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SEASONAL DOWNTIME ANALYSIS OF DP AND NON-DP OFFLOADING OPERATION IN BRAZILIAN WATERS

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ABSTRACT

Oil offloading from Spread Mooring System (SMS) FPSO is usually done by means of a shuttle tanker (ST) in tandem configuration. The ST receives the oil pumped by the FPSO from a bow or stern offloading station, and the operation may take up to 3 days. In order to minimize the risks associated with the operation, the shuttle tanker (ST) should be kept within a safety zone with respect to the FPSO, which is usually given as a minimum distance between the two ships and an aperture angle from the FPSO centerline. In order to guarantee the tanker position during the whole operation, the operation is usually assisted by tug boats or performed with tankers provided with DP (dynamic positioning) systems. Since SMS FPSOs may be not aligned to the environmental forces, keeping the shuttle tanker in position may be a hard task either for the DP system or for the tug boats, depending on the environmental conditions. There are non-rare situations in which the ST must be disconnected and the operation interrupted.

The present paper presents a methodology based on fully-nonlinear dynamic simulations for evaluating the downtime of such offloading operations, considering both DP and conventional non-DP tankers, in the later case assisted by a tug-boat. Typical Brazilian waters environmental conditions (current, wind and waves) are considered for each seasonal period of the year. The main objective is to provide a quantitative comparison between both cases in each season. The results may also be used for strategic definition concerning logistics of oil production. The procedure is based on exhaustive dynamic simulations, and a statistical analysis of the oceanographic data was used to generate a representative set of environmental conditions together with the corresponding probability of occurrence for each season. A full time-domain dynamic simulation is then carried out for each case, considering detailed models for the dynamics of each floating structure, mooring lines and DP system. The vessel excursion, hawser tension and other operational parameters are then evaluated for each case, and the occurrence of unsafe conditions may be properly evaluated. A statistical procedure is finally applied to compute the associated downtime. Illustrative results for two different classes of ST (Aframax and Suezmax) are presented and discussed, and the advantages of employing DP assisted vessels become clear.

INTRODUCTION

Offloading operations of FPSO (Floating Production Storage and Offloading) systems are usually performed by means of a shuttle tanker which receives the oil pumped by the FPSO. The shuttle is connected to the FPSO by a hawser, such connection being made, in many cases, either at the stern or at the bow of the platform. The two ships are thus connected in tandem and the dynamics of the two floating bodies under wave, current and wind action may present a very rich behavior.

Fig. 1 Offloading operation at Campos Basin, Brazil

Risk control is an important issue concerning offloading operations and FPSO owners establish safety procedures that must be followed by the crew. Such criteria normally specify that the shuttle tanker should be kept within a safety zone with respect to the FPSO, which is usually given as a minimum distance between the two ships and an aperture angle (for example, ±45^o) from the FPSO centerline. In order to guarantee the tanker position during the whole operation, which may take up to 3 days, the operation is usually assisted by tug boats or performed with tankers provided with DP (dynamic positioning) systems. Unlike the turret configuration, SMS FPSOs may be not aligned to the environmental forces (see Fig. 1) and this may put an extra power demand for keeping the shuttle tanker in position.

The role of dynamic simulation packages in the study of offloading operations is crucial, because it allows evaluating any possible combination of waves, wind and current conditions. The Numerical Offshore Tank (TPN) at the University of São Paulo (USP) is a simulation package with very large numerical processing capability, allowing for the analysis of full-scale offshore units with coupled dynamics of risers and mooring lines (Fig. 2). It also includes models for DP simulation.

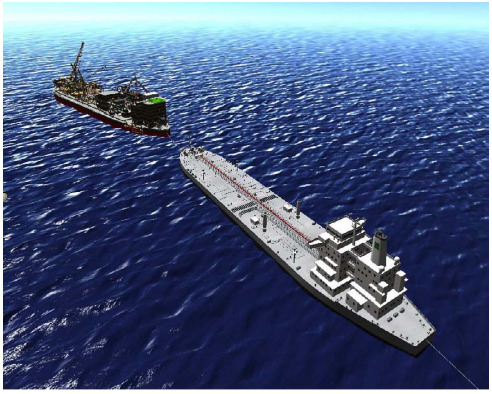

Fig. 2 Illustration of an offloading operation simulated in the TPN code

Several works demonstrated applications of numerical simulation tools for the design and analysis of offloading operations. For example, simulations were used for determining the limiting environmental conditions for offloading operations, considering either a non-DP or a DP Shuttle Tanker (ST) in Gulf of Mexico [1]. In another work, simulations were used for defining the required tug-force that must be applied in the shuttle tanker in order to guarantee a safe operation under critical environmental conditions of Brazilian waters [2]. An interesting evaluation of DP FPSO station keeping and the offloading operation by conventional ST has been presented in [3]. Finally, simulation was used to define a safe positioning procedure for the offloading of a FPSO that is close to a jack-up platform [4].

Another application of the simulation tool is the estimation of the downtime associated with offshore operations, including the offloading operation. A statistical analysis of the oceanographic data is primarily done to generate a representative set of environmental conditions together with the corresponding probability of occurrence for each season. After that, full time-domain dynamic simulations are carried out for each case, considering detailed models for the dynamics of each floating structure, mooring lines and DP system. The vessel excursion, hawser tension and other operational parameters are then evaluated for each case, and the occurrence of unsafe conditions may be properly evaluated. A statistical procedure is finally applied to compute the associated downtime. Due to the large number of simulations, such procedure requires a large processing and storage computational capability.

This methodology for downtime evaluation is more accurate than the traditional one. In that case, Metocean data (scatters of wind, waves and current) is analyzed and the occurrence of conditions with either wave, wind or current above the limiting condition defined for the specific offshore operation are estimated. This approach does not consider the statistical dependence between the environmental agents (mainly waves and winds), neither the directional misalignments between then.

The methodology of downtime estimation based on fully non-linear time domain simulations was already applied to several offshore analyses. For example, the downtime of a offloading with DP and non-DP ST in Gulf of Mexico, considering a turret moored FPSO, was presented in [5]. The downtime for crane and pipe-laying operation was also discussed in [6].

In this paper, a similar methodology for evaluating the downtime of offloading operations, considering both DP and non-DP ST is presented. Typical Brazilian waters environmental conditions (current, wind and waves) are considered for each seasonal period of the year, aiming to provide a quantitative comparison between both cases in each season.

SYSTEMS DESCRIPTION

In the present analysis, the FPSO platform consists of a unit in Spreads Mooring System (SMS), based on a VLCC tanker. Two classes of Shuttle Tankers have been considered. The first one (named as ST-S) is a Suezmax class vessel and the second one is Aframax class vessel (named as ST-A). The main particulars of the floating bodies are given in Table 1.

Table 1 FPSO an Shuttle Tankers Main Characteristics

Property	FPSO	ST-S	ST-A
Length Overall	337 m	273 m	232 m
Beam	54 m	47 m	42 m
Draft Full	27.0 m	16.0 m	14.2 m
Draft Ballasted	9.0 m	8.0 m	5.3 m
Depth	27.0 m	23.3 m	21.0 m
Displ. Full MTon	310720	173000	117000
Displ. Ball MTon	127510	79500	39800

For each floating body, hydrodynamic coefficients were then obtained by means of a potential wave analysis code (WAMIT). As an illustration, Fig. 3 shows the numerical mesh used to evaluate hydrodynamic coefficients of the FPSO, in both loaded and ballasted conditions.

Vessels current forces and moments were evaluated through a cross-flow model. Current coefficients for the FPSO were obtained by towing tank drift tests [7]. Coefficients given in [8] were adopted for the shuttle tankers. As an example, current coefficients of the FPSO in ballasted condition are given in Fig. 4.

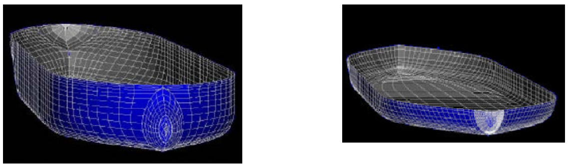

Fig. 3 FPSO hull numerical mesh: (left) full, (right) ballasted conditions

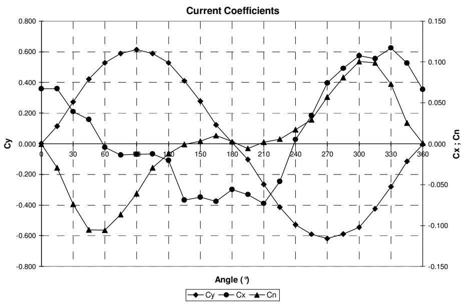

Fig. 4. Current force and moment coefficients, Ballasted FPSO (extracted from [7])

Wind effects on the FPSO hull were estimated in the towing tank by means of capsized model technique [7]. Shuttle tankers wind loads were evaluated by means of the standard wind coefficients given in [8]. As an example, wind coefficients for the FPSO in ballasted condition are given in Fig. 5.

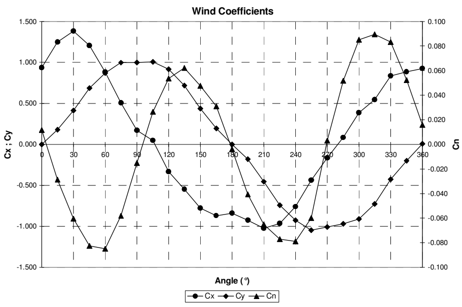

Fig. 5. Wind force and moment coefficients, Ballasted FPSO (extracted from [7])

In the present analysis, the aerodynamic and hydrodynamic interaction between the shuttle tanker and the FPSO is not considered. Of course, this is a simplification assumption, since those effects may play an important role in the dynamic behavior of the vessels and in the DP power consumption, since the distance between them is small. Previous works have evaluated such effects on DP power requirements for offloading operations in specific environmental conditions ([9] for current interaction, [10] for wave interaction and [11] for wind interaction). It was demonstrated in those works that simulations that do not take into account interaction effect, normally overestimate the DP power. However, in some specific relative positions between the shuttle tanker and the FPSO, an amplification of DP power requirement may occur. Reliable and simple numerical models for the interaction effects are still a research topic, and are not fully validated by means of model-scale experiments or real-scale measurements.

The FPSO spread mooring system is composed by 18 lines, and the mean equilibrium heading of the unit is 208^{o} related to the North direction. Fig. 6 shows the mooring line systems.

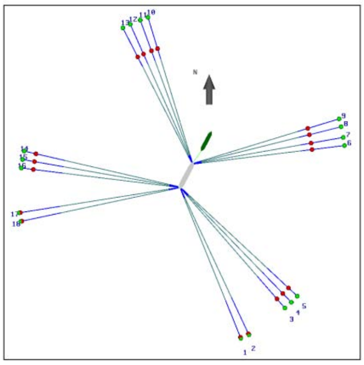

Fig. 6. FPSO-SMS Mooring lines. A ST connected is also indicated

A 160m long nylon hawser connects the ST to the FPSO, with approximately 500tf maximum breaking load (MBL).

Tugboats are modeled as an equivalent force acting in the ST stern, for the conventional case. The net force in the ST is computed considering that the tugboat will operate with a 80% of its full capacity, and an extra reduction factor of 10% is included in order to take into account non-modeled effects and losses associated to the tugboat own dynamics. For example, a 120tf bollard pull tugboat delivers 84tf in the ST stern. Tugboats of up to 120tf bollard pull were considered in the analysis.

The DP layout of ST-A is presented in Fig. 7 and the thrusters specifications are given in Table 2. For the ST-S, the layout is given in Fig. 8 and the thrusters data are presented in Table 3.

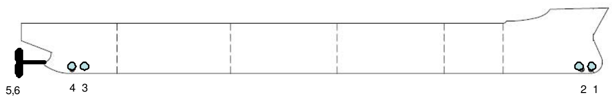

Fig. 7. ST-A DP layout

Table 2 ST-A DP – thruster specification

	Pos. (X,Y) (m)	Power (kW)	Maximum Thrust (tf)	Minimum Thrust (tf)
1.Tunnel Bow	(125,1;0,0)	2200	31	-31
2.Tunnel Bow	(121,6;0,0)	2200	31	-31
3.Tunnel Stern	(-110,7;0,0)	700	10	-10
4.Tunnel Stern	(-114,1;0,0)	700	10	-10
5.Main	(-124,8;7,5)	10010	177	-120
6.Main	(-124,8;-7,5)	10010	177	-120

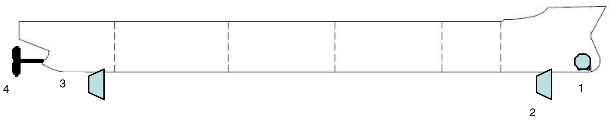

Fig. 8. ST-S DP layout

Table 3 ST-S DP – thruster specification

	Pos. (X,Y) (m)	Power (kW)	Maximum Thrust (tf)	Minimum Thrust (tf)
1.Tunnel Bow	(130,6;0,0)	2200	31	-31
2.Azim. Bow	(125,3;0,0)	2200	38	-19
3.Azim. Stern	(-93,3;0,0)	2200	38	-19
4.Main	(-128,9;0,0)	16853	300	-200

OPERATIONAL CONDITIONS

A large set of simulations was carried out in order to define the downtime. Two loading conditions were considered:

- LC1 – initial phase of the offloading operation, with the ST in ballasted condition and the FPSO in loaded condition
- LC2 – final phase of the offloading operation, with the ST in loaded condition and the FPSO in ballasted condition

Two loading stations were also considered, since several Brazilian FPSOs have a loading station in the bow and other in the stern.

Each case was analyzed by 3-hour numerical simulations using the numerical simulator (see Appendix 1 for a description of the simulation code), and a post-processor was customized to evaluate all operational criteria adopted by Petrobras, to define a safe offloading operation. Such criteria are:

- Hawser tension smaller than 100tonf;
- Minimum distance of 50m between ST and FPSO;
- In case of FPSO offloading, ST must be kept within a green-zone, defined by an angular sector +45^o/-60^o ([12]).

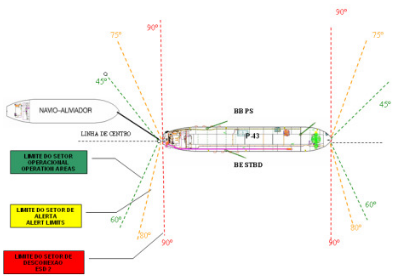

Fig. 9. SMS FPSOs Operational Sectors (extracted from [2]).

A situation is considered safe is all criteria are satisfied, for both LC1 and LC2 loading conditions. For the conventional ST operation, the tug force is in the same direction of the FPSO longitudinal axis, in order to align the ST to that axis. Fig. 10 illustrates tug action. For DP-ST operation, different set-points are considered, for a maximum misalignment of 25^o between FPSO and ST longitudinal axis.

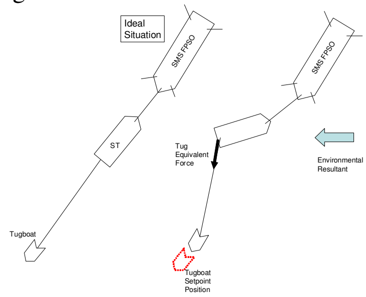

Fig. 10. Tugboat action for SMS FPSO

The decision of eventually interrupting the oil-offloading is in charge of the crew, and contains some subjective aspects, which are not considered in the present analysis.

ENVIRONMENTAL CONDITIONS

A hydrodynamic and a wave model of a specific region of Campos Basin were implemented. They are based on "Princeton Ocean Model (POM)" and on the WAVEWATCH3 (WW3) model. The forcing action of such models is the wind measured data from public NOAA databases, considering a period of 10 years (1998 to 2007).

After that, each environmental agent (wave, wind and current) was grouped as a function of its intensity, as given in the Table 4. Eight directions (N, NE, E, SE, S, SW, W, NW) were considered.

Table 4 Environmental agents - grouping

Wave (signfic. height):	Wind (speed Vw):	Current (speed U):
[a] 0.0m – 2.0m [b] 2.0m – 3.5m [c] > 3.5m	[I] 0 – 25 knots [II] 25knots – 50 knots [III] > 50 knots	[1]0.0m/s – 0.8m/s [2] > 0.8m/s

The number of combinations of directions/intensities of wind, wave and current, in view of the previous considerations, would be prohibitive (9216 combinations). One must remember that each condition must be simulated for the 2 loading conditions, 2 loading stations and 4 ST´s. So, additional considerations were done in order to reduce the total number of environmental combinations. For Campos Basin, more than 80% of the time, the current direction is SE-S-SW (going to). So, it is considered only the direction S, representing all currents of Campos Basin. The other 20% were not simulated. Of course, since the purpose of this work is a comparative analysis of downtime between several vessels, such simplification is possible. Other simplification is the exclusion of wave group [c] and wind group [III]. Those conditions are above the offloading limits defined by Petrobras regulation, and represent only 1% of Campos Basin environmental cases. With all the simplifications, the total number of environmental combinations is reduced to 512.

NUMERICAL SIMULATION

In this section, two examples are presented, in order to illustrate the results obtained by the numerical simulator.

The first case (Case 1) is the conventional offloading with the ST-A (Aframax), in the initial phase of the operation (LC1), using the bow station. A 25tf tugboat is used, and the environmental condition is presented in Table 5 (10.71% of occurrence in winter). Fig. 11 presents the position of the vessels during the offloading. The positioning requirement is satisfied during the operation, since the ST is kept inside the green-zone. Fig. 12 shows the distance between the vessels (always higher than 50m) and the hawser tension. Since the tension is higher than 100tonf for some time intervals, this case in considered unsafe.

Table 5 Environmental condition Case 1

	Intensity	Direction
Current	0.71m/s	S (going to)
Wind	12m/s	NE (Coming from)
Wave	Hs=2.92m ; Tp = 10.02s	E (Coming from)

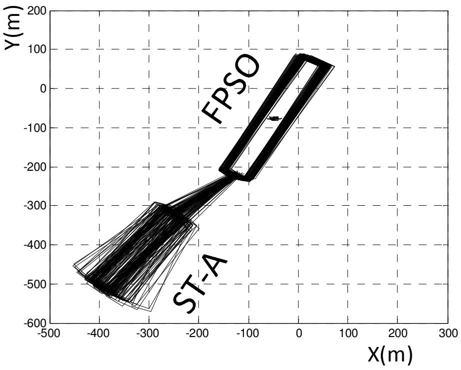

Fig. 11. Case 1 – vessels position.

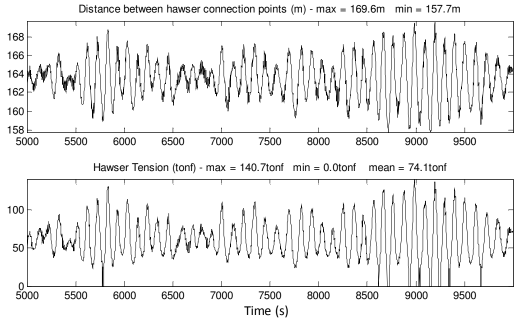

Fig. 12. Case 1 – vessels relative distance and hawser tension.

The second case (Case 2) is the DP offloading with the ST-S (Suezmax), in the initial phase of the operation (LC1), using the stern station. The environmental condition is presented in Table 6 (5.87% of occurrence in winter). Fig. 13 presents the position of the vessels during the offloading. The positioning requirement is satisfied during the operation, since the ST is kept inside the green-zone. Fig. 14 shows the distance between the vessels (always higher than 50m). Hawser tension is not presented since it is always small. Fig. 15 shows the mean thrust utilization. This case is considered safe.

Table 6 Environmental condition Case 2

	Intensity	Direction
Current	0.73m/s	S (going to)
Wind	11.90m/s	NE (Coming from)
Wave	Hs=1.97m ; Tp = 6.77s	NE (Coming from)

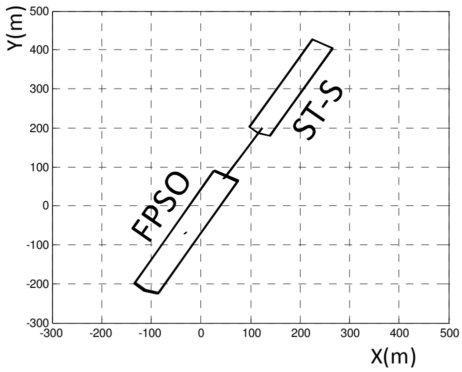

Fig. 13. Case 2 – vessels position.

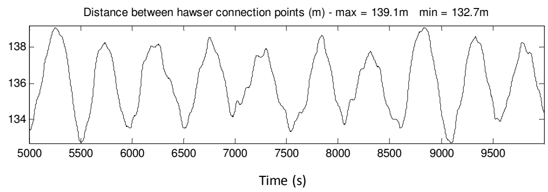

Fig. 14. Case 2 – vessels relative distance and hawser tension.

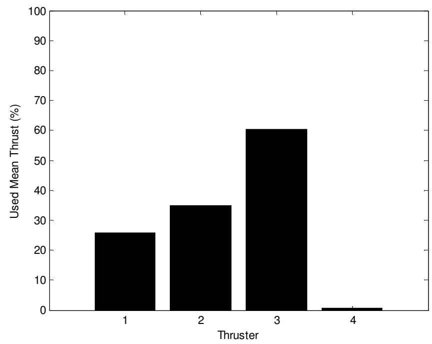

Fig. 15. Case 2 – Mean Thrust Utilization.

DOWNTIME RESULTS

The next tables present the final results of the analysis. The downtime is expressed as a percentage of the time during which the offloading is unsafe, for each seasonal period of the year. A minimum and a maximum value are presented. As already explained, some environmental conditions were not simulated (current going to directions other than SW/S/SE). For those conditions, there is no information abaout the safety of the operation, and they are considered as error margin in the results. Separate results are presented for bow and stern operations. Furthermore, it is included the case Bow/Stern, which corresponds to the case when both stations are operating, and the ST captain can decide from which station the offloading will be executed.

Table 7 ST-A (Aframax) downtime (%)

	ST-A DP (% Downtime)				ST-A Conventional (% Downtime)			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
Bow	0 to 7	7 to 19	8 to 16	4 to 9	4 to 11	15 to 27	31 to 39	15 to 20
Stern	23 to 29	16 to 29	40 to 47	35 to 39	31 to 38	25 to 38	55 to 63	46 to 51
Bow/Stern	0 to 7	7 to 19	8 to 16	3 to 8	4 to 11	10 to 23	27 to 34	14 to 19

Table 8 ST-S (Suezmax) downtime (%)

	ST-S DP (% Downtime)				ST-S Conventional (% Downtime)			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
Bow	0 to 7	7 to 19	8 to 16	2 to 7	8 to 15	30 to 42	42 to 49	24 to 29
Stern	2 to 8	8 to 21	14 to 21	7 to 12	47 to 53	32 to 45	62 to 69	60 to 65
Bow/Stern	0 to 7	7 to 19	8 to 15	2 to 7	7 to 13	15 to 27	34 to 41	19 to 23

From the analysis of both tables one may readily observe:

1) For both vessels (Suezmax and Aframax classes), the utilization of a DP system significantly reduces the downtime, compared to the conventional operation (tug-assisted).
2) ST-S DP presents a slightly better station-keeping capacity compared to the ST-A DP. The utilization of two azimuth thrusts (instead of 4 tunnel thrusters) explains such fact.
3) Winter conditions are more severe, resulting a downtime higher than all other seasonal periods.

CONCLUSIONS

This paper presented a procedure based on exhaustive dynamic simulations for the proper calculation of the downtime of offshore operations. The procedure is applied to the offloading analysis in Campos Basin (Brazil), and a seasonal comparison between two classes of shuttle tankers, for both DP and tug assisted operations.

The results obtained by such kind of approach may be used for strategic definition concerning logistics of oil production as well as design and analysis of vessels and operations.

As a future improvement of the present study, the authors emphasize the inclusion of numerical models for the interaction effects (hydrodynamic and aerodynamic) between the shuttle tanker and the FPSO in the simulations.

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APPENDIX: THE TPN OFFSHORE SYSTEM SIMULATOR

The TPN is a time domain numerical procedure designed for the analysis of moored and DP offshore systems. The inputs of the simulator are:

- Floating body main parameters (dimensions, mass matrix, etc.);
- Aerodynamic drag coefficients (following standard given by [8]);
- Current coefficients (following standard given by [8]) or hydrodynamic derivatives;
- Hydrodynamic coefficients (potential damping, added mass, first and second order wave force coefficients);
- Environmental conditions (wave and wind spectra, current);
- Mooring and risers system characteristics;
- Thrusters characteristics, saturation and layout;
- DP modes and parameters.

The non-linear time-domain simulation runs in a cluster computational system and outputs time series describing the motions of up to two floating unities (FU) in six degrees of freedom (6dof), tensions on the mooring lines and hawser, propellers thrust and power, etc., and a corresponding statistical summary. 3D visualization outputs are also available. The floating body high frequency motion (HF) due to the wave action can be evaluated in two different ways. In the simpler one the HF motion evaluated by the RAO is added to the low frequency motion (LF) that is calculated by the 3rd order Runge-Kutta integration method. Alternatively, the wave 1st order forces are applied to the body and all motion components (6 dof) are obtained dynamically solving the equations of motion. The current force can be evaluated through 3 different models: OCIMF Model, Cross flow Model, Maneuvering Model or Short Wing Model (in-house development). It is possible to analyze 3D constant or oscillatory current profile. The simulator allows constant wind and gust wind. The wind spectra implemented in the code are Harris, Wills and API. The wave can be regular and irregular. For irregular waves the spectra formulations available are Pierson-Moskowitz, JONSWAP and Gaussian. The wave first and second-order effects are modeled besides wave-drift damping effects. The wave coefficients are evaluated by WAMIT.

Three main classes of algorithms used in commercial DP systems are also implemented in TPN. A low-pass filter, called wave-filter, is employed to separate high-frequency components (excited by waves) from measured signals. Such decomposition must be performed because the DP system must only control low-frequency motion, since high-frequency motion would require enormous power to be attenuated and could cause extra tear and wear in propellers. Furthermore, an optimization algorithm, called thrust allocation, must be used to distribute control forces among thrusters. It guarantees minimum power consumption to generate the required total forces and moment, positioning the vessel. At last, a control algorithm uses the filtered motion measurements to calculate such required forces and moment. Normally, a wind feedforward control is also included, enabling to estimate wind load action on the vessel (based on wind sensor measurements) and to compensate it by means of propellers. Furthermore, the simulator also includes models for propellers, taking into account their characteristics curves, being able to estimate real power consumption and delivered thrust. It also evaluates time delay between command and propeller response, caused by axis inertia. A real-scale DP offloading operation was used for the preliminary validation of the DP system implemented in the simulator [13]. In that work, the total and individual thrusts are measured and compared to the values obtained in the simulations. Very good agreement for mean values and spectra was verified, validating the DP algorithms and propeller models included in the simulator.