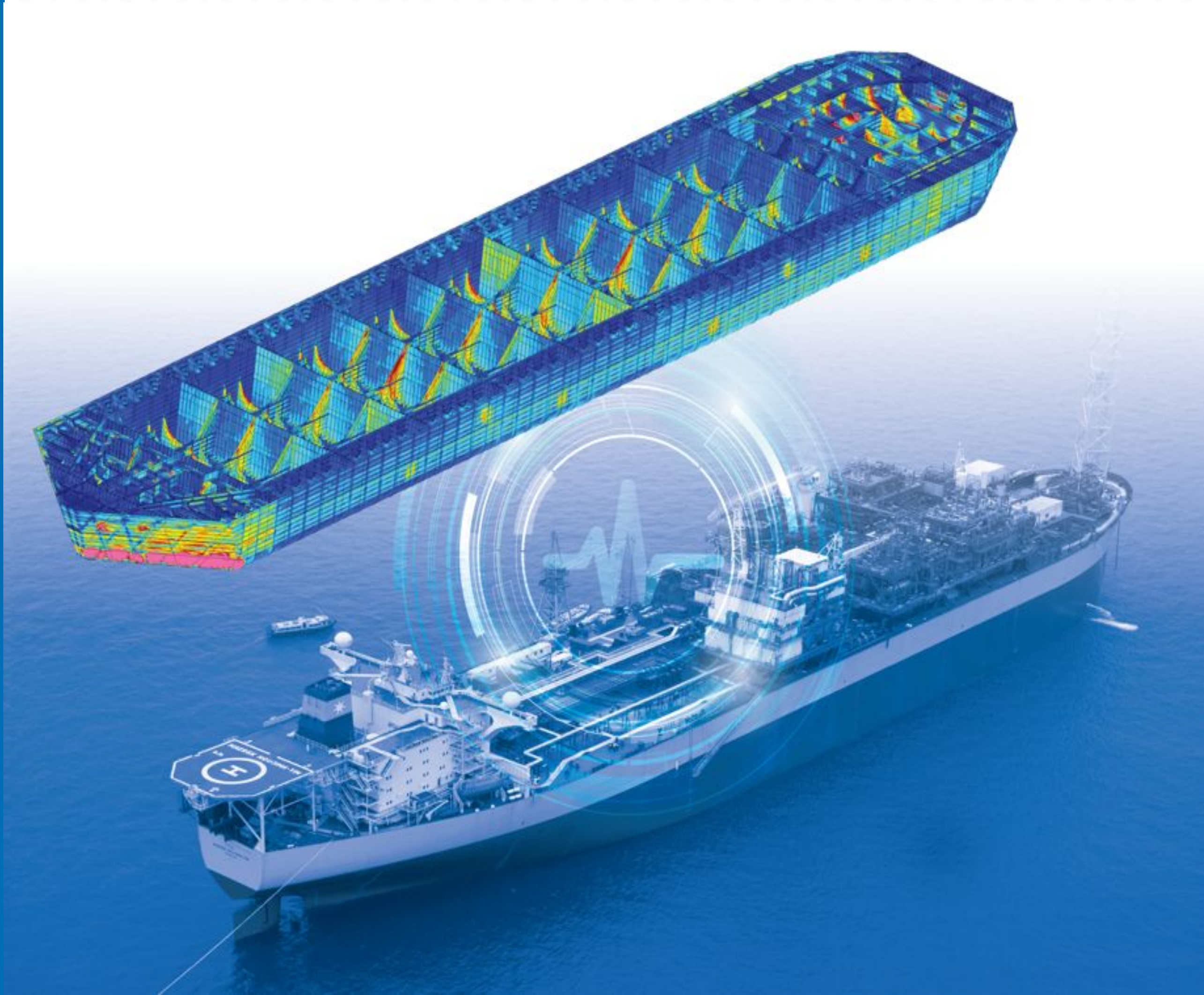
INNOVATION FOR CONSTRUCTION AND THE ENVIRONMENT

AKSELOS

Digital Twins of Large Infrastructure



Shell Ventures

INNOGY VENTURES

$10M INVESTMENT

LONDON

LAUSANNE

BOSTON

HOUSTON

HO CHI MINH CITY

12 YEARS OF RESEARCH AT MIT
BEHIND PATENTED ALGORITHMS

AKSELOS

1. Digital Twin Context
2. Technology Overview
3. Examples and Case Studies
4. Mathematical Background

Akselos's Take on Digital Twins

Digital Twins of large and critical engineering systems, e.g:

- Offshore structures for oil & gas (FPSOs, tankers, semisubmersibles, platforms)
- Rotating machinery (compressors, turbines, mills)
- Wind farms
- Mining machinery
- Civil infrastructure (bridges, buildings)

Akselos's Take on Digital Twins

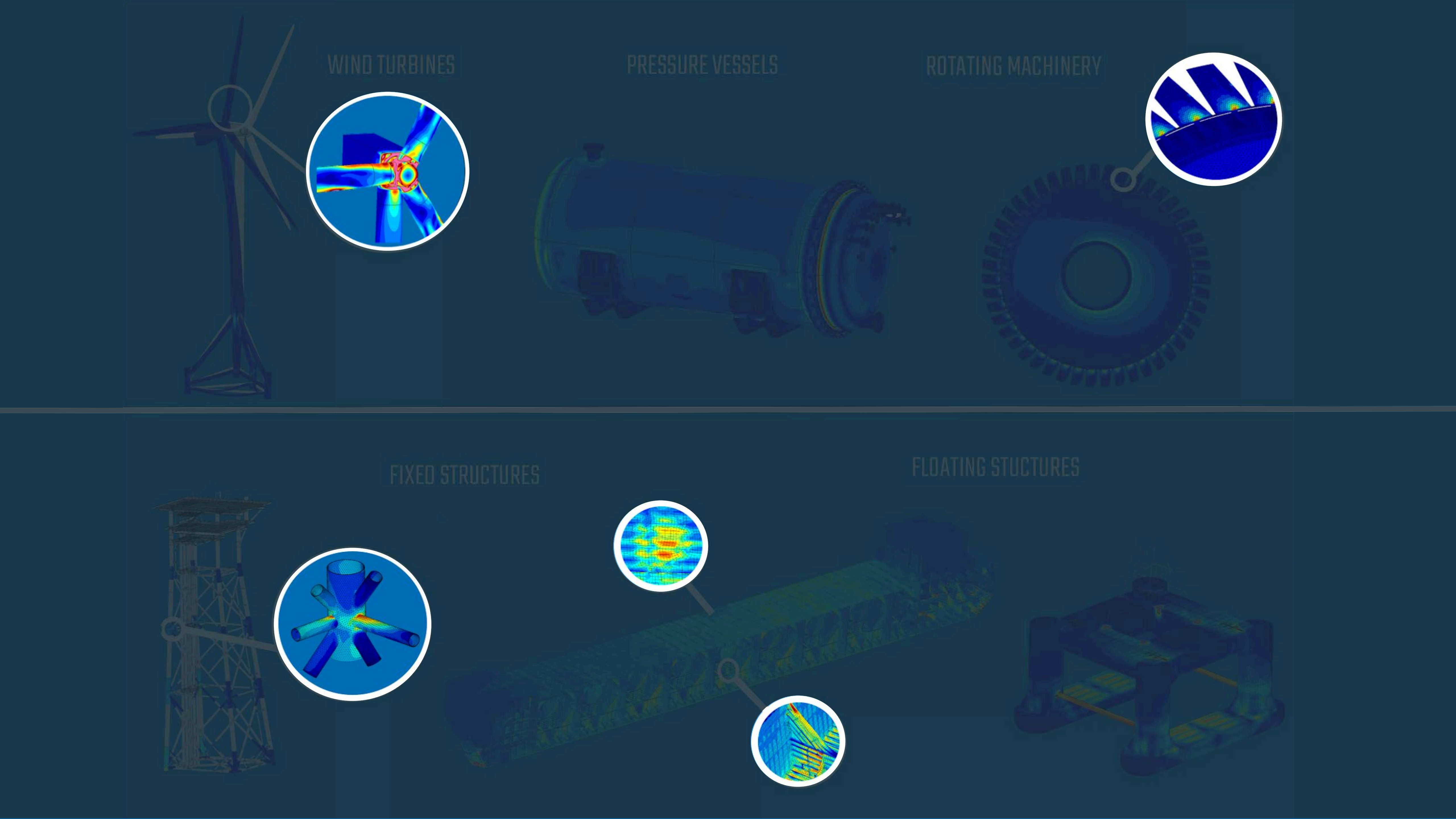
Operators face a number of significant challenges with systems of these types:

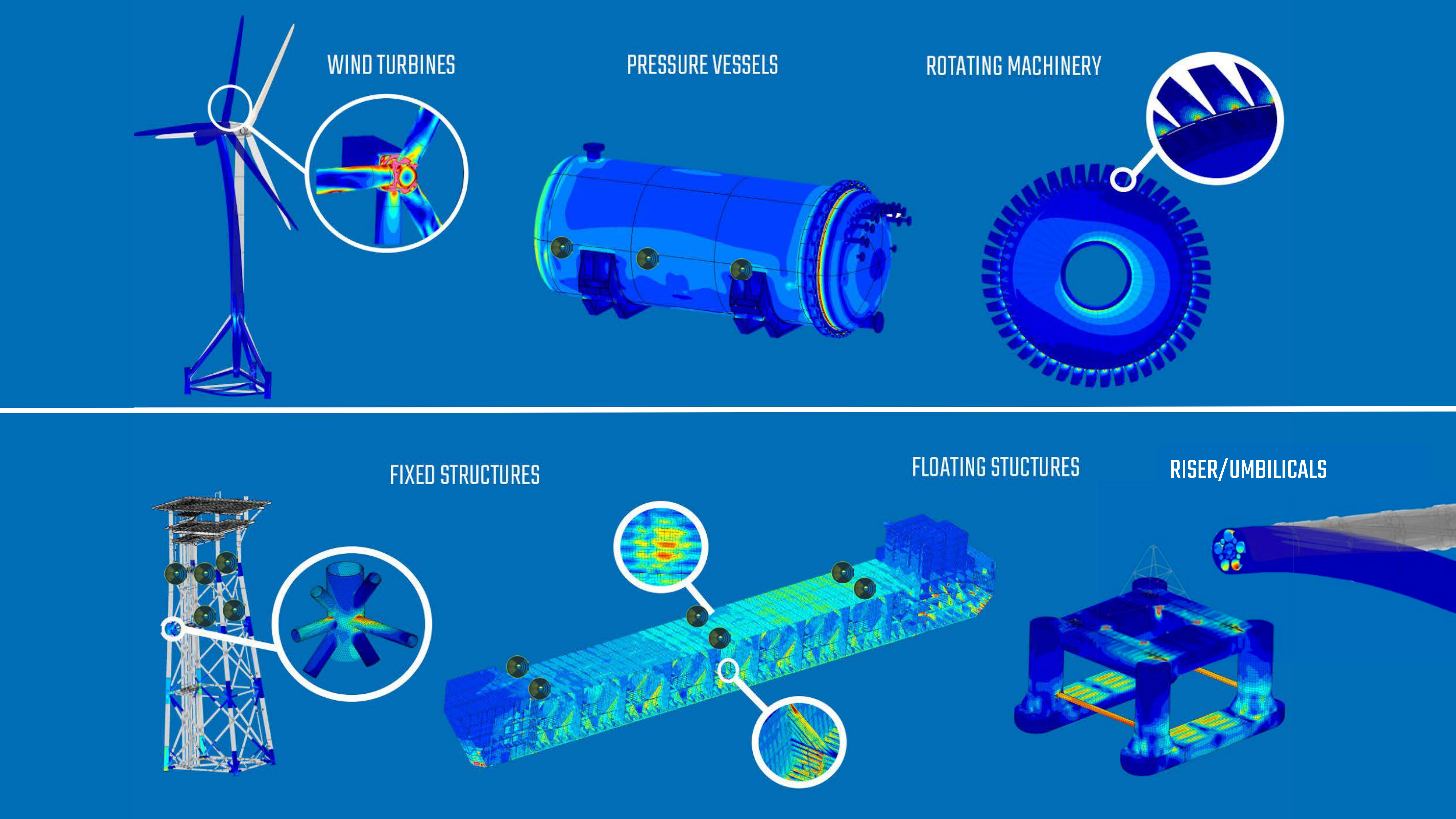
- Systems are large and complex, deployed for decades, often operated beyond original design life
- Failure leads to safety and environmental risks
- Downtime is extremely costly in terms of lost revenue and repairs
- Reliability is driven by structural integrity issues such as structural fatigue, buckling, and cracking
- Inspection and maintenance is often based on ad hoc rules with significant uncertainty and which require engineering judgement and interpretation

Akselos's Take on Digital Twins

To meet these major challenges, heavy industry is increasingly looking toward Digital Twins to provide **quantitative** guidance for the inspection, maintenance, and operation of critical assets

Akselos Digital Twin: Physics-based model of an entire asset which incorporates the current condition (e.g. based on inspection data), and enables fast high-fidelity structural integrity analysis, optionally linked to sensor data (IIoT)


WIND TURBINES
PRESSURE VESSELS
ROTATING MACHINERY
FIXED STRUCTURES
FLOATING STUCTURES


WIND TURBINES
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FIXED STRUCTURES
FLOATING STUCTURES
RISER/UMBILICALS

1. Digital Twin Context
2. **Technology Overview**
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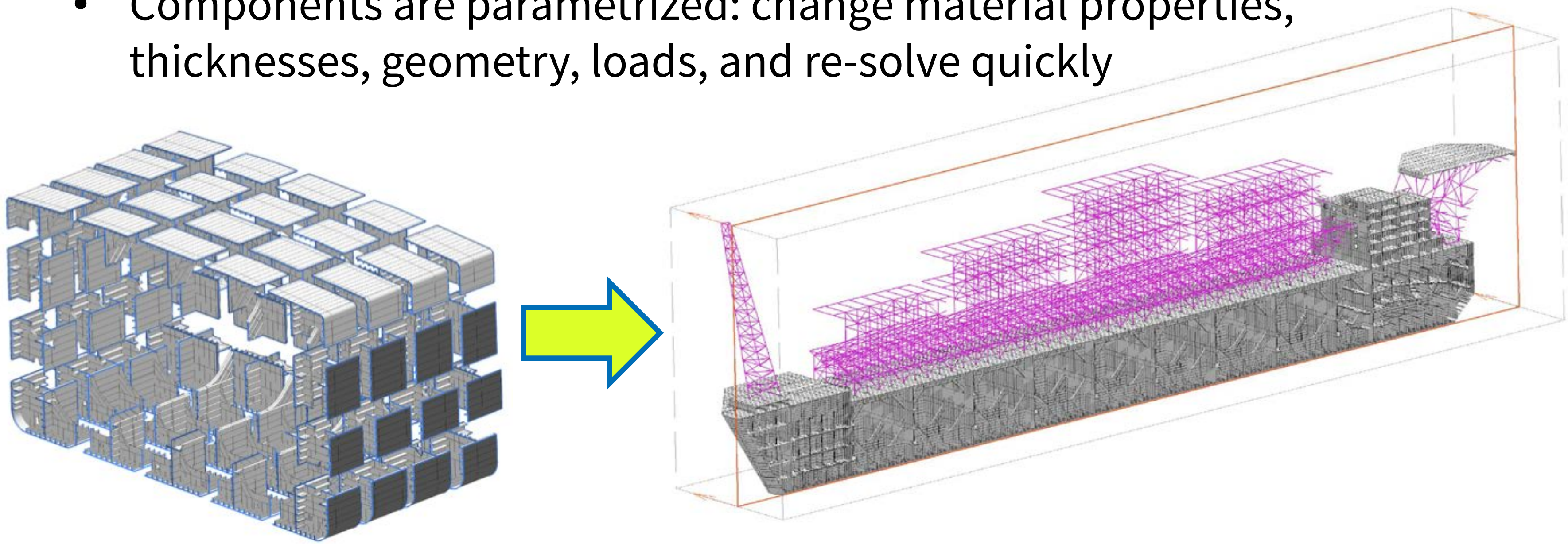
Akselos accelerates and "scales up" FEA via a new solver type:

RB-FEA (Reduced Basis Finite Element Analysis)

- Component-based reduced order modeling
- Two-phase approach gives ~1000x speedup compared to FEA: (1) **Component Pre-analysis** and (2) **Model Evaluation**
- Components are parametrized: change material properties, thicknesses, geometry, loads, and re-solve quickly



AKSELOS AT A GLANCE

MIT developed technology protected by issued patents

RB-FEA TECHNOLOGY AT A GLANCE

100 academic publications

100

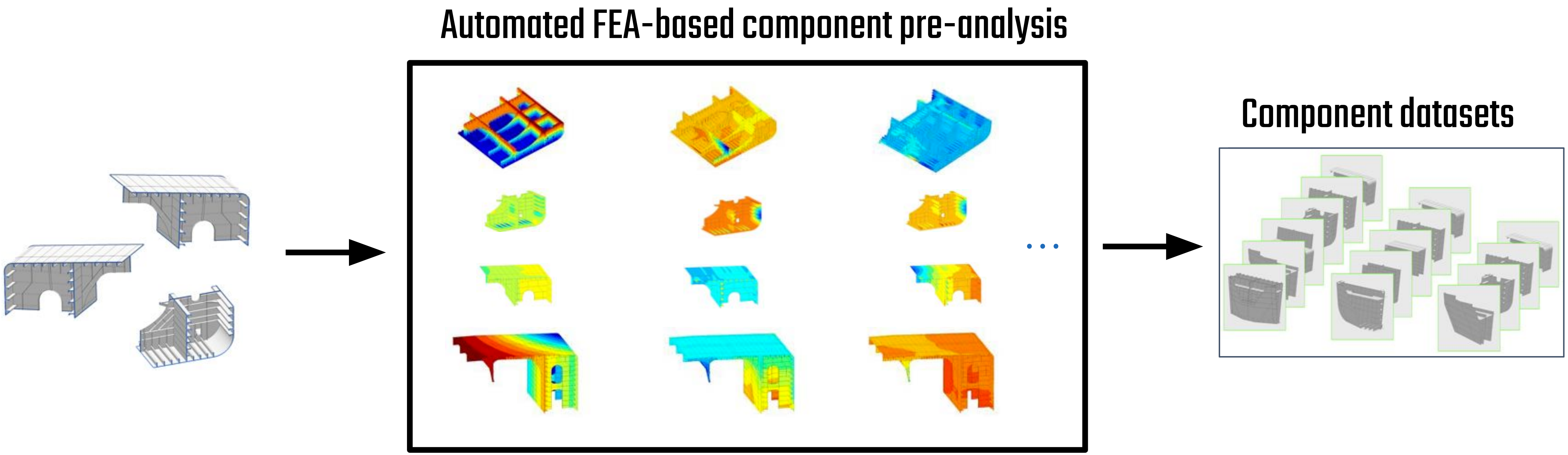
AKSELOS AT A GLANCE

R&D funded by US Department of Defence

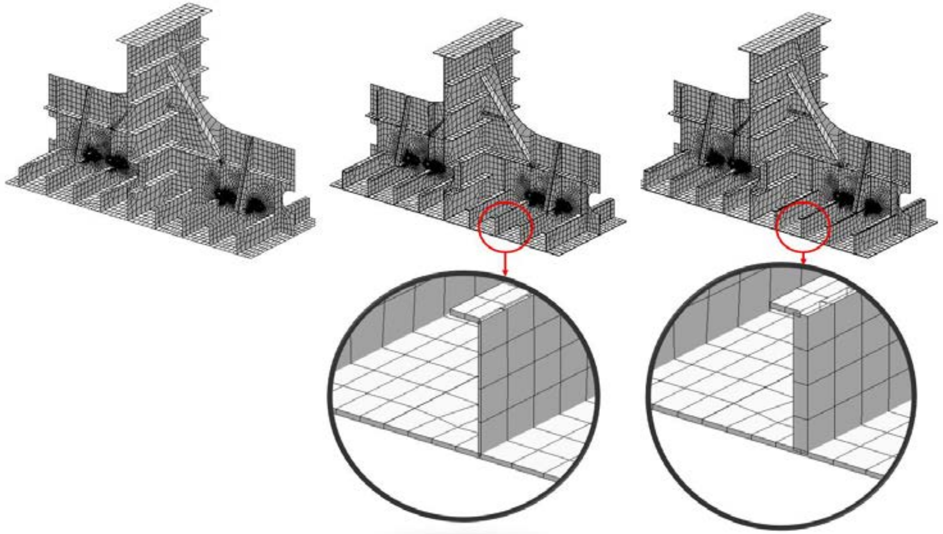
Component Pre-analysis

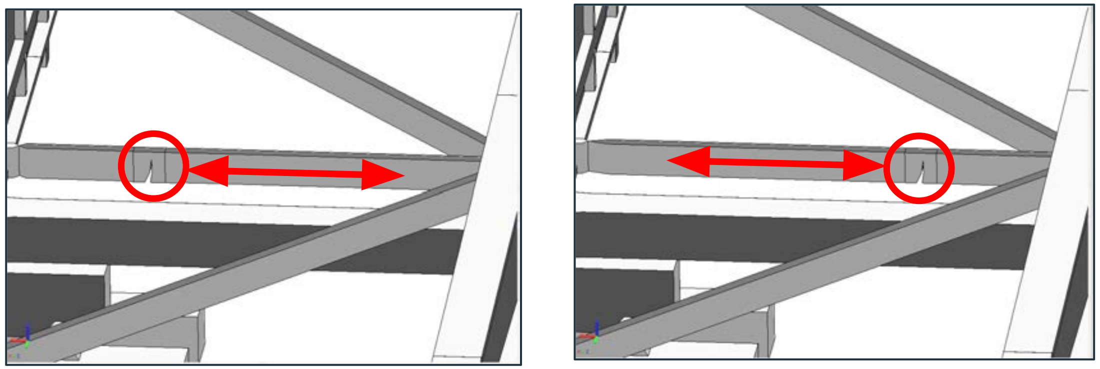
- Automated FEA + postprocessing of components (individual and groups) to construct accurate reduced model of component physics and interactions

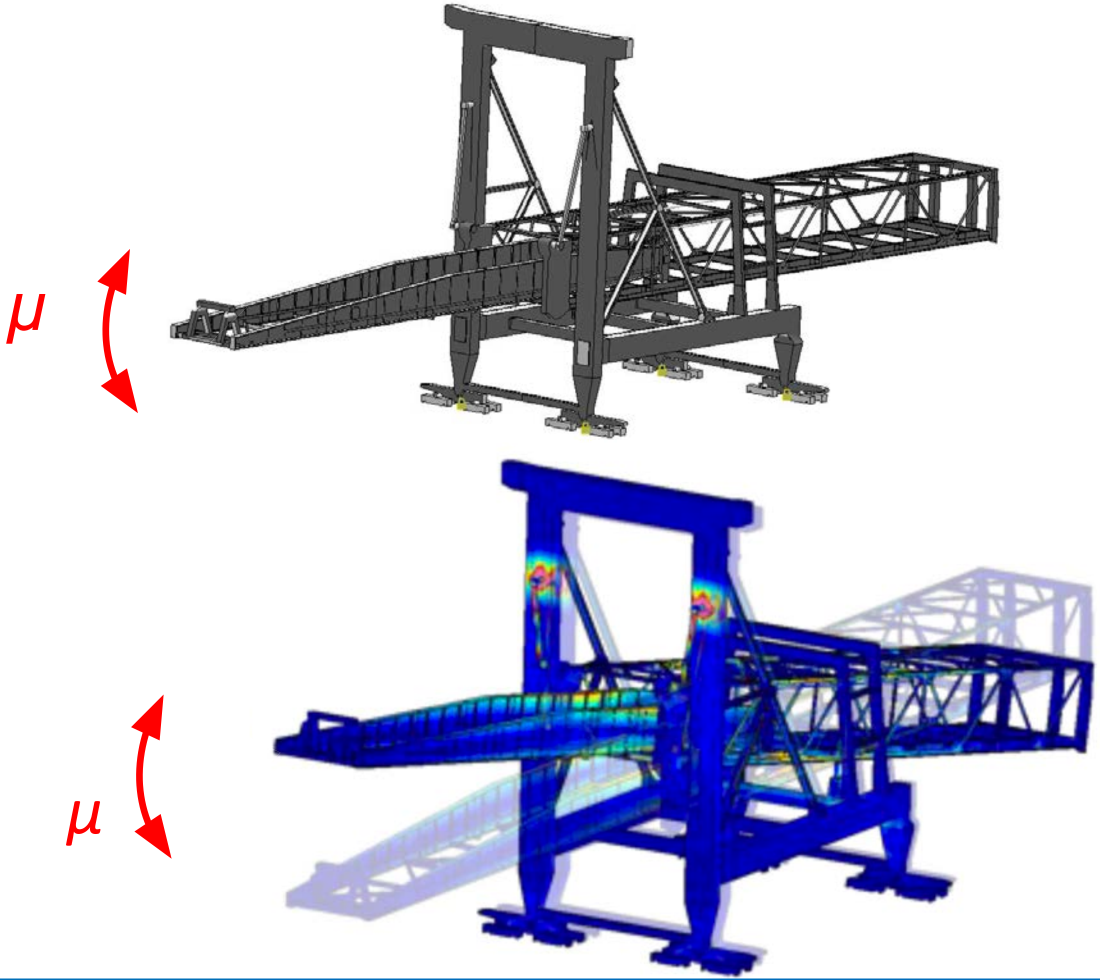
- **Performed upfront (during Digital Twin setup)**, datasets **stored** and **reused** over the asset's lifetime



Components are Parametrized







AKSELOS

Akselos RB-FEA technology at a glance

1000X FASTER

Provides major speedup compared to FEA for linear PDEs, e.g. **>1000x** for large-scale problems

1000X LARGER MODELS

Easily solve models with **>100m** FEA DOFs. This enables true condition-based models of entire assets (Digital Twins).

PARAMETRIC

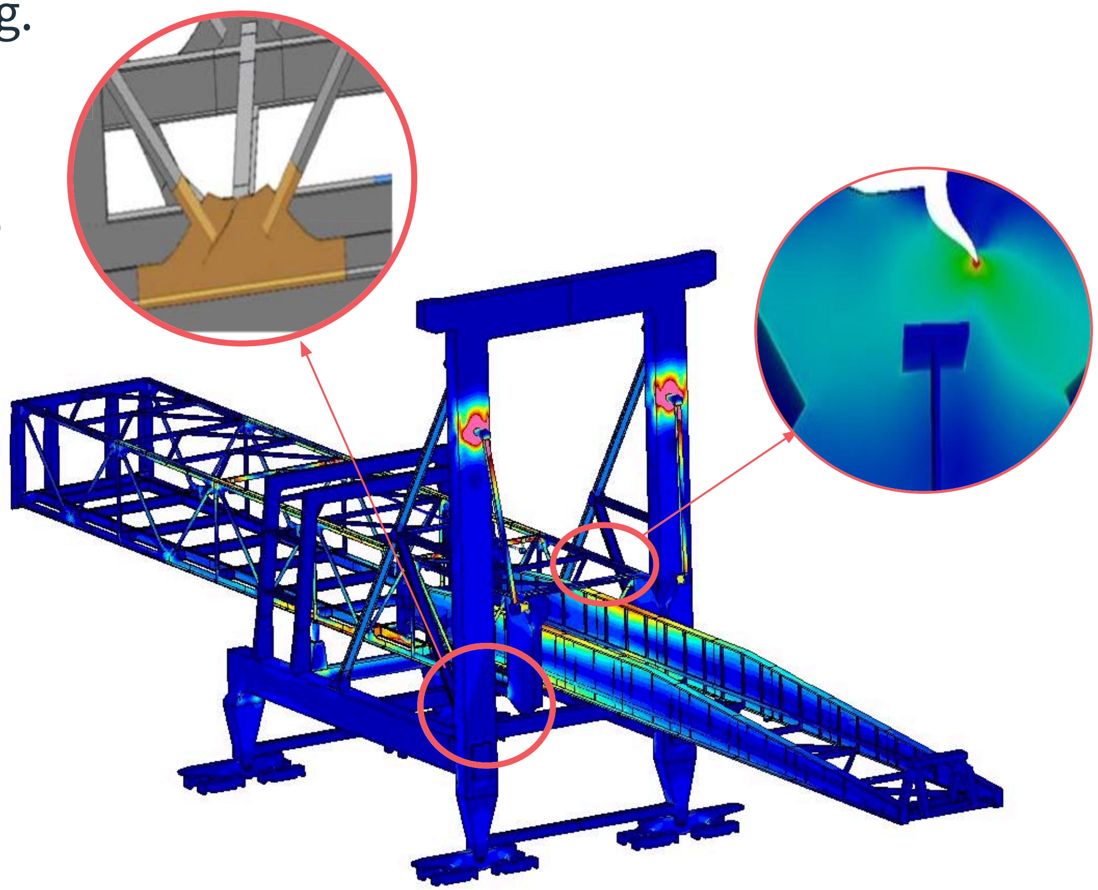
Modify models by changing parameters. Efficiently handles systems with many parameters, e.g. **>1000**

COMPONENT-BASED MODELING

Modular designs, easily add/remove/replace components

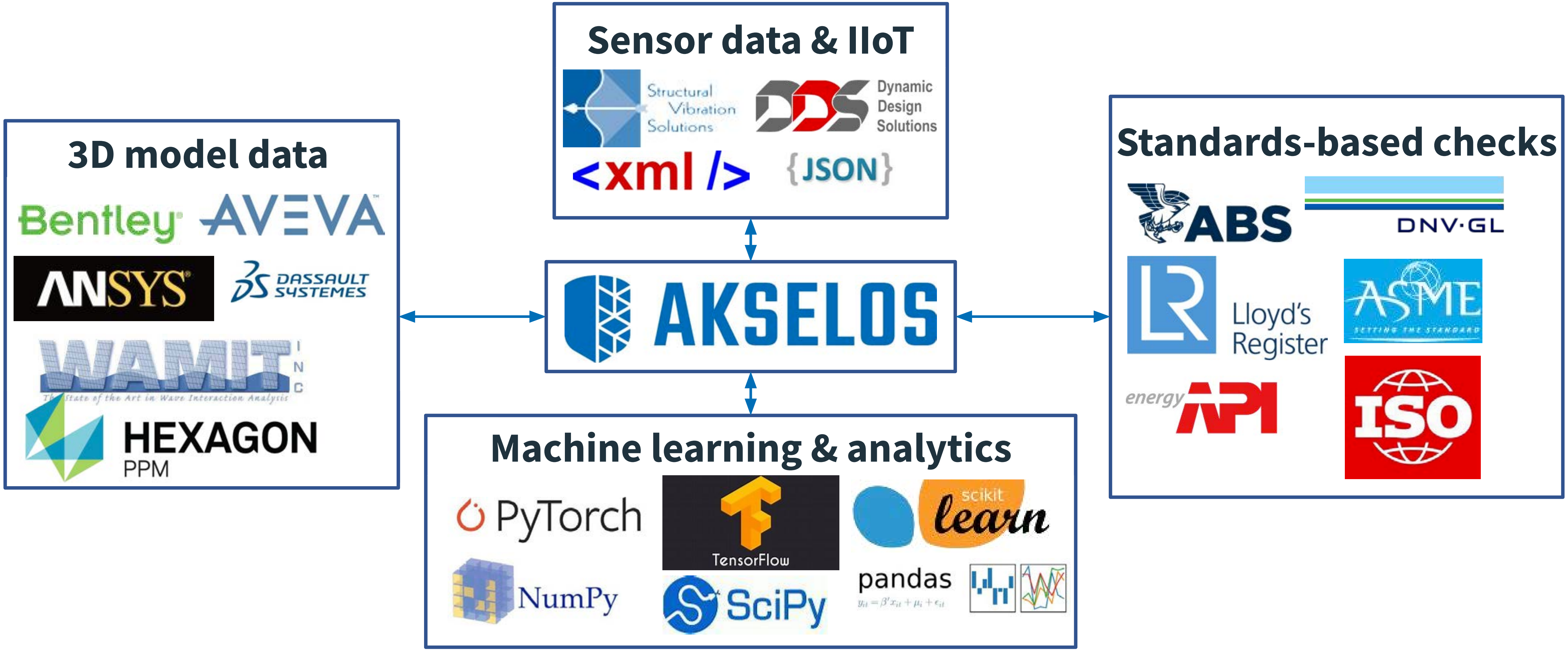
CLOUD-BASED PLATFORM

Provide all users with powerful computational platform via secure client-server architecture

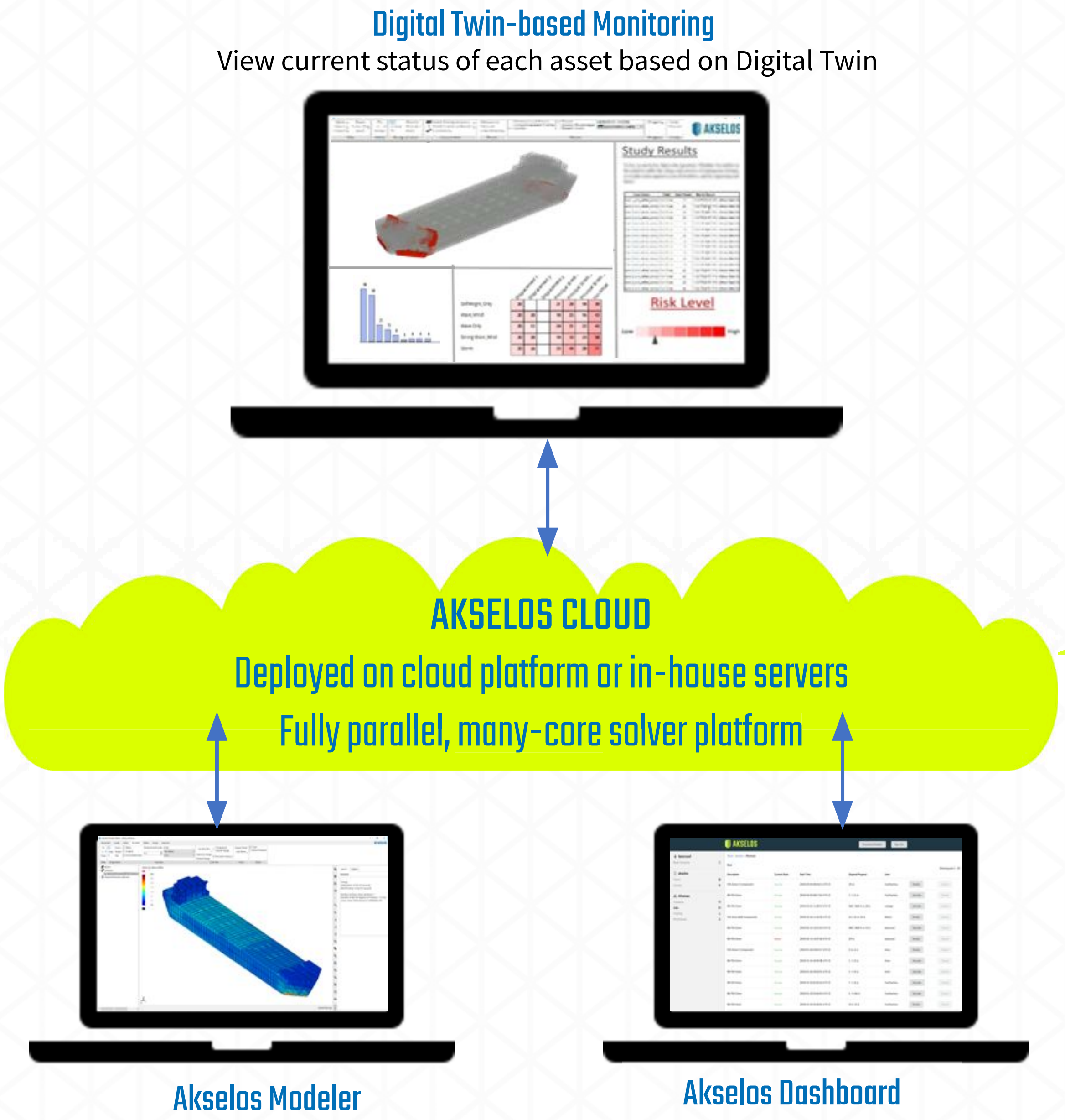


Integrates with the Digital Transformation Ecosystem

Open API (Python-based), open data formats, import/export data and models



Akselos Cloud



Cloud-based digital twins for live asset monitoring from any office around the world

1. Digital Twin Context
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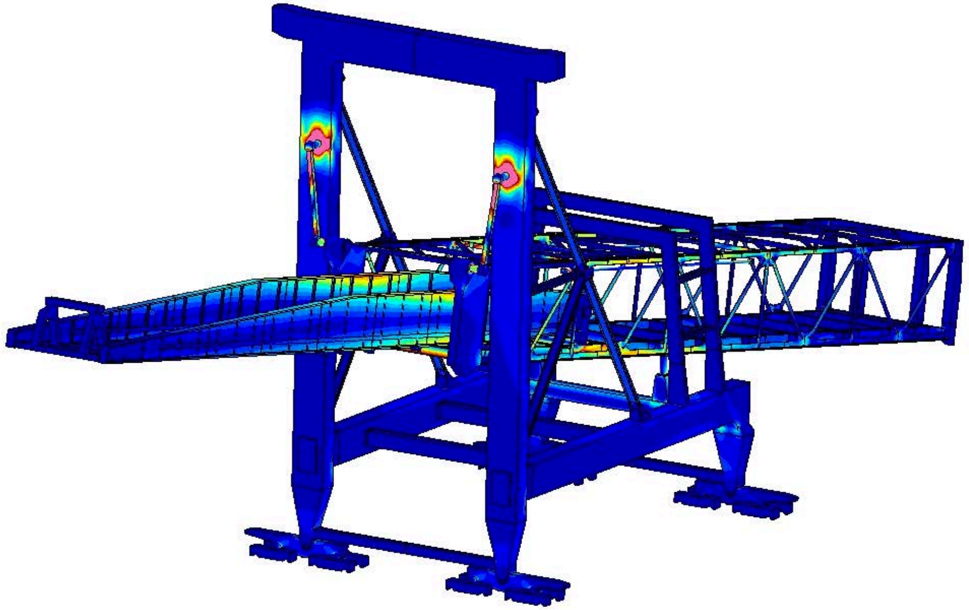
Example: Shiploader

FEA DoFs: 20 million (P2 TET elements)

RB-FEA: 166 components, 287 connections



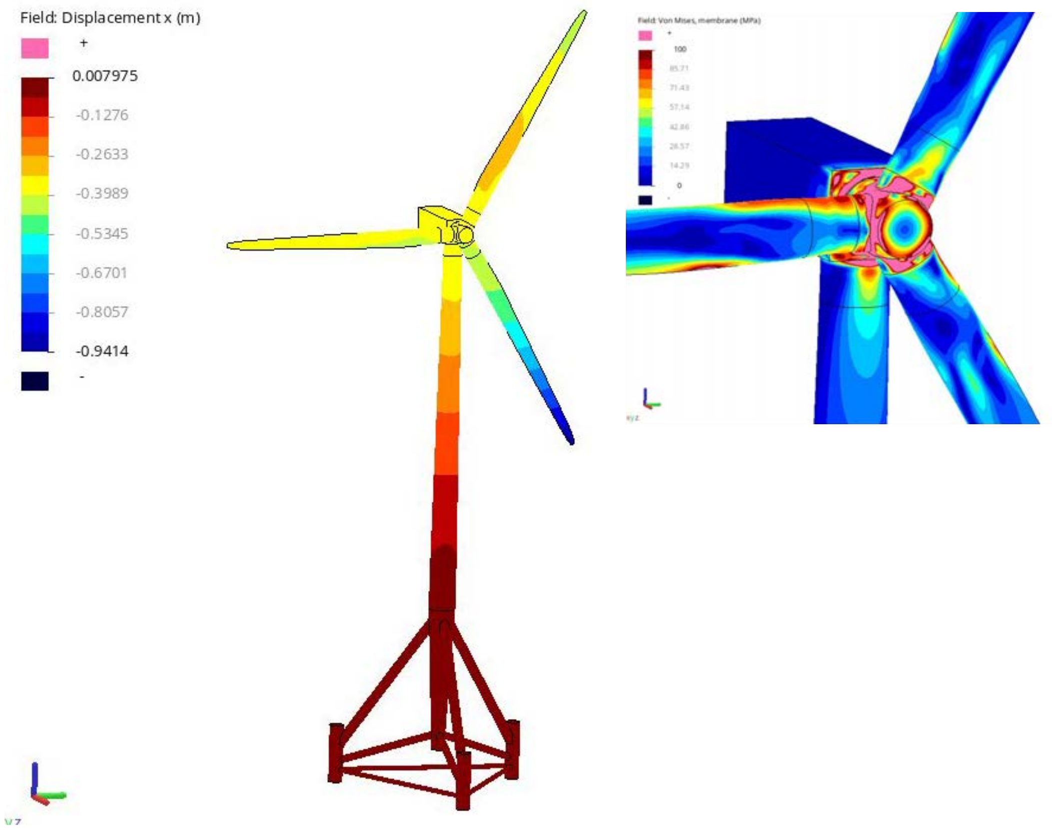
RB-FEA: ~ 1 second

Accuray validated for submodels: < 1% wrt to FEA

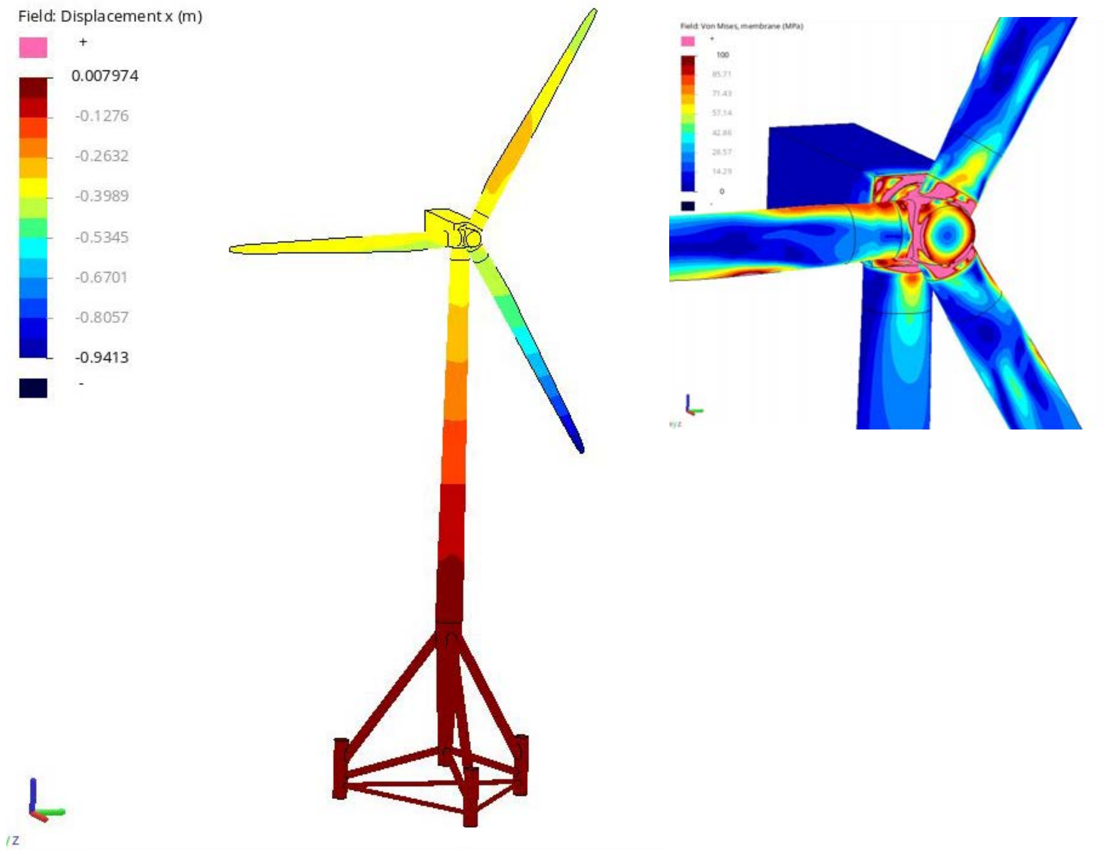
Example: Windturbine

FEA DoFs: 9.8 million (MITC4 shell elements)

RB-FEA: 31 components, 36 connections

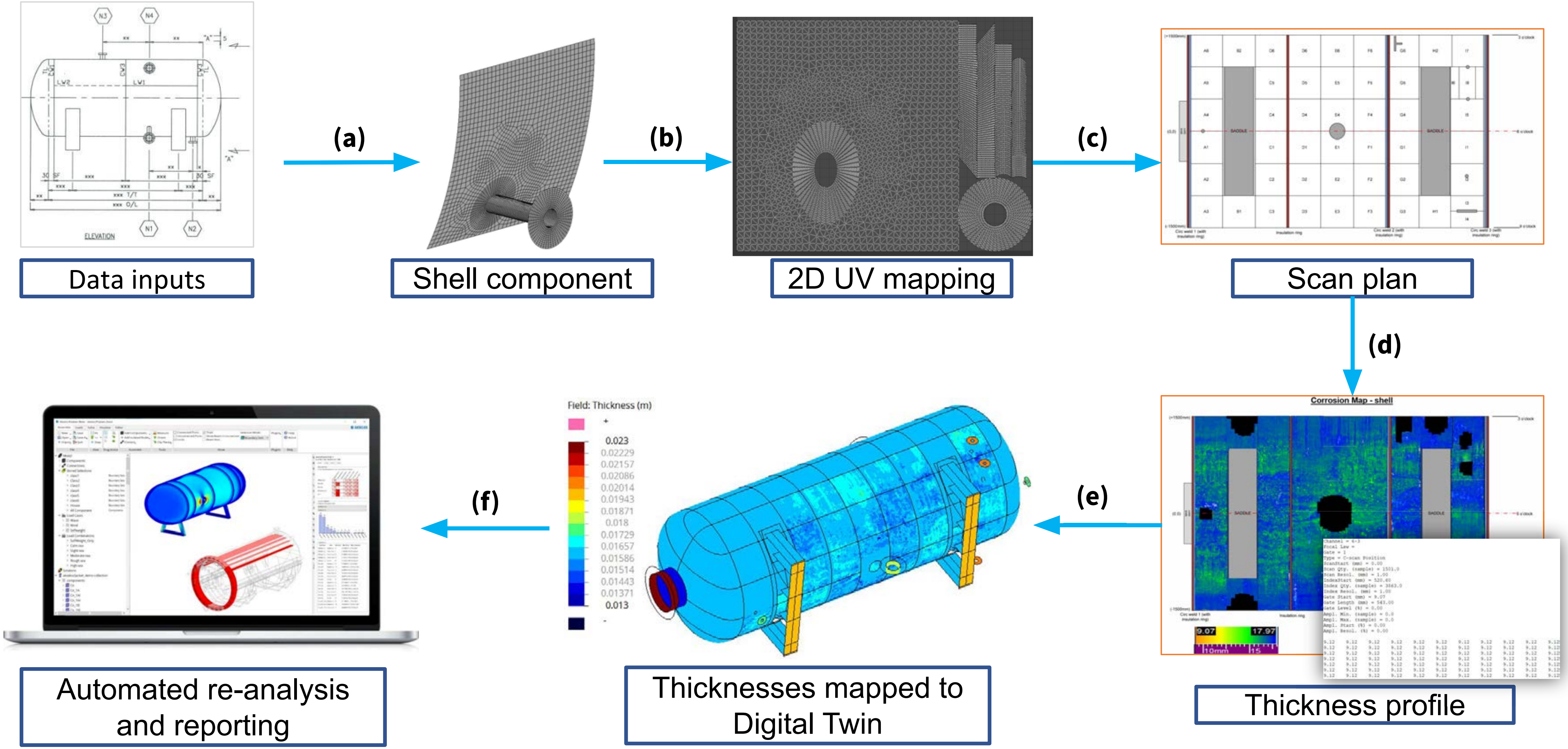


FEA: 155 seconds



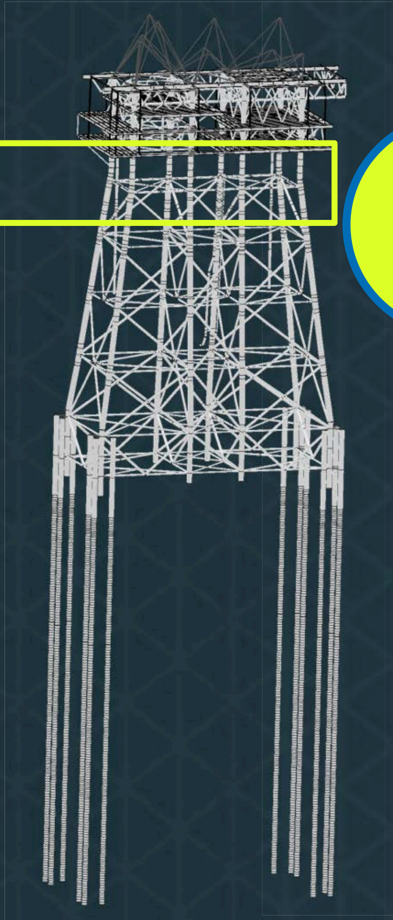
RB-FEA: 0.06 seconds

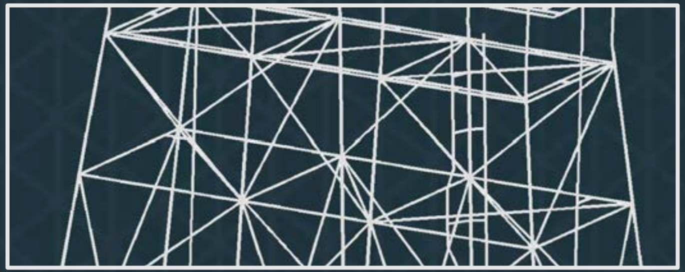
Example: Digital Twin for Pressure Vessels



Life Extension for Offshore Platforms

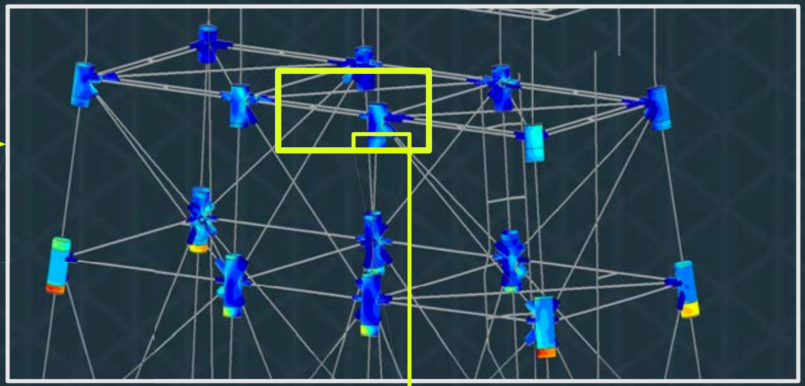
Beam model

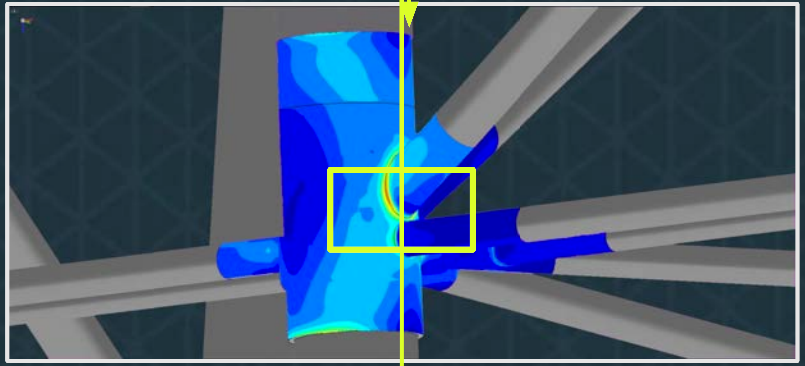


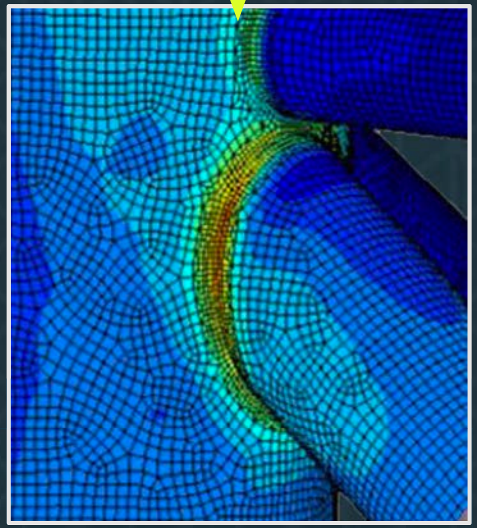


VS

AKSELOS Model







Also fully supported in Akselos Integra

With 3D joint mesh modeling

AKSELOS AND VALUE GENERATION – FPSO CASE STUDY

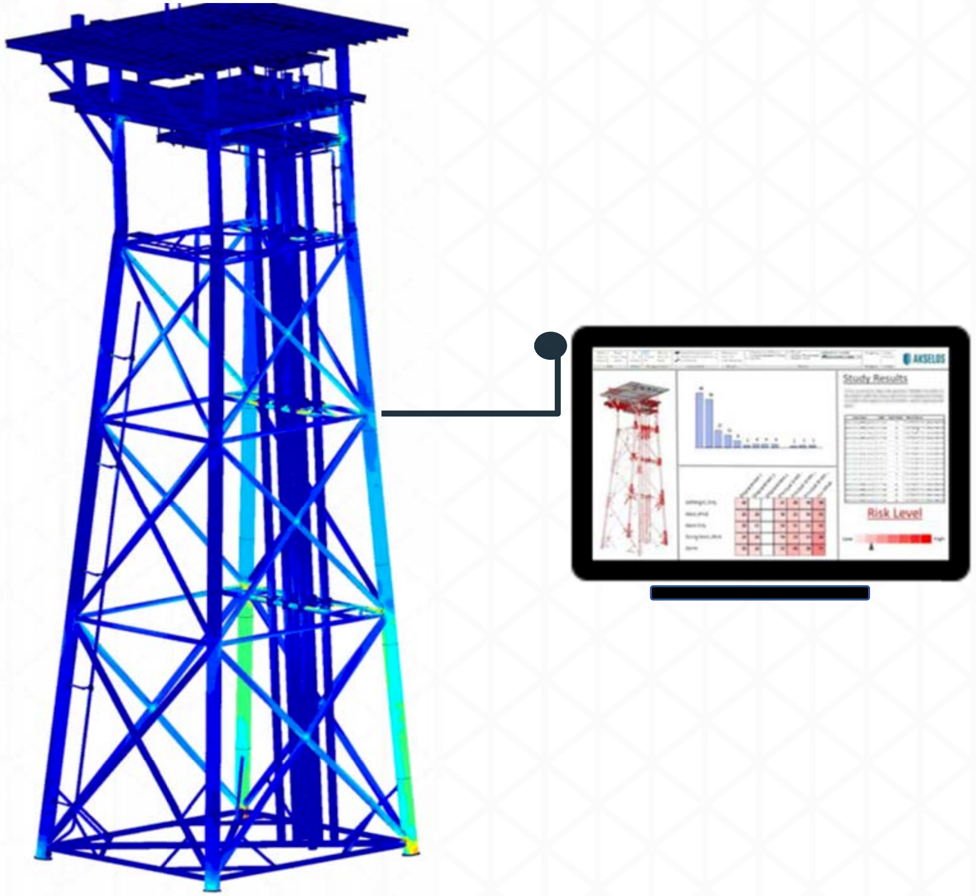
OPEX improvement

Reduce OPEX achieved by improving the quality and timing of the inspection; also reduced down time.

Life Cycle management

Further wins in cost improvement are achieved with decision support for the FPSO.

Case Study:
Fixed Offshore Platform

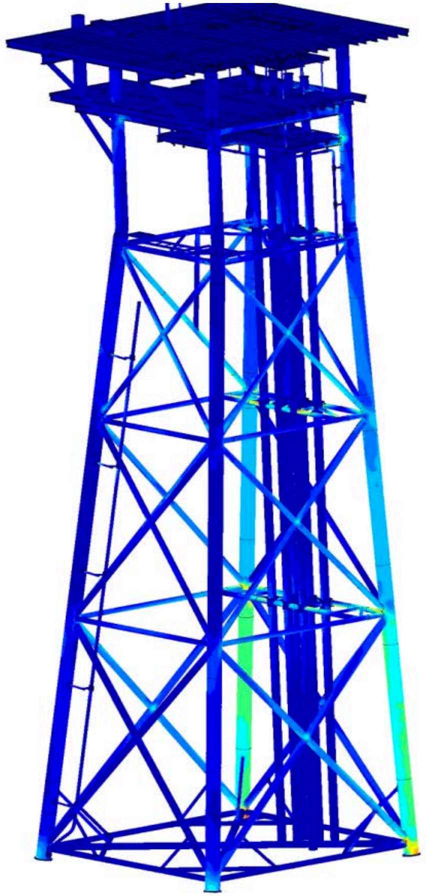


Digital Twin of Fixed Offshore Platform

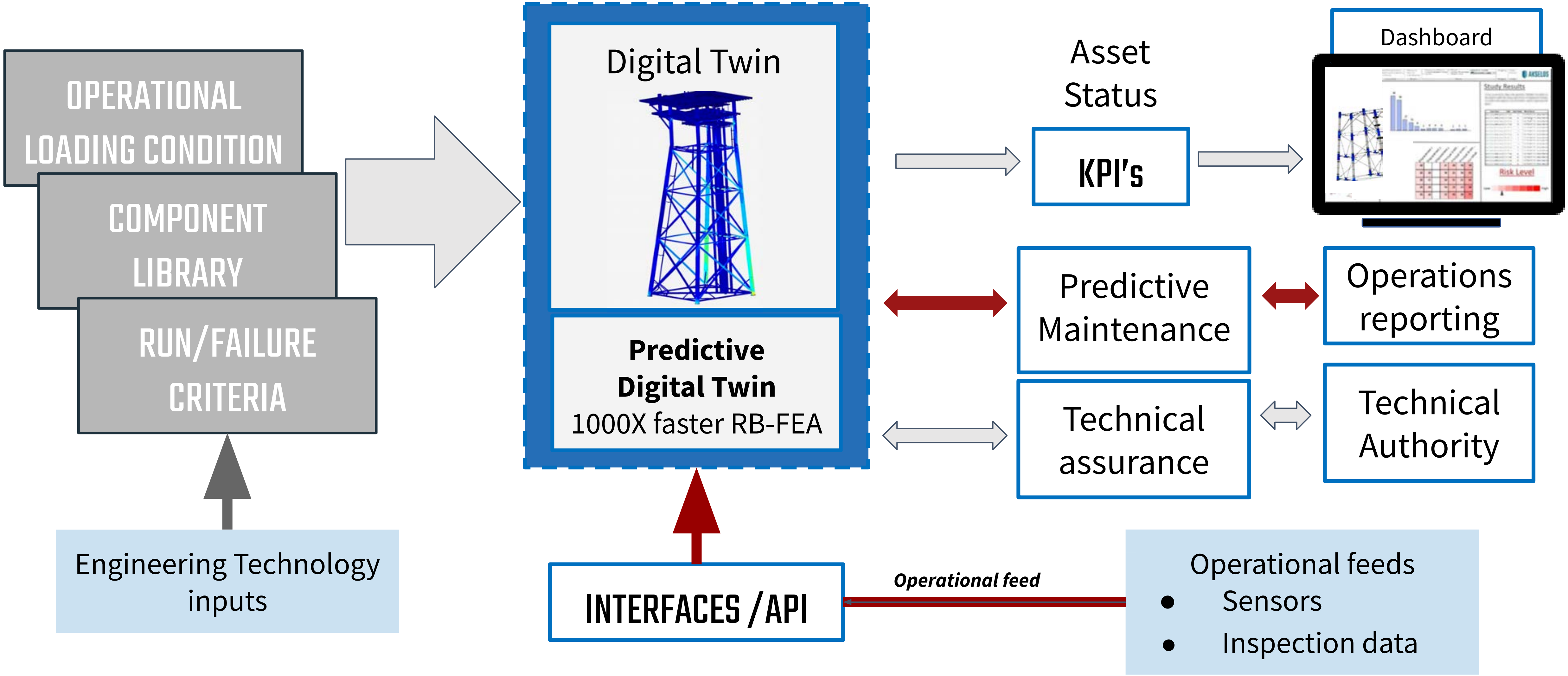
- Large fixed Platform in UK sector of North Sea
- Long Field life expected for the Asset

Motivation:

- Extend Asset Life
- Improve operations and responsiveness
- Improved economics



AKSELOS DIGITAL TWIN: BUILD AND RUN

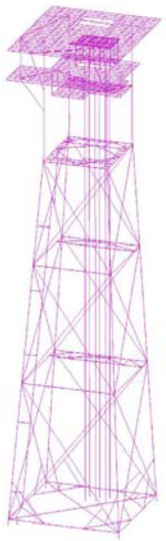


TRUE REPRESENTATION IN REAL TIME (1/4)

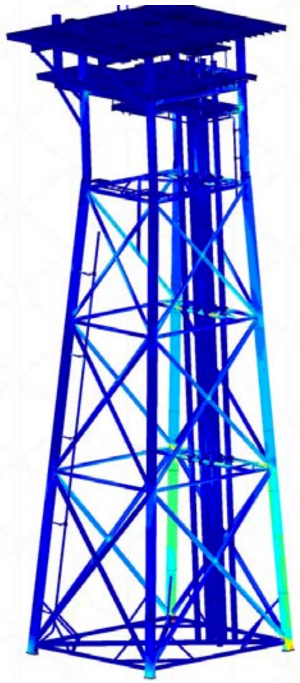
1. Create high-fidelity Digital Twin

Create a **condition-based model** that includes all relevant information from the design stage up to inspection data

Traditional beam model using SCF



New approach



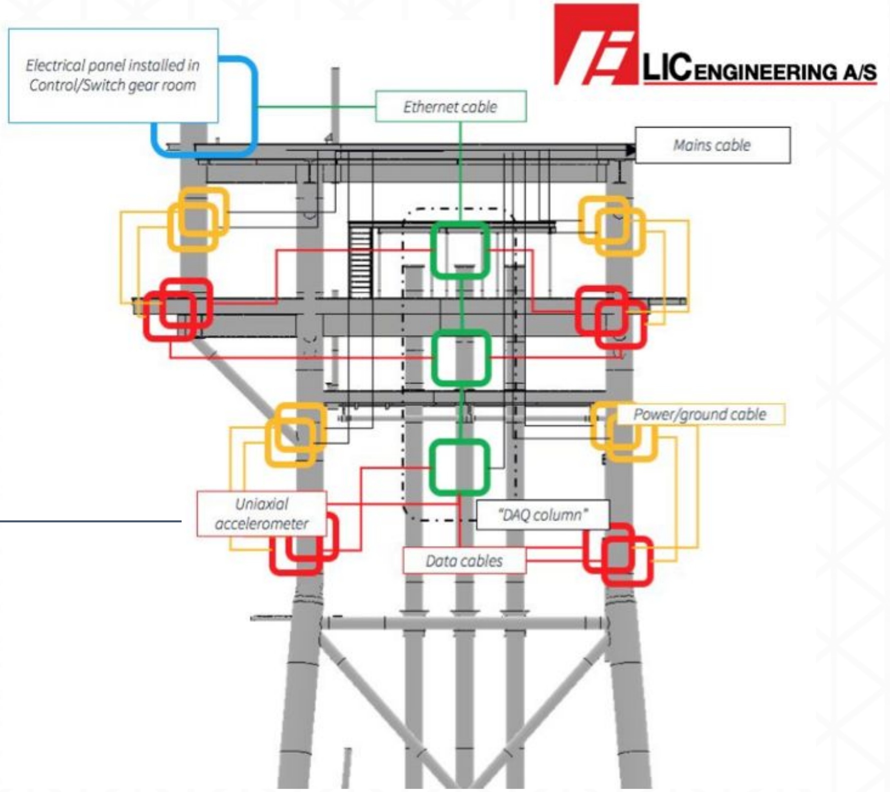
Dynamic, holistic 3-D calculated Digital Twin

TRUE REPRESENTATION IN REAL TIME (2/4)

2. Install sensors on asset, link to Digital Twin

Installation of sensors (accelerometers, strain gauges, etc..) and connections for the platform

Sensors provide continuous data stream for **real-time monitoring**



Sensor data is linked to the Digital Twin

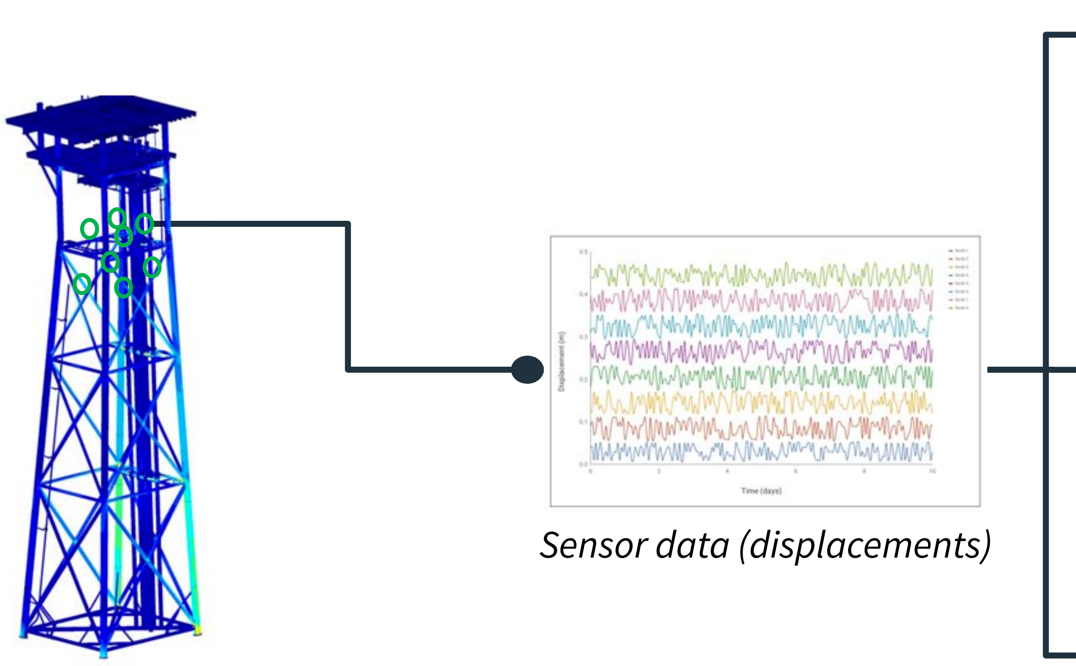
TRUE REPRESENTATION IN REAL TIME (3/4)

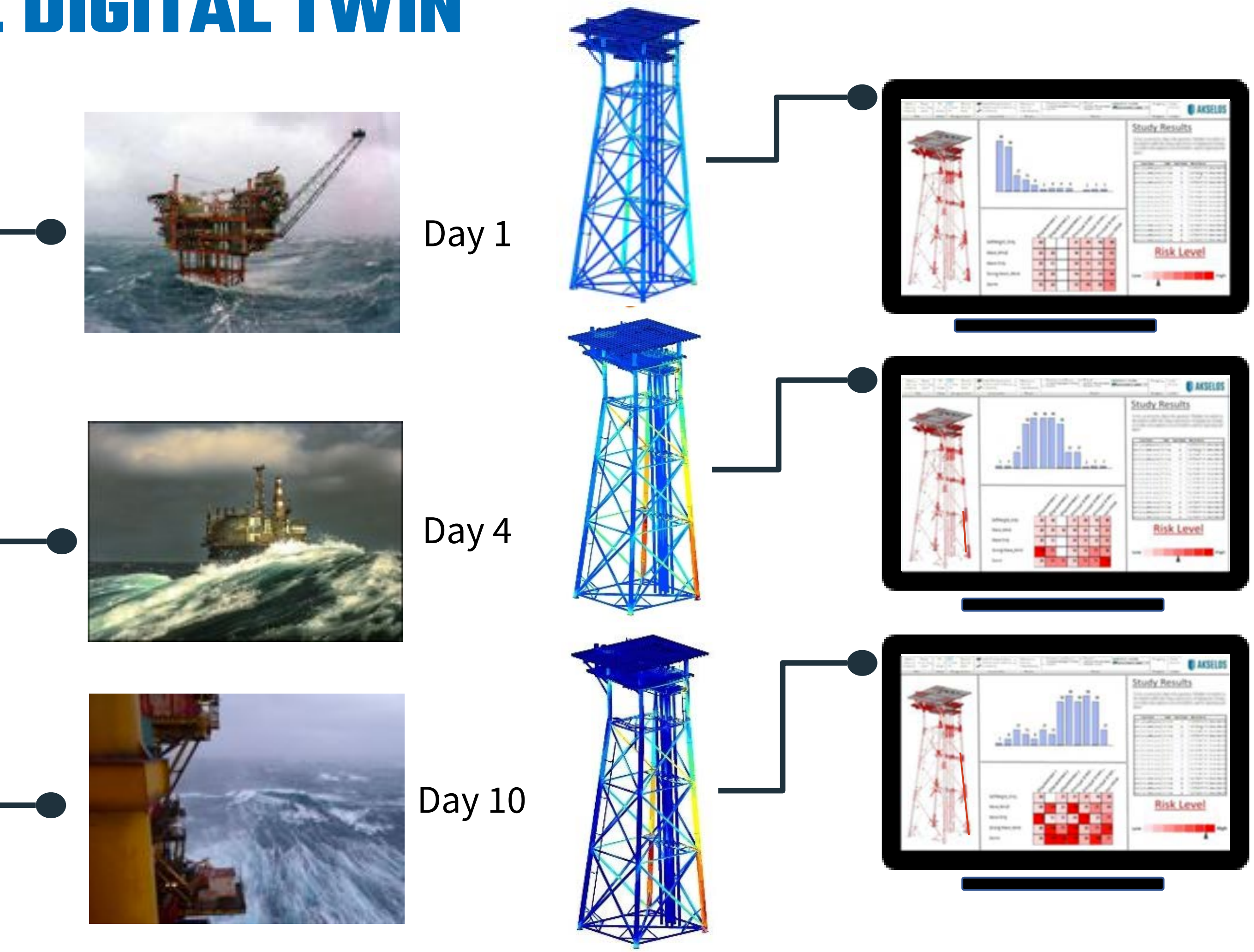
3. Calibrate Digital Twin based on data flows

1 DATA COLLECTION	2 DIGITAL TWIN CALIBRATION	3 DIGITAL TWIN EVALUATION
Initial data collection of reference data	Tuning/updates based on new inputs	New state of the asset assessed

CONDITION BASED PREDICTIVE DIGITAL TWIN

4. Integration with sensor data





The calibrated displacements and stresses enable measurement-based analysis of the entire structure *(e.g. fatigue and buckling code checks such as ISO 19902, API, AISC, DNVGL, etc., soil/pile monitoring, failure mode analysis, anomaly detection).*

AKSELOS AND VALUE GENERATION – FIXED PLATFORM CASE STUDY

Asset Life Extension (ALE)

Over 15 years of additional structural life was unlocked from the asset.

OPEX improvement

Lower OPEX that anticipated. Better Economic outcome.

Life Cycle Management

Reduced one time engineering costs.

Case Study:
Life Extension of Hydro Plant
- Pump storage unit

Life Extension of Hydro Plant – Pump storage unit

BUSINESS CHALLENGE

- Ageing assets approaching end of design life
- Unqualified structural risks plus high Inspection costs
- Decommissioning

BENEFITS

- Extend Electrical Generation capacity & increase revenue

AVOID OR POSTPONE A MAJOR CAPEX PROJECT

SCOPE

Hydro Pump Station Asset

- Identify a new minimum operational life
- Identify best fit analog data for digital model

OPPORTUNITY

- Life Extension of existing Pressure manifold with improved structural modelling and assessment
- Lower Inspection Cost
- Upside: Assess future modes of operation

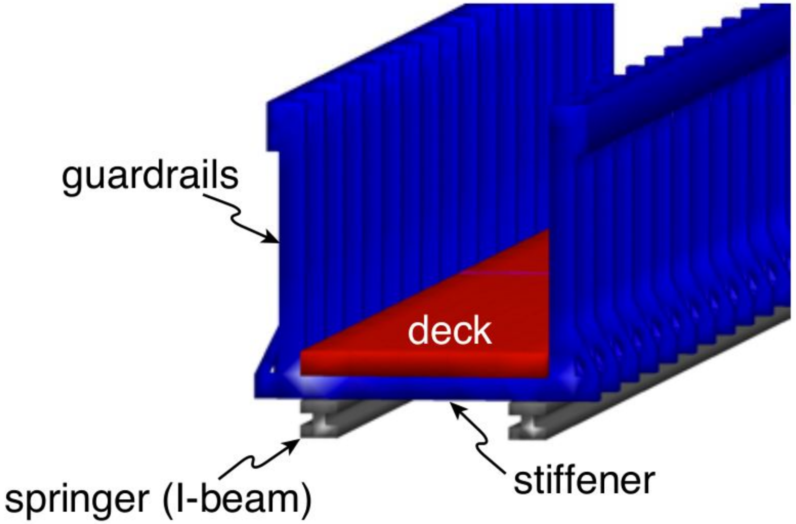
EXPECTED VALUE

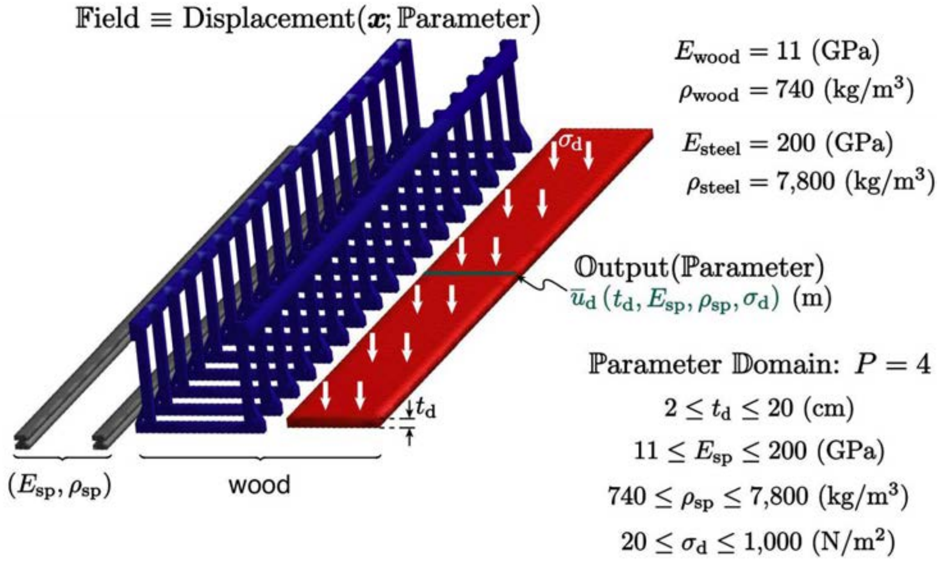
> > 5 X ROI

1. Digital Twin Context
2. Technology Overview
3. Examples and Case Studies
4. **Mathematical Background**

Partial Differential Equations

- used to model physical systems (e.g. structures, fluids, thermal, acoustics, electromagnetics, …)
- depend on model parameters (e.g. material properties, model geometry, loads, boundary conditions, …)





PDE:
$$\begin{aligned} -\nabla \cdot \sigma &= f, && \text{on } \Omega, \\ \sigma \cdot n &= t, && \text{on } \partial\Omega_t, \\ u &= u_d, && \text{on } \partial\Omega_d. \end{aligned}$$

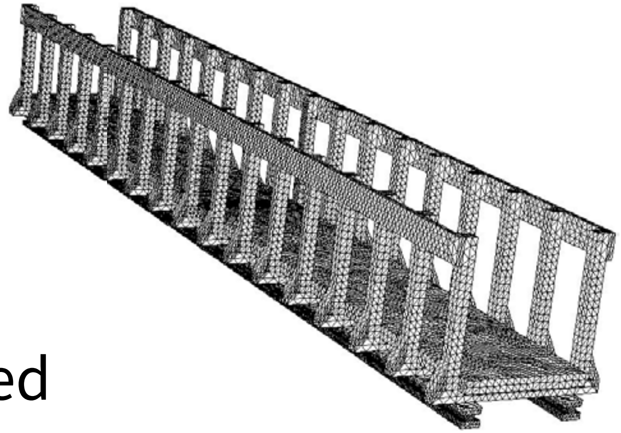
Many Query Context

Task:

- Solve the PDE many times with different parameter values
- Required in, e.g., optimization and uncertainty quantification

Typical approach with FEA:

- For each new parameter value, solve PDE from scratch
- For a large mesh and associated many degrees of freedom, the response time is slow and it hence becomes computationally infeasible if solutions for many different parameters are required



Goal:

- Develop reduced order models which allow for fast online evaluation time while maintaining accuracy

Reduced Order Models

Reduced order modeling is a family of numerical methods for reducing the computational cost associated with evaluating high-fidelity models such as FEA, CFD, finite differences

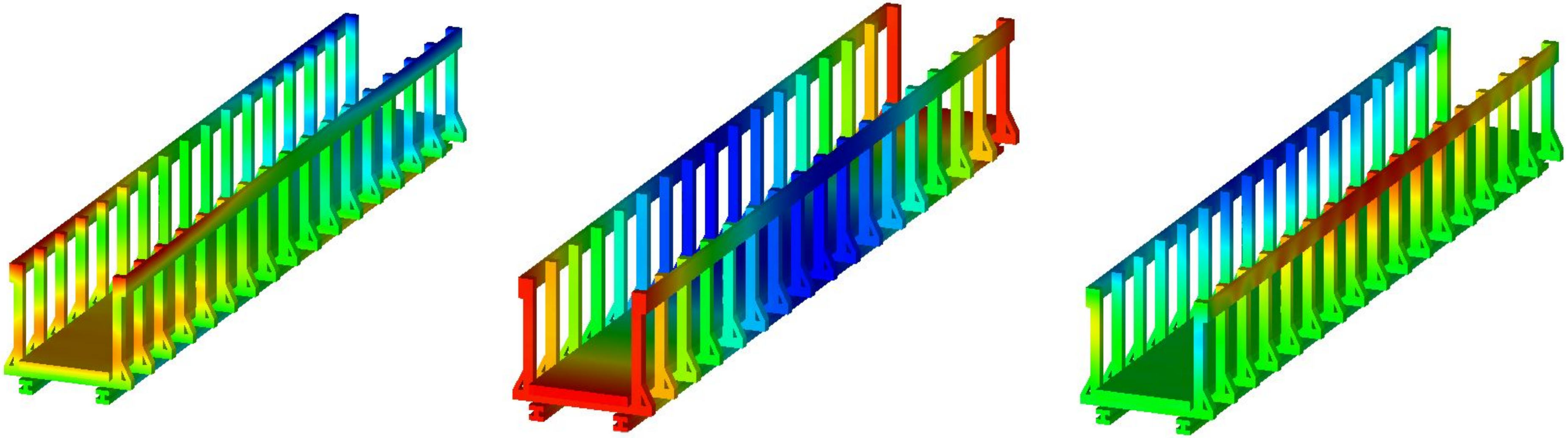
Very active research topic in academia for at least 2 decades, with a range of different methods, e.g.:

- Proper Orthogonal Decomposition (POD)
- Reduced Basis (RB) methods
- Low-rank tensor methods
- Gaussian Process Regression
- …

Yields surrogate models that are well-suited in **real-time** or **many query** contexts

The Reduced Basis Method

- Offline/Online decomposition to separate model training from fast model evaluation
- Model training by FEA solves at greedily chosen parameter samples (offline)
- Very fast evaluation in online stage

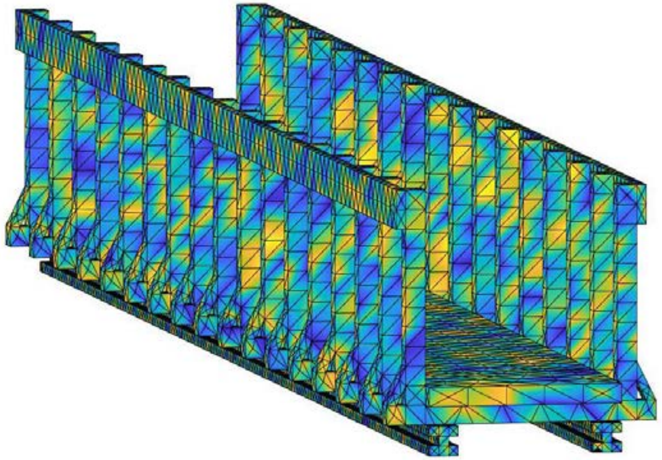


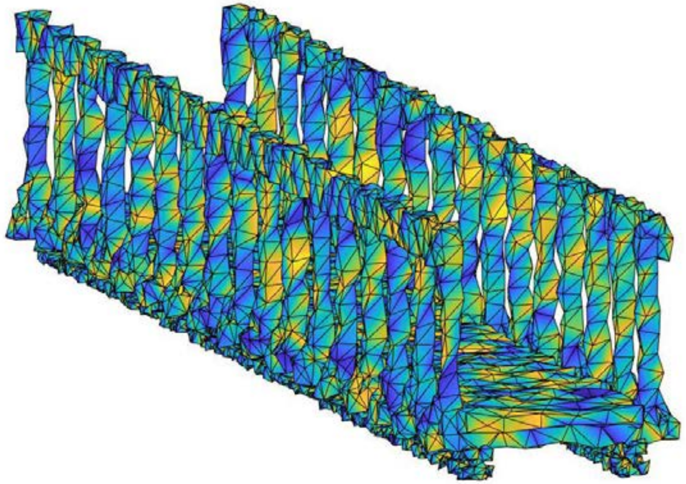
$n = 1$ $n = 2$ $n = 3$

Accuracy with $n = 28$ samples: $\epsilon = 10^{-4}$ in this case

The Reduced Basis Method

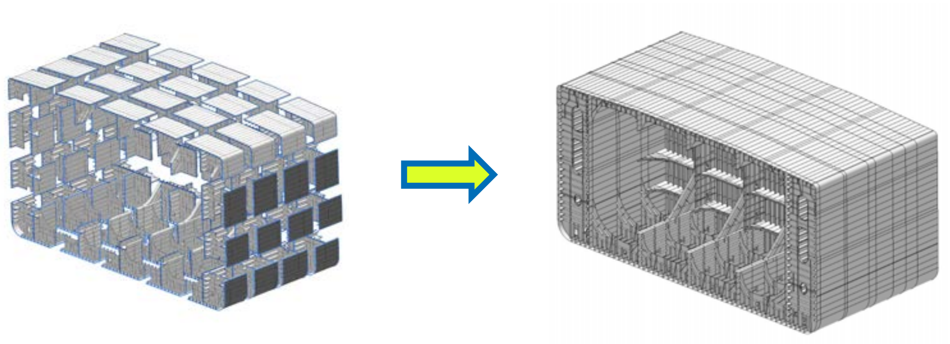
- RB method automatically constructs an approximation space that is highly targeted for solving the PDE
- In contrast, the full FEA approximation space is completely untargeted, e.g. it can represent arbitrary data irrelevant to solving the PDE, such as “random noise”:





Extension to Components

Construct RB models for components, and connect components together to form large parametrized models:



- Large models: Component training involves individual components or small groups of components only, hence never need to solve full model with FEA during Offline stage
- Many parameters: RB method requires relatively few parameters, but each component may possess a different (small) set of parameters
- Topology changes: Simply add/remove/replace components and re-solve

Retain the speed of RB: Typically observe 1000x speedup or more compared to FEA for large-scale models

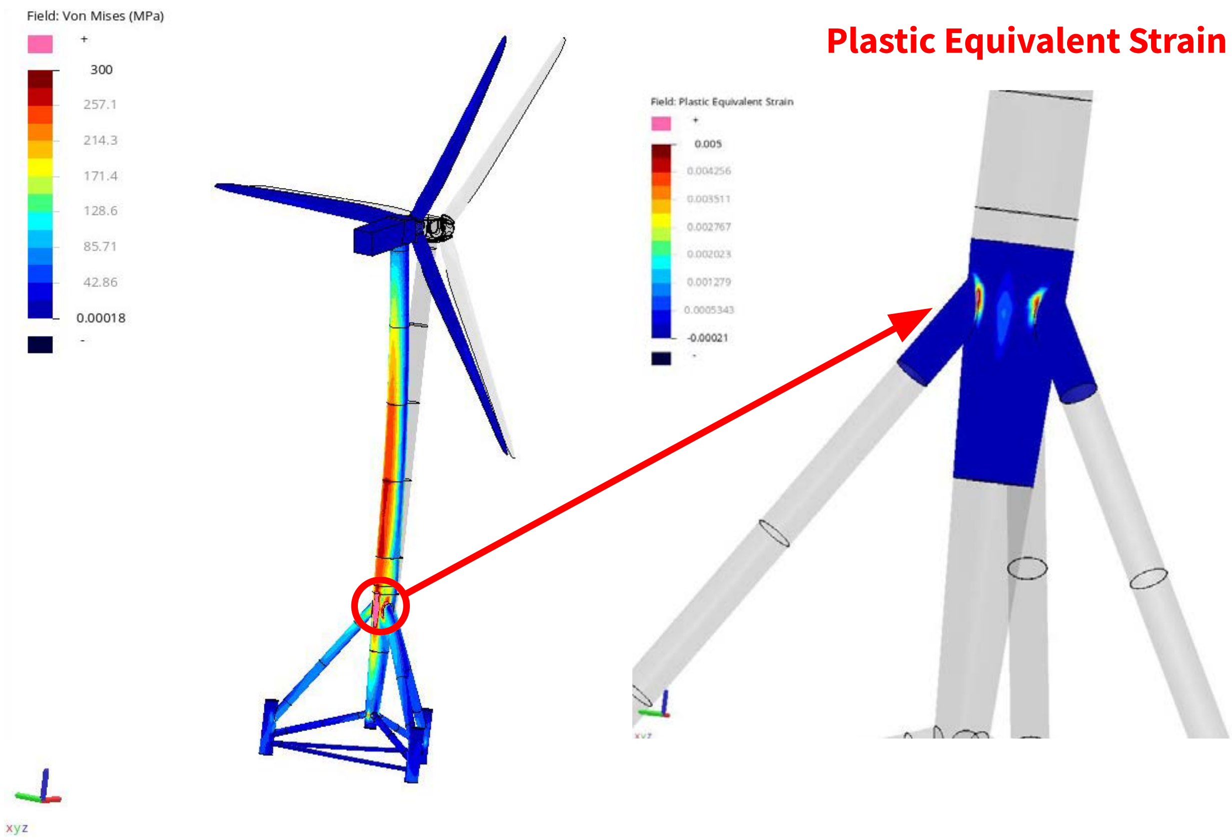
Incorporating Nonlinear Analysis

RB method applies to linear problems, but many engineering problems involve nonlinearities:

Core idea: Split domain into "linear" and "nonlinear" regions

Key points:

- Arbitrary nonlinearities in FEA region (e.g. contact, plasticity, finite strain)
- Accelerate the linear region, fast for "localized nonlinearities"
- Formulation is fully conforming, numerically robust



A revolution in how we build, manage, and protect our critical infrastructure

SAFETY

Manage **structural safety** risk for your **entire asset**.

EFFICIENCY

Reduce **unplanned downtime, OPEX.**

ASSET INTEGRITY

Lead operators towards **optimal asset integrity**.

DIGITAL ENABLER

Interact with your entire asset.

DIGITAL TRANSFORMATION

Create intelligent, **machine DNA.**