Accurate FOWT fatigue assessment at all design stages

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SUMMARY

From a substructure designer standpoint, floating wind engineering requires a new mindset compared to classic offshore oil & gas. Alongside the topics of serial fabrication and installation, these structures must be designed with full incorporation of a living payload: a large wind turbine generator.

Most of the substructure and mooring system's operational life will be spent with the turbine in production, largely determining fatigue (cyclic) loading. It is widely recognised that in such condition the mechanics of the system are strongly coupled; hence, reliable fatigue assessment can only derive from coupled load analysis.

Coupled analysis-based fatigue assessment at early project stage is here advocated to help quick design convergence and minimise risk and cost. Due to the multiplicity of load cases involved and the need to process each time series in full for damage computation, an efficient time-domain calculation chain is paramount for project success.

Saipem's in-house tool chain solution based on DNV-certified methodologies is presented, with the following key properties:

- Built to quickly derive stresses at structural details (welds) right from coupled analysis outputs.
- Incorporates substructure flexibility in the coupled analysis for realistic tower frequencies and ready access to internal loads.
- Cascades loads into efficient local structural models, analytical or finite-element. This solution enables a ~100x reduction in the computational cost of stress retrieval compared to a typical offshore FEM-based workbench.
- Methodology compatible with different coupled solvers (Orcaflex, Bladed, …) for prompt redeployment in varying project scenarios.
- Fully applied since the beginning of Saipem's STAR 1 floater design lifecycle. Fatigue proved to be influential by up to 30% on the primary steel mass.

Saipem is an advanced technological and engineering platform for the design, construction and operation of complex, safe and sustainable infrastructures and plants.

Always oriented towards technological innovation, Saipem is today committed to working alongside its customers on the frontier of the energy transition with increasingly digital means, technologies and processes oriented from their conception to environmental sustainability.

It is listed on the Milan stock exchange and operates in over 70 countries around the world with 32 thousand employees from 130 different nationalities.

FLOATING WIND FATIGUE DESIGN

Just like conventional offshore structures, floating offshore wind turbine (FOWT) substructures undergo cyclic wave and wind loading throughout their operational life, requiring adequate sizing and verification.

The presence of an operating wind turbine generator (WTG) introduces a novel loading regime on the substructure compared to a classic floating platform:

Novel item	FOWT LOADING SIDE	FOWT RESPONSE SIDE	CONVENTIONAL FLOATING STRUCTURES
Detailed wind	Wind becomes an important loading process, high sensitivity to turbulence	Low-frequency cycles from wind: thrust, gravity actions due to inclination, mooring tensions	Generally insensitive to wind loading details
Vibration	WTG aero-servo-elastic loads, esp. 3P and 6P synchronous excitations below 1 Hz	Synchronous excitations introduce vibrations, amplified by fore-aft & side-side tower bending resonances	No significant global vibrations (excluding ringing and springing)
Coupling	Strong coupling of all loadings through WTG controller and moving parts	Wave-induced motions and wind turbulence affect control, which has knock-on effects on motions and vibrations Aerodynamic damping from revolving rotor & control	Fairly decoupled loading processes Dominance of wave loading over the rest

In this setting, fatigue becomes more prevalent and more complex to assess accurately. Fatigue loads must be derived from coupled time-domain simulations (Figure 1) at all practicable stages, that is from early design to the latest detail design verification, for a low-risk project. Most present normative and guidance frames regarding the design process of a FOWT, including IEC [1], DNV [2], and BV [3], acknowledge this fact.

Figure 1 Coupled floating wind turbine simulation and constitutive processes.

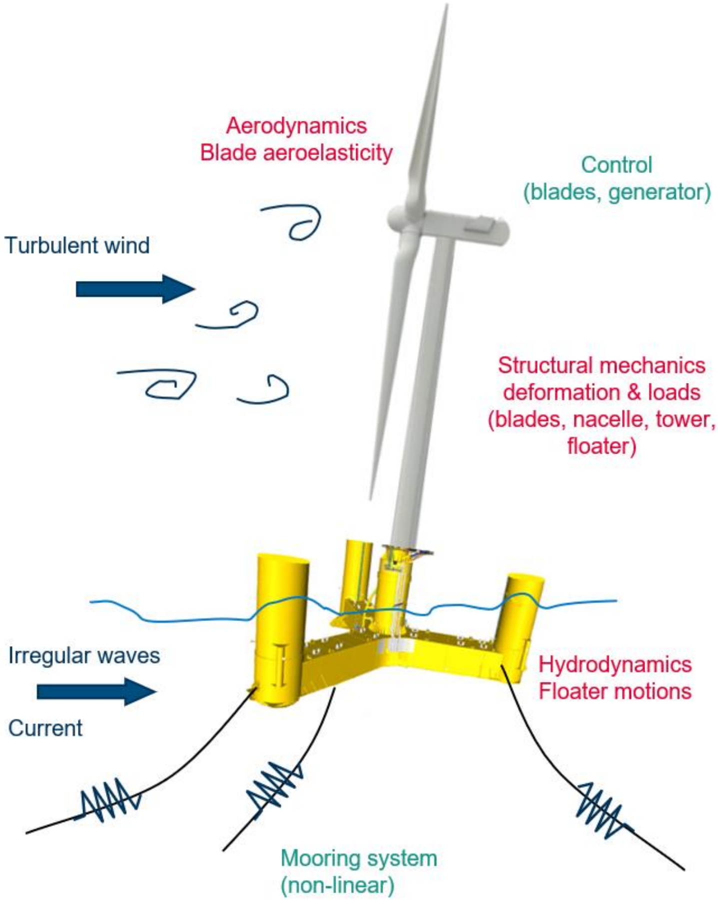
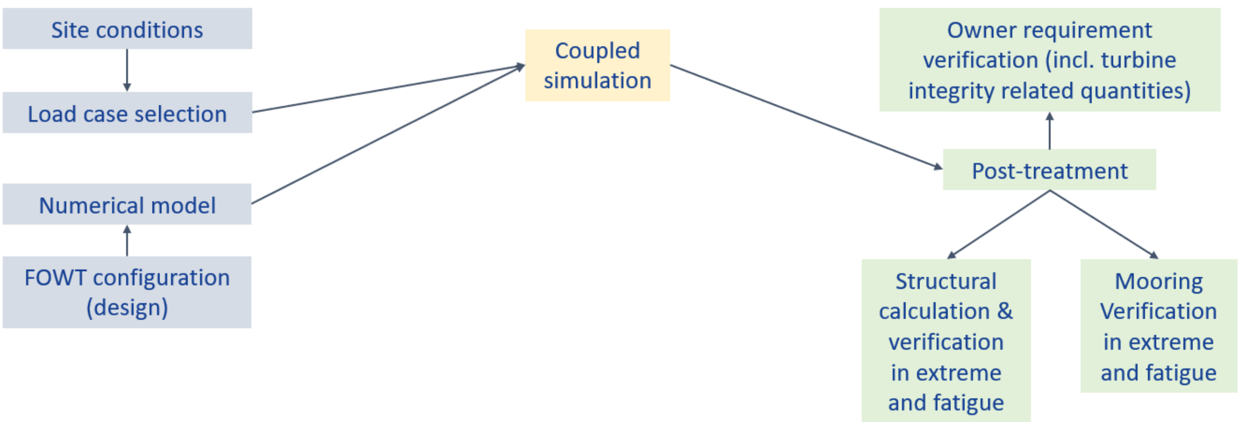


Figure 2 Integrated modular calculation chain.



INTEGRATED CALCULATION CHAIN

Selecting coupled simulations as the main source of the design loads brings to the numerical workflow depicted in Figure 2. For any project, before running the coupled simulations:

- Site conditions are determined and discretised into a set of design load cases (DLC), associated with parked and production states of the WTG.
- A WTG and floating substructure design freeze is made, leading to the creation of a numerical (aero-hydro-servo-elastic) model.

Then a few hundreds to tens of thousands of coupled simulations are carried out, depending on the project stage. Post-treatment follows, elaborating the response time series to inform requirement verifications and, crucially, substructure component verifications. The goal of this process is to reach both **structure reliability and competitiveness by performing full optimisation**, which requires being able to calculate accurately and efficiently the local extreme stresses and fatigue damage **in every part of the structure**.

It is at the post-treatment stage that **the way the calculation chain is designed determines the ability to carry out verifications with a reasonable computational effort**.

THE POST-TREATMENT CHALLENGE

With focus on fatigue, the following conditions must be met:

- Floating conditions imply long simulations to sample enough low-frequency cycles associated to horizontal station-keeping modes; typically, 20-30 minutes per simulation versus 10-minute simulations used in the bottom-fixed world.
- Within the structure, load effects (mostly stresses) are not readily available from the coupled simulation. A viable method is needed to obtain them from the simulation outputs.
- The entire response time series from each DLC must be processed to enable rainflow counting of the loads or load effects.
- The sampling rate must be high enough to represent cycles originating from blade passing harmonics, to prevent excessive amplitude shaving. For instance, logging a 0.6 Hz loading process (within the common FOWT vibration frequency range), at sample intervals considered fine for classic wave-frequency analyses can lead to underprediction of damage by up to 40%.

Meeting the above conditions means that at mid-project stages (e.g. preliminary design), stresses in the structural details must be resolved for **tens of millions of time stamps**. This is an entirely new feat compared to conventional offshore structure engineering; being able to realise it at time and cost is an enabler for FOWT substructure designers. And this is what is enabled by Saipem's solution.

SAIPEM IN-HOUSE SOLUTION

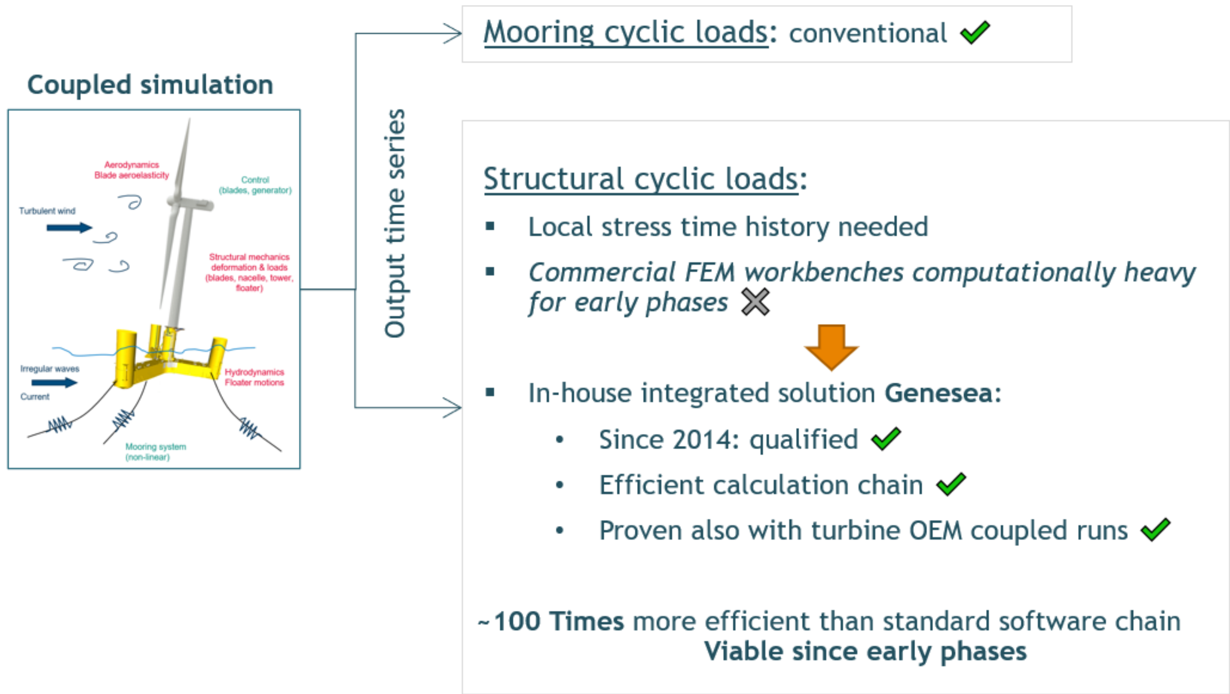
Saipem's answer to the post-treatment challenge is a standardised in-house computing framework denoted **Genesea**, organised around the following steps:

- Step E1 - Quick semi-automated model setup.
- Step E2 - Coupled simulations:
    - on either own solver FastHydro, or commercial solvers (Bladed, Orcaflex-VTS, etc.) for project-specific scenarios.
    - hydrodynamics based on DNV-validated full-Morison segmented model, a key enabler of the beam approach below.
- Step E3 - Coupled simulation outputs are treated by a mechanical solver based on beam theory for the whole floating platform (instead of relying on heavy shell element-based FEM workbenches). On a modern generic CPU, the "wall clock time to simulated time" ratio of this step is around unit.

Step E3's outputs are internal load time series at all structural member ordinates, with simultaneous kinematic data from the coupled simulation. From here, post-treatments can zoom into each area of interest separately (see dedicated "Structural fatigue" section below), which is key for efficiency. **Structural damage for a multi-thousand-run ILA (integrated load analysis) can be estimated from Step E3 outputs in a matter of days**, offering a ~100x reduction in the computational cost compared to a typical offshore FEM workbench.

The above framework is validated through cross-comparisons and experimental testing campaigns and achieved DNV certification (Figure 6) in 2020 for use with semi-submersible FOWTs [4].

Figure 3 Synthesis of coupled simulation post-treatments enabled by Saipem's Genesea framework.



DESIGN CONSIDERATIONS

From the designer standpoint, fatigue could be viewed as difficult to address from the start, as generally related to “detail issues” (local reinforcements, welds, etc.); also, it can necessitate intensive calculation incompatible with early endeavours. But as seen in previous sections, fatigue is highly influential for FOWTs.

An efficient calculation chain is a game changer for FOWT substructure design engineers, in that it unlocks **early on** access to:

- Fine modal analysis in floating condition, with the whole system flexible (beams).
- Extreme loads and DELs (damage equivalent loads) in every part of the floater. For instance, such values at tower base can confirm tower sizing and WTG integration from the very beginning, based on actual project data (wind, waves, current, depth, etc.).
- Extreme stresses and damage in every part of the structure (including local details), to confirm scantling choices and allowing to optimise locally.
- Extreme loads and damage in mooring lines, to define and optimise mooring components.

Accessing to the above information very soon in the project dramatically reduces design cycle risks. It especially allows to avoid vicious cycles, such as reinforcements making the structure stiffer, with knock-on effect on the bending frequencies and possibly reduced margin vs. 3P… in turn leading to increased loads!

Saipem’s calculation chain gives the opportunity to pinpoint diverging phenomena right away, and then adapt the design to reach all desired performances. It was built originally for (and succeeds today in) tackling this challenge.

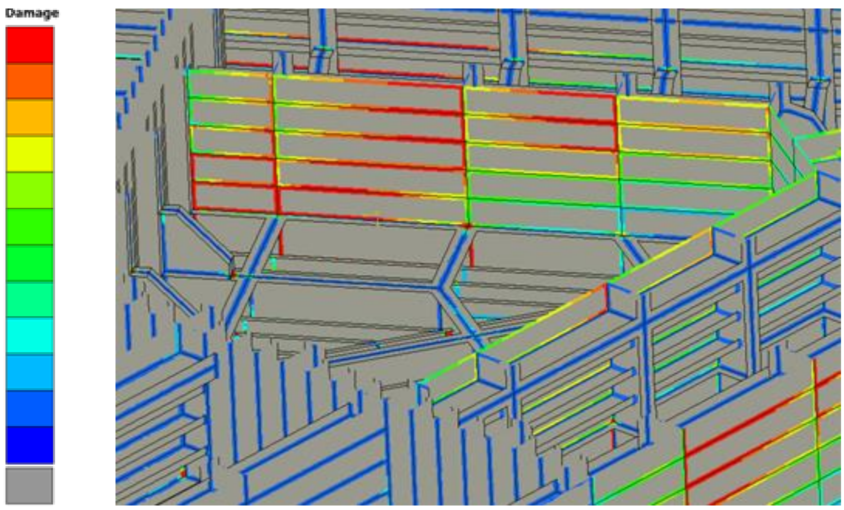
STRUCTURAL FATIGUE

Based on Step E3 outputs, local stress time series (e.g. for cycle counting) are computed in every part of the structure:

- In regular sections: analytically.
- In complex areas: based on linear stress intensification factor (SIF) matrices pre-processed from detailed FEM models[1].

This yields a direct **map of long-term damage in all welds, directly based on the hundreds-to-thousands of fatigue DLC simulations** (Figure 4), and is ideal for optimising the structure. One can hence confidently seek: minimal plate thickness to reduce material usage; weld type with higher or lower S-N curves for an optimal compromise with respect to fabrication workload; etc.

Figure 4 Long-term damage map of a complex structural area on a specific site/project, efficiently derived from hundreds of coupled time-domain simulations.



[1] DNV recommended practices for fatigue assessment in metallic structures lead to relatively small mesh sizes, in the order of 50 mm for some structural details. The high computational cost of resolving this in finite element form prompted the implementation of a computationally efficient SIF stress solver.

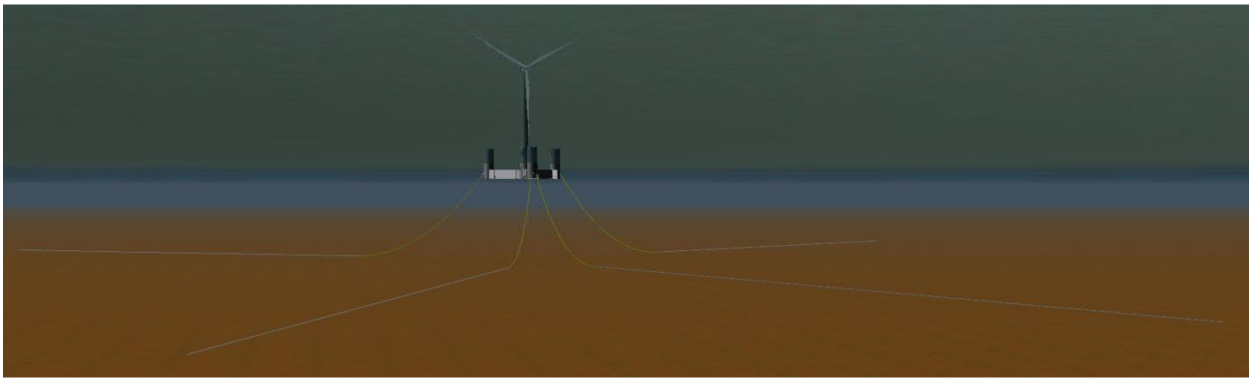
MOORING SYSTEM FATIGUE

FOWT station-keeping systems could be considered akin to conventional permanent moorings. Again, experience shows that this application has indeed its own peculiarities, listed below:

- Possible very low-depth sites: most floater concepts are designed for 50-60 m water depth and upwards; in typical energetic oceanic sites, mooring loading regimes at such depths can be very intense and complex to design for.
- Time-domain methods: again, a frequency-domain approach is not always relevant due to nonlinearities and turbine coupling.
- Cost constraint and series effect: in upcoming commercial farms, cost optimisation of each mooring component will be multiplied by multiple lines and tens of units!
- And again, fatigue: turbine vibrations can travel through the floater to the fairleads and then dynamically excite mooring lines. This must be identified soon for a safe design route.

Following these observations, specific design methodologies were developed and integrated in Saipem's time-domain calculation chain; special attention was applied to facilitate early and careful assessment of fatigue, including the effects of turbine coupling.

Figure 5 Four-leg mooring system for a STAR 1 FOWT.



STAR 1 FLOATER

Saipem's calculation framework has been developed since 2014 including intensive verification and qualification, notably by DNV and by comparison with basin tests. Historically and in parallel, the STAR 1 floater concept was designed and adapted to project-specific conditions using this tool set.

As seen above, fatigue could be studied right away based on hard data, yielding accurate mass predictions. **Disregarding it would have led to underestimating primary steel mass by up to 30%**. To fully secure the design in this respect, damage was checked on every part of the substructure and mooring and integrated in the design philosophy, resulting in a sound and largely de-risked structure.

The above endeavour led to certification by DNV of the complete STAR 1 Preliminary Design package [5].

Figure 6 DNV certification reports of FOWT design briefs, basin tests, and STAR 1-specific preliminary design. Tens of documents reviewed for a total well in excess of a thousand pages.


DNV·GL
NAVAL ENERGIES FLOATING WIND SEMI-SUBMERSIBLE – DESIGN BRIEFS
Certification Report
Design Briefs
Naval Energies
Report No.: CR-DB-DNVGL-SE-0422-06233-0
Date: 2020-06-12

DNV·GL
NAVAL ENERGIES FLOATING WIND SEMI-SUBMERSIBLE – BASIN TESTS
Certification Report
Basin tests
Naval Energies
Report No.: CR-DB-DNVGL-SE-0422-06232-0
Date: 2020-06-05

DNV
NAVAL ENERGIES FLOATING WIND SEMI-SUBMERSIBLE
Certification Report
Preliminary Design
Naval Energies
Date: 2021-06-25

Figure 7 STAR 1 scaled testing in waves at SINTEF Ocean, also certified by DNV [6], and general view.

CONCLUSION

Floating wind projects are taking shape worldwide. To move forwards successfully, design uncertainty must be tackled upfront to gain stakeholder confidence. A major stake lies in the ability to obtain overall design convergence under the novel FOWT engineering realm. Fatigue in the substructure deserves special consideration, as it can govern structural mass and hence cost with impacts up to 30%.

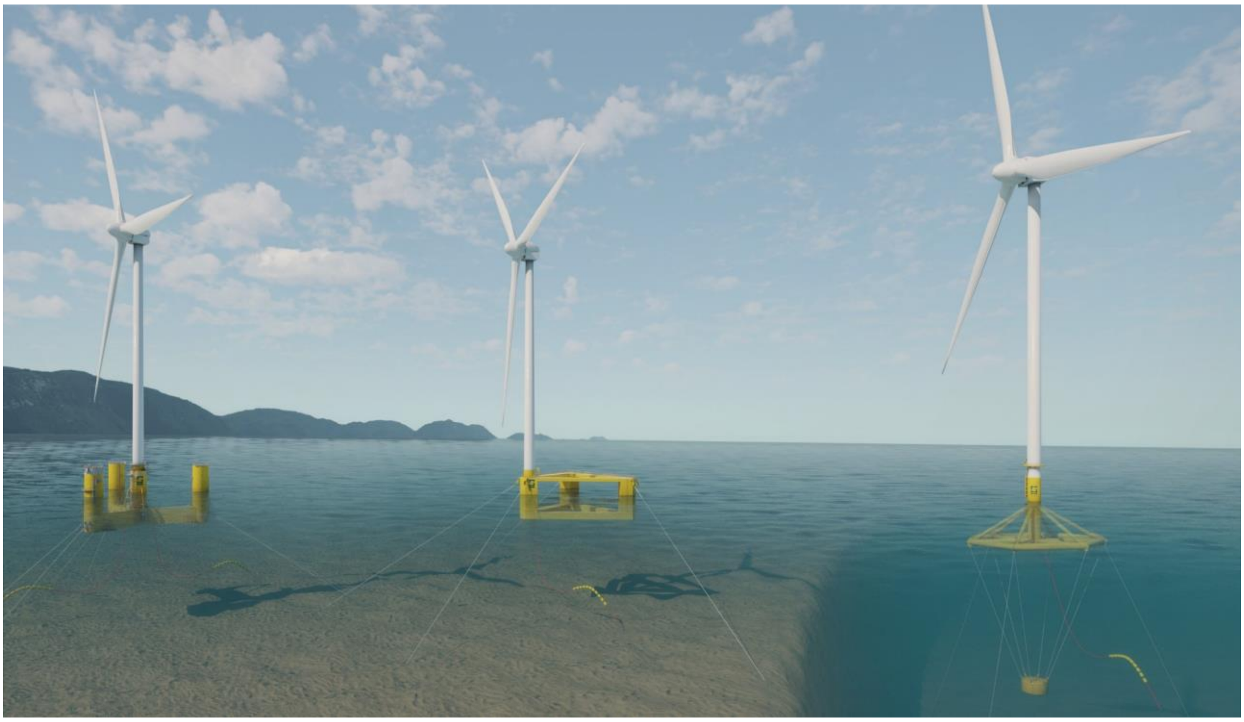
Saipem's recommendations to face the above challenge are the following:

- Turbine is king: adapt conventional oil & gas design practices to this new payload.
- Compute substructure fatigue from coupled simulations very soon in the project. Efficient propagation of loads into the structural details is key for risk identification and cost optimisation.
- Keep the stiffness of the system (hence frequency behaviour) under close control to avoid design divergence through vicious cycles.
- Work with a certifiable / certified basis of design from the start.

The aim of the above predicament is to optimise the substructure whilst avoiding excessive conservatism or risk exposure, thereby securing project cost and schedule. At the end of the day, this will reduce the resulting LCOE which is the industry's primary goal.

Saipem's floating solutions, shown in Figure 8, are designed with these principles in mind. Today, under any given project, they are investigated using the presented calculation chain since the early feasibility stage, providing robust and low-risk estimates to stakeholders.

Figure 8 Saipem floating wind substructure solutions.



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[5]. CR-DB-DNVGL-SE-0422-07636-0 "Certification Report Preliminary Design" (Saipem internal)
[6]. CR-DB-DNVGL-SE-0422-06232-0 "Certification Report Basin Tests" (Saipem internal)