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Methodology for definition of new operating sectors for DP assisted offloading operations in spread-moored platforms

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To my fiancé who supported me throughout the whole duration of this work and understood the need of my constant travels between São Paulo and Rio de Janeiro.

To my parents who provided me the best education opportunities and taught me the moral values I carry along every day.

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Education is the most powerful weapon which you can use to change the world.

Nelson Mandela

Live as if you were to die tomorrow. Learn as if you were to live forever.

Mahatma Gandhi

You are always a student, never a master. You have to keep moving forward.

Conrad Hall

RESUMO

ORSOLINI, A. L. B. **Metodologia para definição de novos setores operacionais para operações de offloading com navios DP em plataformas ancoradas em Spread Mooring.** 2017. 142 p. Dissertação (Mestrado) – Departamento de Engenharia Naval e Oceânica da Universidade de São Paulo, São Paulo, 2017.

Esta dissertação define e aplica uma metodologia para analisar a possibilidade de extensão do setor operacional de navios aliviadores DP para operações de *offloading* em plataformas FPSO ancoradas em *Spread-Mooring*. Esta proposta apresenta como vantagens o aumento da disponibilidade das operações e redução na demanda de energia do navio DP em certas condições ambientais. O estudo é importante tendo em vista que várias desconexões de emergência já ocorreram durante operações de alívio na Bacia de Santos, porque o navio-tanque foi empurrado para fora do setor verde por resultantes ambientais que apontavam para oeste. No entanto, a proposta deve ser cuidadosamente analisada para garantir que o novo setor não aumenta os riscos de colisão, de poluição ambiental e de segurança às pessoas. A metodologia consiste em cinco etapas básicas: Análise Preliminar de Riscos (APR); avaliação do ganho de disponibilidade da operação; avaliação da demanda de energia do sistema DP nos setores original e estendido; simulações de manobra em tempo real; e, finalmente, testes em campo para validação da proposta. Esta dissertação apresenta a contextualização do problema, pesquisa bibliográfica, conceitos teóricos, a metodologia detalhada e os resultados de cada etapa. Os resultados mostram que o ganho médio de disponibilidade é significativo nas bacias de Campos e de Santos – até 9% e 13%, respectivamente – e que os riscos adicionais criados pela extensão do setor são devidamente mitigados se as recomendações levantadas na APR forem implementadas. A conclusão desta dissertação é que estender o setor operacional é, não somente benéfico, mas também seguro.

Palavras-chave: offloading, operações de alívio, alívio, NADP, Posicionamento Dinâmico, navio aliviador, FPSO.

ABSTRACT

ORSOLINI, A. L. B. **Methodology for definition of new operating sectors for DP assisted offloading operations in spread-moored platforms.** 2017. 142 p. Thesis (Master's Degree) – Naval architecture and Marine engineering department of University of São Paulo, São Paulo, 2017.

This thesis defines and applies a methodology for analyzing the possibility of extending the operating sector of DP shuttle tankers for offloading operations in Spread Moored FPSO Platforms. Extending the operating sector is beneficial to increase operations' availability and to reduce DP power demand under certain environmental conditions. This study is important, since several emergency disconnections have occurred during offloading in Santos Basin because the shuttle tanker was pushed out of the green sector by environmental resultants that pointed to the West. However, this proposal has to be carefully analyzed in order to guarantee the operations' safety and not to increase the risks of collision between FPSO and shuttle tanker, of oil pollution and of personnel safety. The methodology consists in five basic steps: Preliminary Risk Analysis to assess the potential hazards associated with the new sector; evaluation of the uptime gain through static analysis; evaluation of DP power demand inside the original and extended sector; real time simulations to evaluate the operation in a realistic environment; and, finally, field tests to validate the proposal. This thesis presents the contextualization of the problem, a bibliographical research, theoretical concepts, the detailed methodology and results of each step. The results show that the average uptime gain is significant both in Campos and Santos Basins – up to 9% and 13% respectively – and that the additional risks created by the sector extension are well mitigated if some recommendations are put into place. The conclusion of this thesis is that extending the operating sector is not only beneficial but also safe.

Keywords: offloading, DPST, Dynamic Positioning, shuttle tanker, FPSO.

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LIST OF ACRONYMS

ABS	American Bureau of Shipping
BC	*Bacia de Campos* (Campos Basin)
BLS	Bow Loading System
BOMOSHU	Brazil Offshore MetOcean Storm Hindcast Update
BS	*Bacia de Santos* (Santos Basin)
CALM	Catenary Anchor Leg Mooring
CONAPRA	*Conselho Nacional de Praticagem* (National Council of Pilots)
CPP	Controllable Pitch Propeller
DARPS	Differential Absolute and Relative Positioning Sensor
DNV GL	Det Norske Veritas Germanischer Lloyd
DP	Dynamic Positioning
DPS	Dynamic Positioning System
DPST	Dynamically Positioned Shuttle Tanker
E&P	Exploration & Production
EHS	Enhanced Class Notation
FEM	Finite Element Analysis
FPS	Floating Production System
FPSO	Floating Production Storage and Offloading
FSA	Formal Safety Assessment
FSO	Floating Storage and Offloading
GPS	Global Positioning System
HPU	Hydraulic Power Unit
HYCOM	HYbrid Coordinate Ocean Model
IMCA	International Maritime Contractors Association
IMO	International Maritime Organization
JIP	Joint Industry Project
JONSWAP	JOint North Sea WAve Project
LNG	Liquefied Natural Gas
LOA	Length Over All
LPP	Length Between Perpendiculars
NE	North East
OCIMF	Oil Companies International Marine Forum

OESD	Offloading Emergency Shut Down
OIM	Offshore Installation Manager
PID	Proportional Integral Derivative
POB	People On Board
PRA	Preliminary Risk Analysis
S	South
SB	Santos Basin
SE	South East
SMH	*Simulador Marítimo Hidroviário* (Maritime and Waterway Simulator)
SMS	Spread Mooring System
SOPEP	Ship Oil Pollution Emergency Plan
SPM	Single Point Mooring
SS	Semi-submersible
SSE	South-South East
SSW	South-South West
ST	Shuttle Tanker
TLP	Tension Leg Platform
TPN	*Tanque de Provas Numérico* (Numerical Offshore Tank)
UK	United Kingdom
UKOOA	UK Offshore Operators Association
USP	*Universidade de São Paulo* (University of São Paulo)
VLCC	Very Large Crude Carrier
WAMIT	Wave Analysis at Massachusetts Institute of Technology

LIST OF SYMBOLS

η_1	translational movement through x axis, or surge
η_2	translational movement through y axis, or sway
η_3	translational movement through z axis, or heave
η_4	rotational movement through x axis, or roll
η_5	rotational movement through y axis, or pitch
η_6	rotational movement through z axis, or yaw
F_{1C}	current load in the longitudinal, or surge, direction
ρ_w	water density
U	current speed
L	shuttle's length between perpendiculars
T	shuttle's draft
$Cx(\alpha_r)$	current drag coefficient in function of α_r in longitudinal direction
α_r	current incidence angle
F_{2C}	current load in the transversal, or sway, direction
$Cy(\alpha_r)$	current drag coefficient in function of α_r in transverse direction
F_{6C}	current moment about the vertical axis, or yaw
$Cn(\alpha_r)$	current drag coefficient in function of α_r regarding vertical moment
F_{1Wi}	wind load in the longitudinal, or surge, direction
ρ_a	air density
V	wind speed
Afrontal	frontal windage area
$Cwix(\beta_r)$	wind drag coefficient in function of β_r in longitudinal direction
β_r	wind incidence angle
F_{2Wi}	wind load in the transversal, or sway, direction
Alateral	lateral windage area
$Cwiy(\beta_r)$	wind drag coefficient in function of β_r in transverse direction
F_{6Wi}	wind moment about the vertical axis, or yaw
$Cwin(\beta_r)$	wind drag coefficient in function of β_r
$S(\omega)$	JONSWAP wave spectrum in function of wave frequency
α_0	constant that relates to the wind speed and fetch length
g	gravity
ω	incident wave frequency

ω_0	peak frequency
γ	constant parameter, peak enhancement factor
σ	constant that depends on the incident wave frequency
T_P	peak period
H_S	significant wave height
F_{jDM}	mean drift force or moment in the *j* direction (j = 1, 2 or 6)
$D_j(\omega, \beta_0)$	drift coefficient in the *j* direction (j = 1, 2 or 6)
β_0	wave angle of incidence
$D_{j,U}(\omega, \beta_0)$	drift coefficient affected by the presence of current
c	wave celerity
b_{wj}	coefficient used to calculate drift coefficient affected by current
b_{rj}	coefficient used to calculate drift coefficient affected by current
F_T	vector of environmental loads
F_{1T}	load in surge direction (longitudinal)
F_{2T}	load in sway direction (transverse)
F_{6T}	moment in yaw (vertical axis)
T_F	vector of thruster forces
$T_{x_1 i}^A$	azimuthal thruster force in longitudinal direction (i = 1 to n_{azim})
n_{azim}	number of azimuth thrusters
$T_{x_2 i}^A$	azimuthal thruster force in longitudinal direction (i = 1 to n_{azim})
T_j^F	fixed thruster force in longitudinal direction (j = 1+n_{azim} to n_{prop})
n_{prop}	total number of thrusters
α_{jP}	angle of fixed thruster
A	matrix of linear relationship between F_T and TF
c_j	cosine of α_{jP}
s_j	sine of α_{jP}
m_j	constant parameter of fixed thrusters (depends on angle/position)
L(T)	function to be minimized
T_i	total thruster force (i = 1 to n_{prop})

SUMMARY

1 INTRODUCTION

Oil extraction activity at sea initiated between the 30s and the 50s, first in Venezuela and then in the Gulf of Mexico using fixed platforms, which consist of large metal or concrete structures carved on the seabed. In these types of system, the Christmas tree (set of valves controlling the well production) and processing units are positioned above water level on the platform's deck, which is called dry completion, and the produced oil flows through subsea pipelines to the onshore terminals.

Along with the technology of fixed units, a series of drilling platform technologies was developed - including rigs on barges, on ships, on semi-submersible platforms (SS) and jack-ups (self-elevating units) - which allowed the continued expansion of offshore activity.

Thus, at the beginning of the 80s it became clear that although there was seismic and drilling technology to operate in deep water, the same did not occur with the production technologies. Fixed production systems have assumed increasing dimensions and their costs tend to increase exponentially with increased water depth.

A number of solutions were proposed to overcome this problem, including compliant tower platforms, articulated towers and tension leg platforms (TLP). The latter started to gain importance in the exploration and production activities in the Gulf of Mexico and the North Sea as it allowed to be installed in deeper fields and still keeping dry completion.

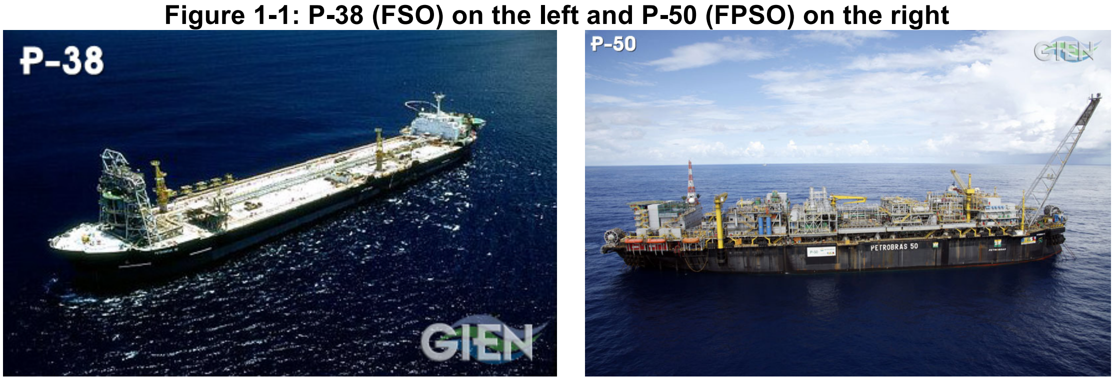
The first applications of wet completion technology, in which the Christmas tree are installed underwater lying on the seabed, were introduced in the North Sea. It was in this region that the first floating production systems (FPS) were developed, during the 70s (Furtado, 1996), but only in the 80/90 decades that the first floating units with wet completion were implemented.

The uprising of the concept of semi-submersible production units overcame the barrier of deep water and allowed reaching even ultra-deep waters. PETROBRAS installed the first SS in Brazil in 1983, in Corvina oil field whose depth is 230m.

Even though the SSs have represented an important development for the offshore activities, oil field discoveries in more distant areas from the coast have imposed major challenges with regard to the transportation of produced oil to the shore. The SSs, as well as the fixed units, are designed to treat the oil extracted from the well and then transfer it to the onshore terminals by major underwater pipelines. The increasing distance of the oil fields to the coast makes the projects of underwater pipelines ever more complicated and costly.

Therefore, the concepts of Floating Storage and Offloading units, (FSO), and of Floating Production Storage and Offloading units (FPSO) started to gain more importance. The first consists of an anchored tanker that stores the oil produced by other platforms in its cargo tanks inside the hull and exports it to a ship called shuttle tanker – in an operation called offloading – that transports it to the coast. The second consists of a more complete and independent unit, which produces the oil extracted from the well, stores it in its cargo tanks and performs the offloading. Figure 1-1 below shows examples of FSO and FPSO units. It is possible to differentiate easily the two types of units because FPSOs present several facilities installed on the topsides – which is the production plant – while the FSOs present a not so congested main deck, because they do not need a production plant.

Figure 1-1: P-38 (FSO) on the left and P-50 (FPSO) on the right



Source: PETROBRAS internal archives

The first FPSO in the world, Shell Castellon, was installed in 1977 in the Mediterranean Sea (Offshore Post, 2017). In Brazil, the first FPSO was installed in 1979 as an early production system, but the boom of FPSO construction and installation only happened at the beginning of the 90s due to the increased production of Campos Basin (Henriques and Brandão, 2007). This concept has become so important in the offshore industry that more than 150 units are now operating worldwide being 30 units in Brazil.

Over the years, PETROBRAS has demonstrated its great preference for FPSOs for oil exploration, especially in Santos Basin (BS), a region where part of the

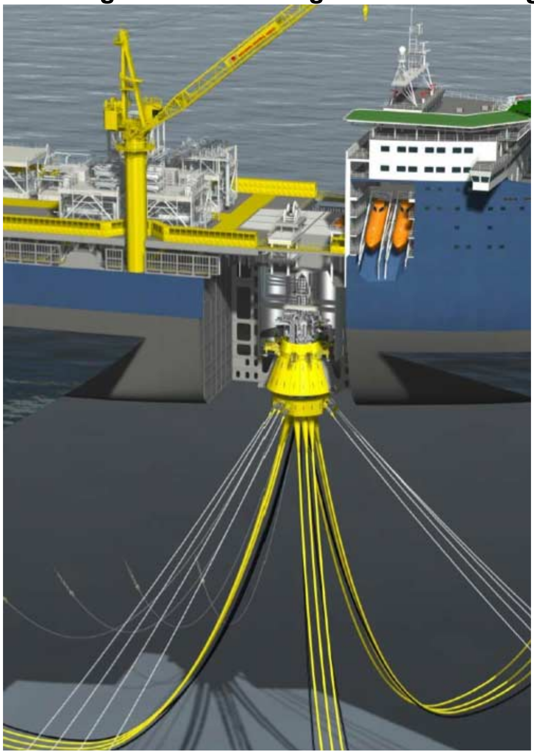
Brazilian pre-salt is found, where the fields are located up to 300 km from the coast and water depths are up to 2,500 m. Only 16 semi-submersible units make part of PETROBRAS fleet and, until 2020, 20 more FPSO units will be installed in Santos and other basins (PETROBRAS, 2015a).

1.1 FPSO mooring systems

It is important to define the two types of FPSO mooring systems that can be found in the industry: Single Point Mooring (SPM) and Spread Mooring System (SMS). The definition is important, because depending on the mooring system the oil export operations are performed with different types of tankers, as it will be explained in section 1.2, and this study concerns FPSOs moored with Spread Mooring System only.

The first type of mooring, the SPM, consists in an assembly of bearings and swivels, that is integrated into a vessel’s hull (internally, as shown in Figure 1-2, or externally, as shown in Figure 1-3) and permanently fixed to the seabed by means of a mooring system or a fixed structure. The bearing system allows the vessel to weathervane, i.e., rotate around the fixed part. The risers that bring the oil up from the well to the FPSO are connected to the swivels. They can be seen in Figure 1-2 as yellow lines (white lines are mooring lines, yellow lines are risers or injection lines and black lines are umbilicals).

Figure 1-2: Single Point Mooring – internal arrangement



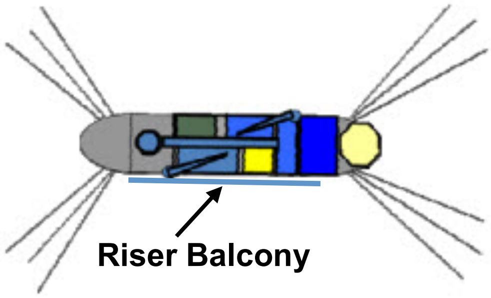
Source: (Scanmatic, 2016)

Figure 1-3: Single Point Mooring – external arrangement

Source: (Petróleo e Construção Naval, 2015)

The second type of mooring, SMS, consists in a multi-point system that moor vessels to the seabed using multiple mooring lines. They are usually composed by four clusters of mooring lines tied to each corner of FPSO and to the seabed as shown in Figure 1-4. This system, in the other hand, does not allow the FPSO to weathervane, i.e., its heading is permanently fixed, and in this configuration, the risers are connected to the FPSO through the riser balcony, which is located at portside, on the side of the hull.

Figure 1-4: Spread Mooring System (SMS)



Source: (2b1 Consulting, 2016)

Although the SMS presents the disadvantage of needing more mooring lines than the SPM (because the fixed heading implies greater mooring tensions to hold the FPSO in place), the SMS presents other advantages that made it largely preferred by PETROBRAS to every new FPSO.

Firstly, it demands less maintenance than the SPM, because the mooring lines only need to be re-tensioned from time to time, while bearings of the SPM need very careful lubrication. Any failure on this process might cause major damages to the bearings and it may cause clamping, which means losing the ability to weathervane. If major repairs on that system are needed, as for example, replacement of the bearings, this might mean the need of bringing the FPSO back to a shipyard to fix it. This would generate a millionaire loss for the operator and it is an alternative that is completely off the table.

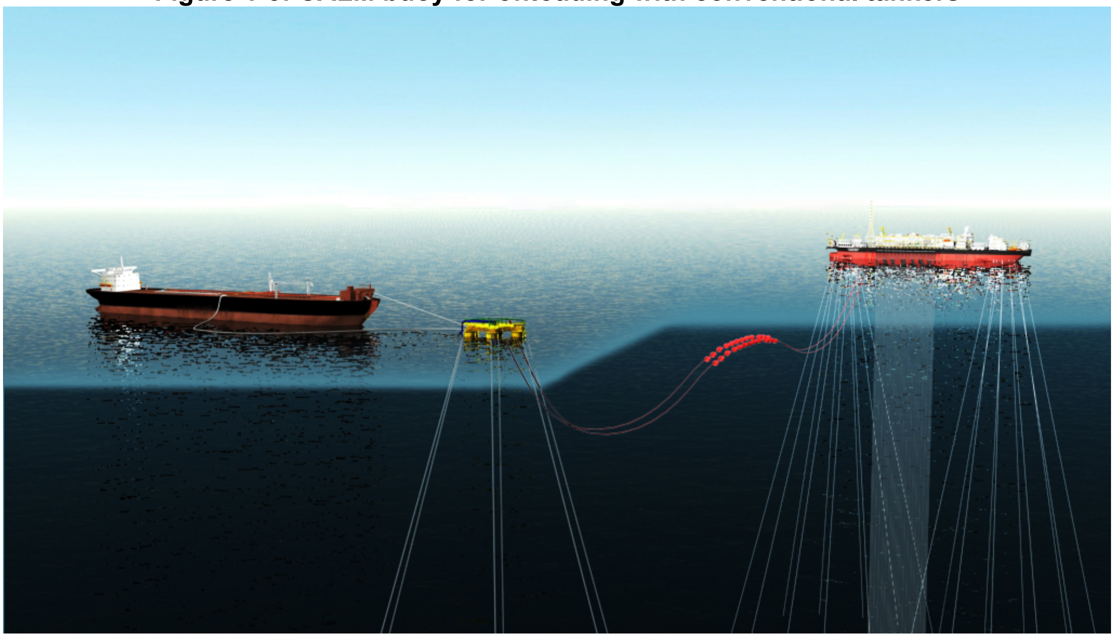
Second important advantage that made the SMS be the most used mooring system in PETROBRAS is that the riser balcony allows the connection of more risers, injection lines and umbilicals. A normal SPM accommodates about 30 slots for lines connection and the biggest one in the world accommodates 75 slots. A normal riser balcony, on the other hand, can accommodate around 100 slots. Hence, the production capacity on a SMS FPSO may be higher than a SPM one. For this reason, today, in PETROBRAS fleet, 22 F(P)SOs are spread moored and only 11 are single point moored.

1.2 Oil export from FPSO units

The oil stored in the F(P)SO must be transported to the coast by a tanker, or a shuttle tanker (ST), which navigates to the location of the platform and receives the oil through a string of flexible hoses. This operation can be performed in two ways: through a Catenary Anchor Leg Mooring (CALM) buoy or directly from the FPSO, which is known as tandem offloading.

The CALM buoy is a floating structure anchored to the seabed and connected to the FPSO by submarine hoses (see Figure 1-5). Its facilities include a hawser, which is generally a nylon rope, to which the tanker can moor, and a string of floating hoses that connects to the tanker's midship manifold through which the oil will be transferred.

Figure 1-5: CALM buoy for offloading with conventional tankers



Source: PETROBRAS internal archives

Traditionally in Brazil, the CALM buoy is used in port terminals for loading and unloading oil. The operation takes place in sheltered waters using conventional tankers.

Although the CALM buoy is able to operate with any conventional tanker, it presents serious disadvantages in terms of personnel and environment safety. The activities of hoisting the hose and its connection to the midship manifold are manual tasks without any automation. During the connection, the workers are closely positioned to a hoisted element that presents many hazards such as fingers or arms clamping or even crushing to death if the crew is not properly trained. Man overboard is another serious hazard in the operation since it happens through the side shell of the hull. Figure 1-6 and Figure 1-7 below illustrate the moment of lifting the hose and the connection to the midship manifold in a conventional shuttle tanker. These pictures were actually taken during a tandem offloading in a SPM FSO, but the operation is very similar to that of a CALM buoy.

Figure 1-6: Hose lifting in conventional shuttle tankers.

Source: PETROBRAS internal archives

Figure 1-7: Hose connection to midship manifold in conventional shuttle tankers.

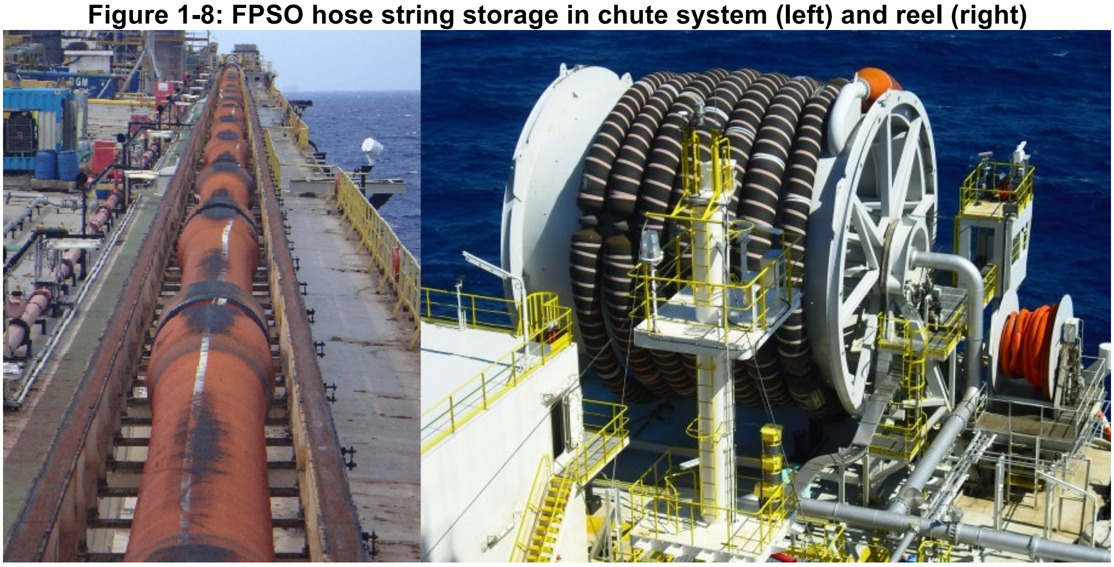
Source: PETROBRAS internal archives

In terms of environmental risks, the midship connection does not present any possibility of quick disconnection between the tanker and the hose string. Hence, an undesired event such as hawser rupture may cause hose string rupture and consequent oil pollution.

Operation with offshore CALM buoys offers, therefore, in the Brazilian context, even greater risks to workers and environment, as the operations would take place under adverse environmental conditions and using exactly the same type of vessel, equipment and personnel. For this reason, PETROBRAS operates four CALM buoys only, in port terminals, and is installing another one in Campos Basin for offloading in shallow water (90 m).

The offloading in tandem is the most frequently used in F(P)SOs in Brazil. Single Point Mooring units have one offloading station at the stern and Spread Moored units have two offloading stations, one at the bow and one at the stern, where the flexible hoses are stored either elongated over a chute or wounded onto reels (see Figure 1-8), the last being the most common alternative.

Figure 1-8: FPSO hose string storage in chute system (left) and reel (right)



Source: PETROBRAS internal archives (right) and Offshore Technology (2016) (left)

In this operation, the tanker approaches the production unit at about 80m away so that the platform personnel shoots a messenger line to be used to hoist the hawser and the hose string from the FPSO to the tanker. At this point, depending on the tanker used, the sequence of activities varies.

For SPM F(P)SOs in Campos Basin, it is still common to use conventional tankers, because the production unit and the tanker tend to be aligned with the environmental conditions at all times, which reduces the risk of collisions between them. However, the activities of hose connection to the midship manifold of the tanker are the same as on the operation of a CALM buoy earlier described, and the risk to workers is still too high.

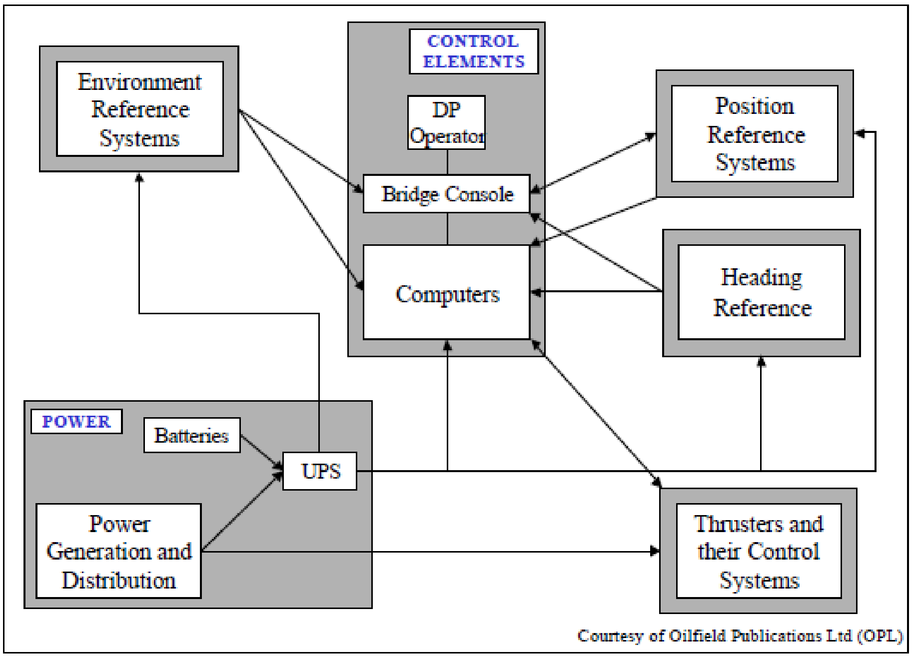
For Spread Moored FPSOs, which do not align with the environmental conditions because of its fixed heading, the risk of operation with conventional vessels is considered not tolerable by PETROBRAS, because in case of a sudden change in the weather the tanker would not be able to keep position and there would be not enough time to disconnect the offloading hoses and avoid collision of both vessels.

For this reason, SMS FPSOs operate only with Dynamically Positioned Shuttle Tankers (DPSTs), or simply Shuttle Tankers (ST), which are better described in section 1.3.

1.3 DP shuttle tankers

The Dynamic Positioning System (DP system or simply DPS) is a system that automatically controls the heading and position of a vessel by means of active propulsion. It consists in a complex control system composed by four subsystems: a set of **sensors** for the detection of position, course, heading and environmental conditions, a central **control module** – which processes the information received from sensors, estimates the environmental forces acting on the ship and calculates the necessary thrusts to keep it in a certain position – a **propulsion system** – which receives the central control commands and drives the thrusters to obtain the desired forces and returns the feedback of the actions to the controller – and finally a **generation and distribution system** - that feeds electric power to all the other systems. Figure 1-9 extracted from Eriksen, Harms and McDonnell (1999), illustrates how these systems are interrelated.

Figure 1-9: General arrangement of a Dynamic Positioning System



Source: (Eriksen, Harms and McDonnell, 1999)

Among the available DP vessels on the market, there are several types of projects that aim at different levels of position keeping ability, reliability and redundancy. In general, the types of DP vessel are divided into three classes, according to the following criteria (ABS, 2013):

• **Class 1:** the loss of position is accepted to occur in a single failure event;

• **Class 2:** loss of position is not accepted to occur in the event of a single failure of a component or system (generators, thrusters, switchboards, control computers, sensors, remotely controlled valves, etc.), excluding the loss of one or more compartments;

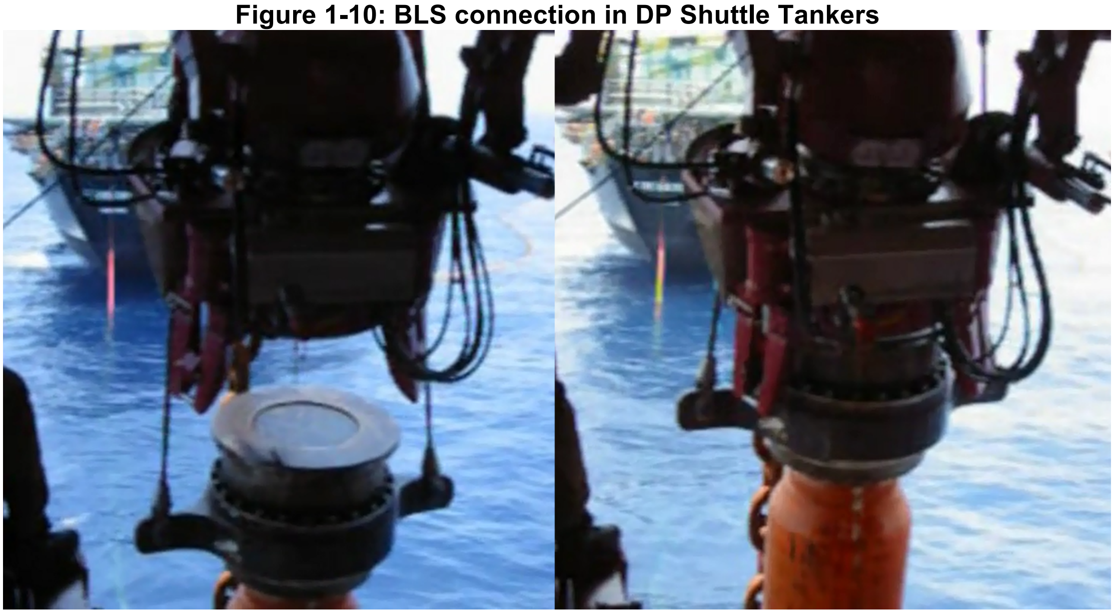
• **Class 3:** loss of position is not accepted to occur in the event of a single failure of a component or system (generators, thrusters, switchboards, control computer, sensors, controlled valves remotely, etc.), including the loss of a whole compartment by fire or flooding.

ABS Guide also provides Enhanced Class Notation (EHS) for DP-2 and DP-3 vessels. This notation provides the basis for the measurement of the enhancement of critical components of the DP system, including power and thruster system, control system and fire & flood protection system. Although EHS notation is not available for DP-1, some shuttle tankers in PETROBRAS fleet are considered to be DP-1 Enhanced, because they present improvements on their power or thruster system.

The DP system was developed in the 60s for offshore drilling activities. The first trials with shuttle tankers took place in the North Sea in 1982 (Helgøy, 2003). The DP shuttle tankers reduce the risk of collision with the production units, since they can counteract the environmental loads.

Nevertheless, they are designed with the Bow Loading System (BLS), shown in Figure 1-10 below, which allows automated connection of the hose string to the ship's bow manifold and contributes greatly to enhancing personal safety, since it eliminates the direct contact of workers with the hose string. A quick release feature is also available in the BLS, avoiding environmental pollution in case of undesired events.

Figure 1-10: BLS connection in DP Shuttle Tankers



Source: PETROBRAS internal archives

Because of these safety advantages, PETROBRAS has adopted since 2002 the exclusive use of DPSTs to carry out offloading operations in SMS F(P)SOs. The first to enter the fleet were Cartola and Ataulfo shuttle tankers. Today the fleet consists of 28 vessels, among which eight are DP Class 1, two are DP Class 1 Enhanced, and seventeen are DP Class 2.

Although there are no official records of all incidents and accidents involving conventional tankers and shuttle tankers for comparison, operational experience shows that DPST incidents and accidents are less frequent. From 2002 to date there has been only one collision recorded in Brazil of Cartola DP-1 shuttle tanker with

FPSO Marlim Sul in 2012, while at least three collisions between FPSO and conventional tankers took place in the history of offloading operations in Brazil.

1.4 Offloading with DP shuttle tankers

The offloading operation consists of five steps: Approach, Connection/Mooring, Offloading, Disconnection/Unmooring and Departure.

The shuttle tanker navigates until the location with its main propeller and rudder. The Captain turns the DP system on when the ST is about 1,500m away from the FPSO. The approximation is aided by the DP system, which actuates on the thrusters to progressively decrease the shuttle's speed from around 3 knots to the complete stop. The tanker always approaches in the opposite direction of the resulting environmental forces to minimize risk of collision in case of blackout.

When the tanker is about 80m away, the messenger line is passed from the platform to the tanker with the help of an air pistol. The ST reaps the messenger line of the hawser and hose string and performs the mooring/connection to both the chain stopper and the BLS, respectively. The whole connection phase lasts around 6 hours in total.

After connection, the ST positions itself from 120 to 155m away from the FPSO to continue the operation. First, a leak test takes place on the hose string and then water is pumped from the FPSO to the ST's slop tank. Finally, the oil starts pumping from the FPSO to the ST's cargo tanks.

After the loading is complete, about 24 hours later, the ship's slop water is pumped back to the FPSO to flush the oil off the hose string, and the ship's crew starts to disconnect the hoses and the hawser. Once disconnected, the ship departs using the main engine only.

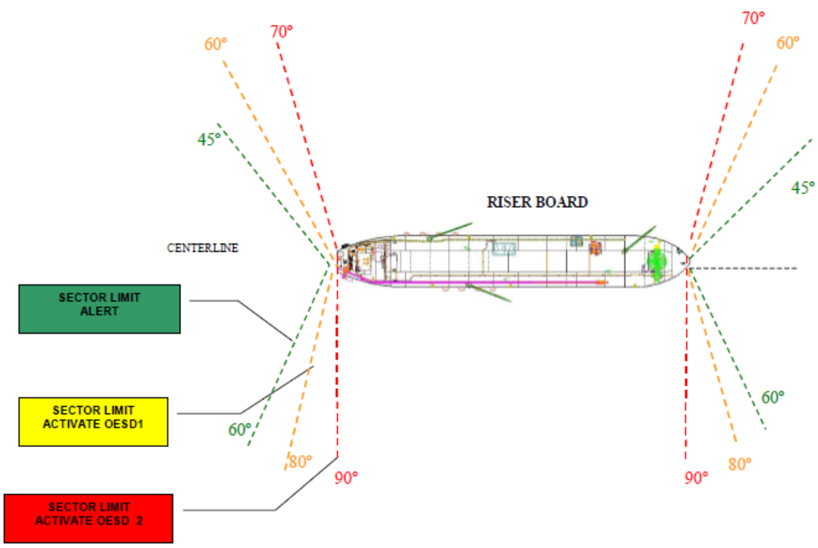
In order to increase the safety of these operations, PETROBRAS has established procedures that limit the operating sector of DPSTs, bordering a green area where the vessel is allowed to be positioned in during all stages of offloading.

Figure 1-11 shows the current operating sector for offloading operations in Spread Moored FPSOs. It can be noted that the limit angles are not symmetrical: the green limit is 45° to portside and 60° to starboard, or simply -45°/+60°. The sector is more restricted at portside because this is the riser balcony side, where all the risers are connected. At this side, the risers come out of the water and are exposed to the surface. Any collision on there would be catastrophic.

The operating sectors are defined as follows:

- **GREEN SECTOR**: the sector within which the shuttle tanker is allowed to stay during the whole offloading operation.
- **YELLOW SECTOR**: the sector within which the ship is allowed to stay as long as necessary for the Captain to try to put the ship back into the Green Zone using the available resources. If the ST reaches 85° to starboard or 60° to port, the Captain contacts the FPSO OIM, requesting the immediate interruption of the offloading operation (OESD I). The shuttle crew must stay alert to perform emergency disconnection of the hose and mooring system (OESD II - Offloading Emergency ShutDown level 2) if necessary.
- **RED SECTOR**: the sector within which the shuttle tanker is not allowed to stay under any circumstances. If the ship reaches 90° to starboard or 70° to port, the Captain should immediately execute the emergency disconnection of the hose line and mooring system (OESD II).

Figure 1-11: Operating sector for Spread Moored Platforms



Source: (PETROBRAS, 2009)

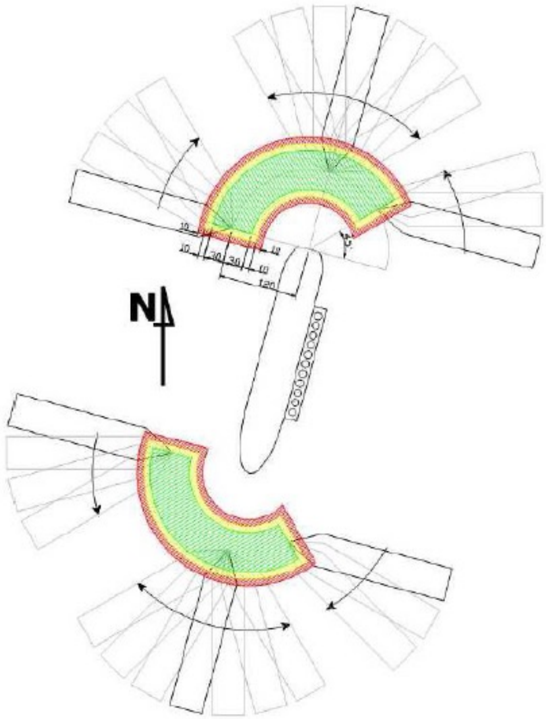
1.5 Objectives

The objective of this work is to develop and apply a meticulous but sufficient methodology to validate a modification of a specification in offloading operations.

The modification under consideration is the proposal of extending the offloading green sector described in section 1.4 from -45°/+60° to -45°/+90°. The main motivation for this is that extending the green sector may increase the operation's availability, or uptime, which may represent financial economy for the platform's operator, as it will be explained in section 1.6.

The extension of the offloading sector was originally proposed by Corrêa (2012), who demonstrated through a series of static analyses that this would result in significant availability gains in offloading operations. Corrêa studied two proposals of extended green sectors: -45°/+90° and -45°/+120° – always maintaining -45° at portside not to increase safety risks on the riser balcony side. His results show that uptime gain would be significant in both proposals: around 10% and 15%, respectively. However, he preferred not to consider -45°/+120° as a feasible proposal because the equipment installed at the FPSO offloading stations (hawser chain stopper and hoses' reel) have physical limitations that may be surpassed if the DPST is allowed to reach +120°. Figure 1-12 is extracted from his study and shows his final green sector proposal, -45°/+90°, which will be evaluated in this study.

Figure 1-12: Extended operating sector proposed by Corrêa (2012)



Source: (Corrêa, 2012)

This proposal, however, still needed to be evaluated through a specific preliminary risk analysis, real time simulations and field tests, and the availability calculations still needed to be improved to consider an operating window of 36 hours, which is necessary to accomplish the offloading operation.

That is why the present work developed and applied the methodology further explained in section 1.7, in order to validate Corrêa's operating sector proposal.

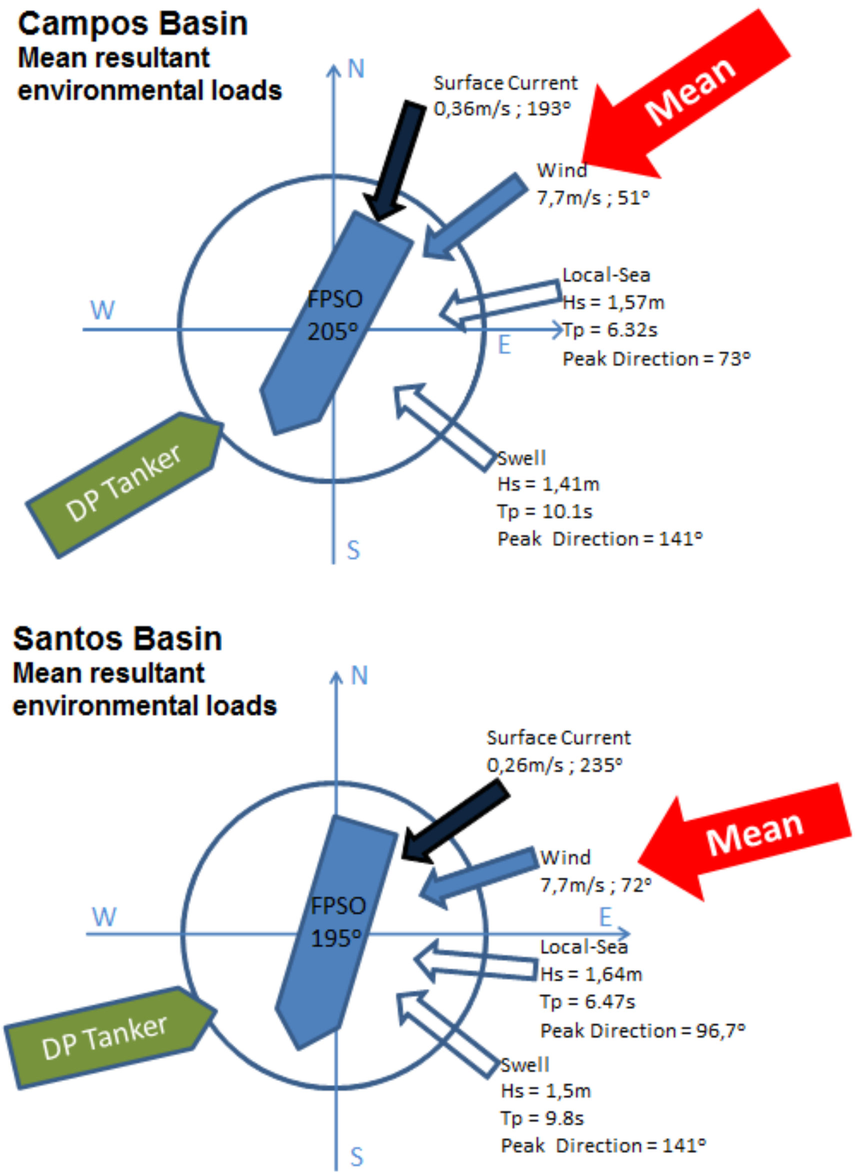
1.6 Justification

Although PETROBRAS has operated with this sector for many years, Santos Basin offloading operations, which are becoming more and more frequent, are very challenging.

As it will be shown in section 5.1.2, Santos Basin's environmental conditions are more severe than Campos Basin's and their mean resultant load tends to push the shuttle tanker to the West, especially when strong currents come from the East. Figure 1-13 below shows the difference between annual mean environmental loads in Campos and Santos Basins. The resultant forces were calculated from hindcast data available for each basin (for more information on hindcast data, see sections 2.5

and 5.1.2). It can be seen that mean environmental loads in Campos Basin tend to push the shuttle tanker to South-West, while in Santos Basins they tend to push the DPST to the West, i.e., pushing it out of the green sector[1].

Figure 1-13: Campos and Santos Basins mean resultant environmental loads



Source: Eduardo Aoun Tannuri

[1] It is important to notice that the FPSO heading on the location is chosen to optimize its mooring system, i.e., to position the vessel in the most favorable heading to handle the incidence of extreme conditions. In Campos and Santos Basins, extreme conditions generally come from South-West, so the FPSOs are headed in a way that unfortunately does not optimize offloading operations.

Consequently, on the last years PETROBRAS has experienced several offloadings being aborted because the DPST could not keep position inside the green sector.

Extending the operating sector is thus crucial to the efficiency of offloading operations on the years to come. Corrêa (2012) was already aware of this issue and showed that increasing the operational sector to -45°/+90° could bring gains of around 10% to 15% in the availability of each offloading station. This would be equivalent to 36 days more to operate in a year.

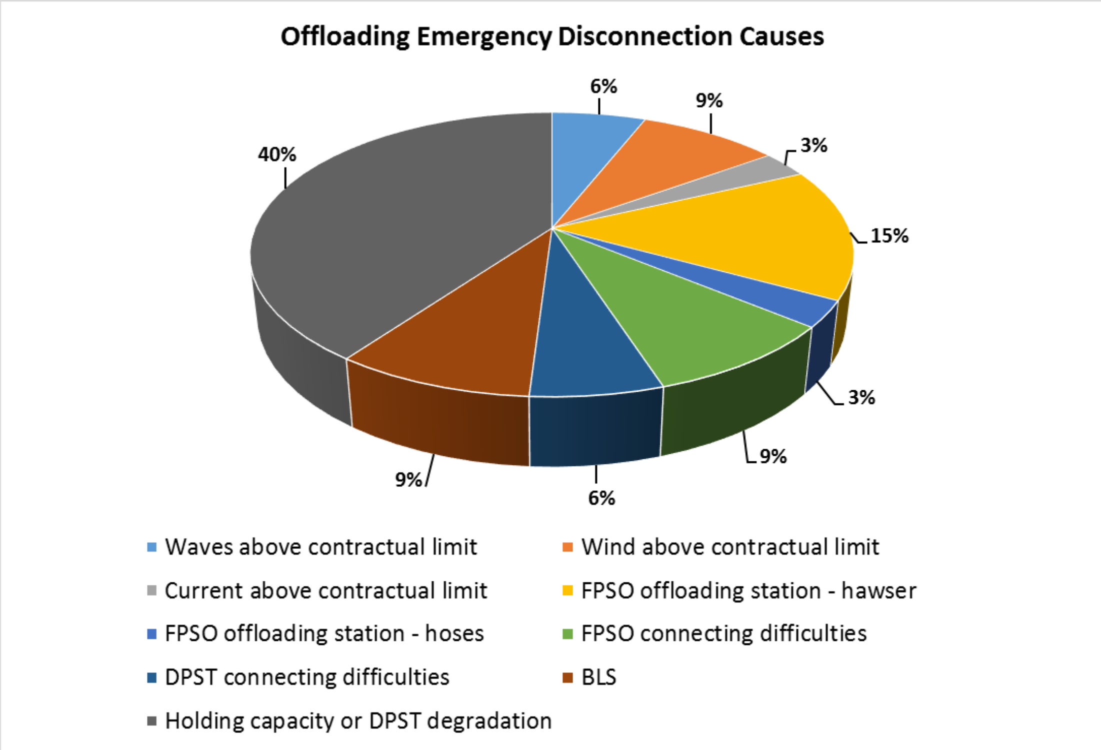
The greater the availability of operations, the lower the risk of interrupting the oil production due to "top". A top happens when the platform has to stop the production plant due to lack of storage space in the cargo tanks. This scenario may occur when the offloading cannot be carried out because of bad weather conditions – that hinder the position keeping of the DPST – or because of operational difficulties – DPS degradation or problems with the offloading station equipment.

Stopping a plant that processes about 100,000 barrels of oil per day generates millionaire losses to the operator and should be avoided to the maximum.

Even if there is no risk of top in a platform, the delay in offloading operations generates extra costs of demurrage of the shuttle tanker. The daily rate of these DP tankers is about U$55,000. For this reason, any demurrage in the operation is quite costly to the oil company.

Corrêa (2012) presents the statistics of emergency disconnections that occurred in offloading operations in Spread Moored terminals, in both in Santos and Campos basins between 2008 and 2011. In total, 33 disconnections took place, of which 13 (about 40%) were motivated by position keeping difficulties by the DPST – which can be either due to vessel degradation or due to environmental conditions pushing the ship out of the operating sector. The other disconnections have been caused by other factors, as shown in Figure 1-14.

Figure 1-14: DPST/SMS FPSO emercency disconnection causes for Campos and Santos Basins



Source: (Corrêa, 2012)

According to PETROBRAS Business Plan (PETROBRAS, 2015a), by 2020, 22 more FPSO units will be installed in Santos Basin to develop the pre-salt fields. In this scenario, the increased availability of the offloading operation can bring economic benefits to the company, reducing the risk of interrupting the production units and of demurrage of shuttle tankers.

Nevertheless, Corrêa (2012) points out that the extension of operating sector could increase operational safety, because it allows the ST to better align with environmental conditions, reducing the power demand on the thrusters and hence the risk of black-out. This work will show in section 6 that this hypothesis is actually true.

1.7 Methodology

The methodology used in this study consists in five different steps. First, a Preliminary Risk Analysis is performed by a group of specialists to assess the potential hazards associated with the operation on the new extended sector. The main purpose is to better understand what can go wrong during the operation at big relative headings and what the consequences are. Drive-off and blackout failures followed by collision with the F(P)SO are the main focus of this work. This step is described in section 4.

Second, a downtime analysis is carried out to evaluate the advantages of the extended sector in terms of availability gain. This is accomplished by performing several static analyses to determine the ship's station keeping capability under the environmental conditions from Campos and Santos basins as further explained in section 5. This analysis differs from Corrêa's because it takes into account an operating window of 36 hours, which is a more conservative approach, and it uses different hindcast data from other locations.

The third step is a power demand analysis, whose main objective is to evaluate the advantages of the extended sector in terms of power demand reduction. As previously mentioned in section 1.6, by operating in the extended sector, the shuttle tanker can better align with environmental conditions which would decrease the power demand on the thrusters and hence the fuel consumption and the risk of blackout. This analysis results in a comparison between the optimized power demand on the DP system when the vessel operates in original and extended sectors through histograms, which are shown in section 6.

The fourth step, detailed in section 7, consists in a series of real time simulations followed by experienced DPST Captains so they can evaluate in practice the extended operating sector and manifest their opinion about the safety of the operations under the new proposed conditions.

Finally, the fifth step, detailed in section 8, consists in performing field tests to evaluate the software update that needs to be installed on the shuttle tanker and to assess the Captain's impression on the safety of the operation, this time in real life.

1.8 Text Organization

This report first provides in section 2 a literature review to show what has been studied about offloading operations that is important to the methodology explained in section 1.7. This involves operating sectors, risk analysis, numerical simulations, downtime analysis and the use of hindcast data.

Then, in section 3, the theoretical concepts, which were used to accomplish the whole methodology, are detailed. Those concern the methodologies for calculating environmental loads (from wind, waves and current) over the shuttle tanker's hull, for thrust allocation – both used in the Downtime Analysis step – and the theory behind Preliminary Risk Assessment, which is used in the fourth step.

Next, it presents in detail each of the methodology's steps that were performed, as follows: Preliminary Risk Analysis (PRA) in section 4, Offloading Downtime Analysis in section 5, DP System Power Demand Analysis in section 6, Real Time Simulations in section 7 and Field Tests in section 8. For each activity, the specific methodology and results are described.

Section 9 finally brings the conclusions that summarize the results that support the proposal of extending the operating sector, and after that, the bibliography, the glossary, the appendices and annexes are presented.

2 LITERATURE REVIEW AND BACKGROUND

Offloading systems and operations are widely studied in the industrial and academic community. Issues such as risk, collision, structural damage are the most frequent, as seen below.

It should be noted that in the North Sea – a very well studied location in the literature – most FPSOs are single point-moored and align with the environmental conditions all the time (some even have stern thrusters to change their heading). In addition, the DPSTs operate at distances between 80 and 100 meters from the FPSO, and, in general, the DP system is operated in Taut Hawser mode – when distance from FPSO is “manually” ensured by the Captain, using the main propeller with a small thrust astern and keeping the hawser tension up to 20 ton –, as reported by Chen and Moan (2004) and Vinnem, Utne and Schjølberg (2015).

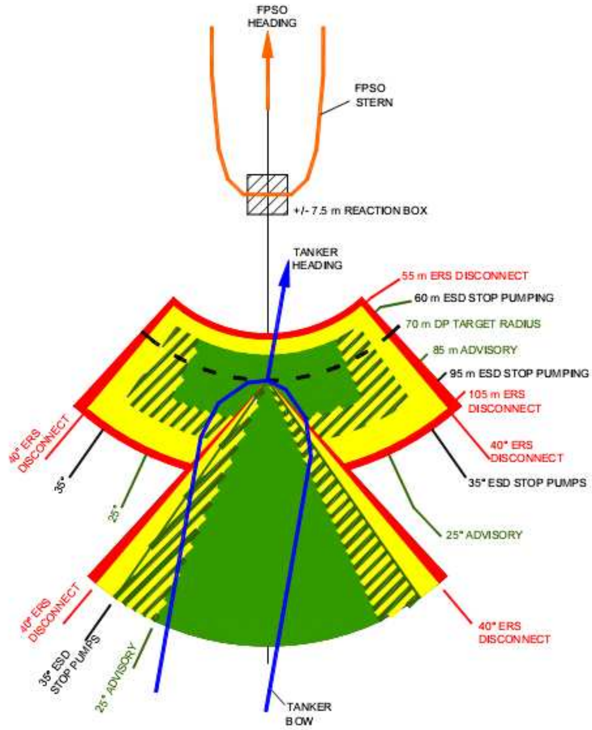
In Brazil, on the other hand, most FPSOs are Spread Moored, the operating distance of the DPST is 150m and the DP operating mode is called Normal Mode – in which the DPS operates automatically with a fixed set point, which is the shuttle’s midship section, and in weathervane mode, i.e., the shuttle aligns automatically with the resultant of environmental conditions and the midship section is a fixed reference point that is kept at the same GPS coordinates all the time.

Therefore, it is interesting to analyze the aforementioned bibliographies with some caution when interpreting their issues and recommendations.

2.1 Offloading operating sectors

The first reference that mentions operating sectors is the UKOOA Tandem Loading Guidelines (UKOOA, 2002), which brings the operating limits shown in Figure 2-1. These limits are less severe than PETROBRAS’ when it comes to distance from the FPSO, as they allow the shuttle to be as close as 60 m from the platform during operation. On the other hand, it is more restrictive when it comes to the position of the shuttle’s bow, which is limited to +/- 25°.

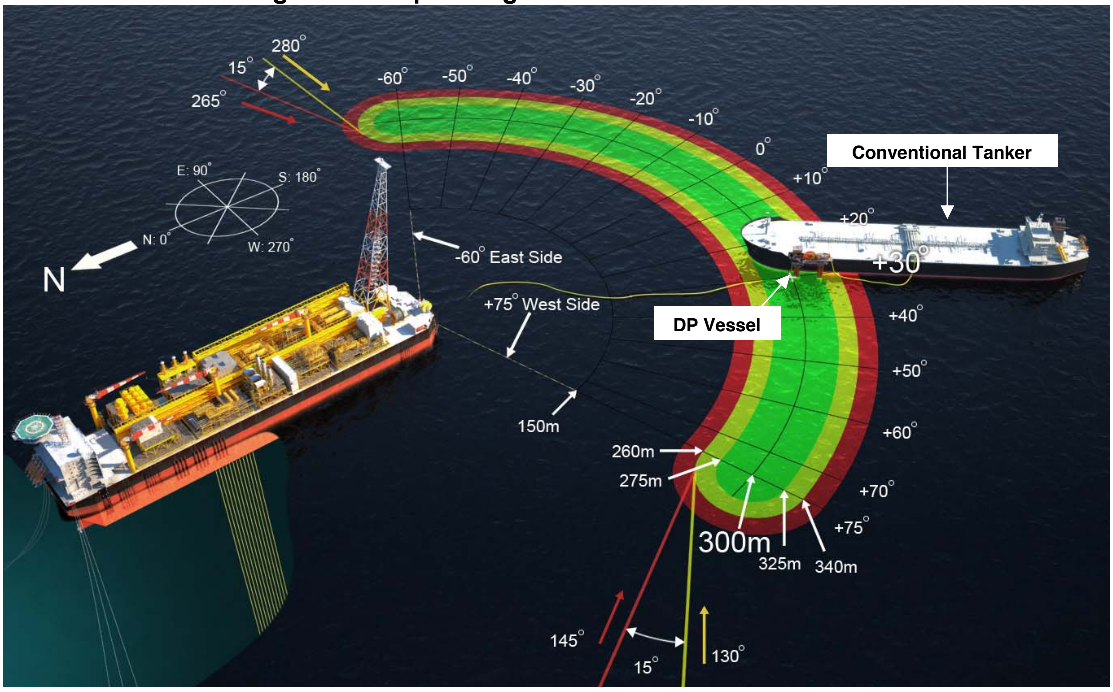
Figure 2-1: Offloading operating limits



Source: (UKOOA, 2002)

Diederichsen and Olsen (2012) present the qualification of a new DP offloading vessel, designed to dock onto conventional tankers and keep them on safe position during the offloading operation. This vessel is designed to operate in a called banana sector, which goes from -60° on portside and +75° on starboard (see Figure 2-2) 300 meters away from the spread moored FPSO. This proposal was validated and considered safe enough with the aid of real time simulations. In this case, the green sector is larger than PETROBRAS', but the same logic applies here: since the DP vessel is 300m away from the FPSO, it seems fair to operate in a bigger sector.

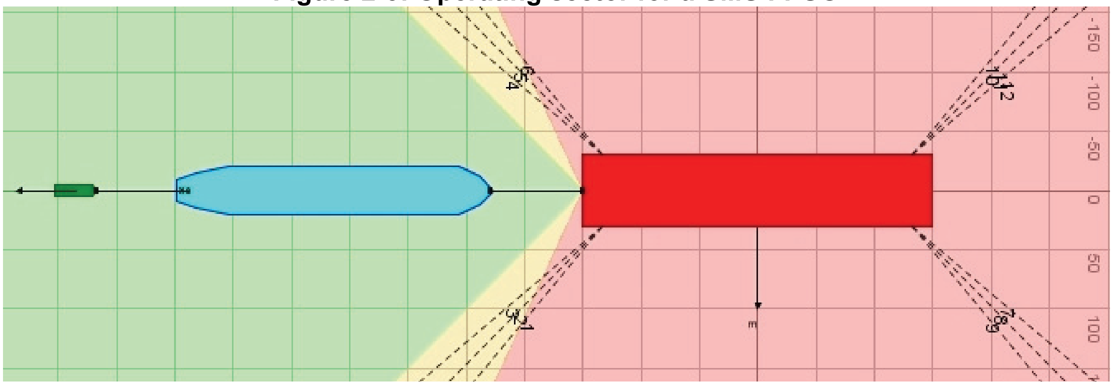
Figure 2-2: Operating sector for a new DP vessel



Source: (Diederichsen and Olsen, 2012)

Voogt and Brugts (2010) discusses about numerical simulations using a computational tool called "Shuttle" to evaluate offloading from a spread moored LNG terminal. At a certain point, its shows an image of a numerical simulation taking into account an operating sector, but never gives the parameters of this sector. However, by analyzing Figure 2-3 and the grid of the drawing it is possible to assume that the green sector is +/- 45° and yellow sector is +/- 60°.

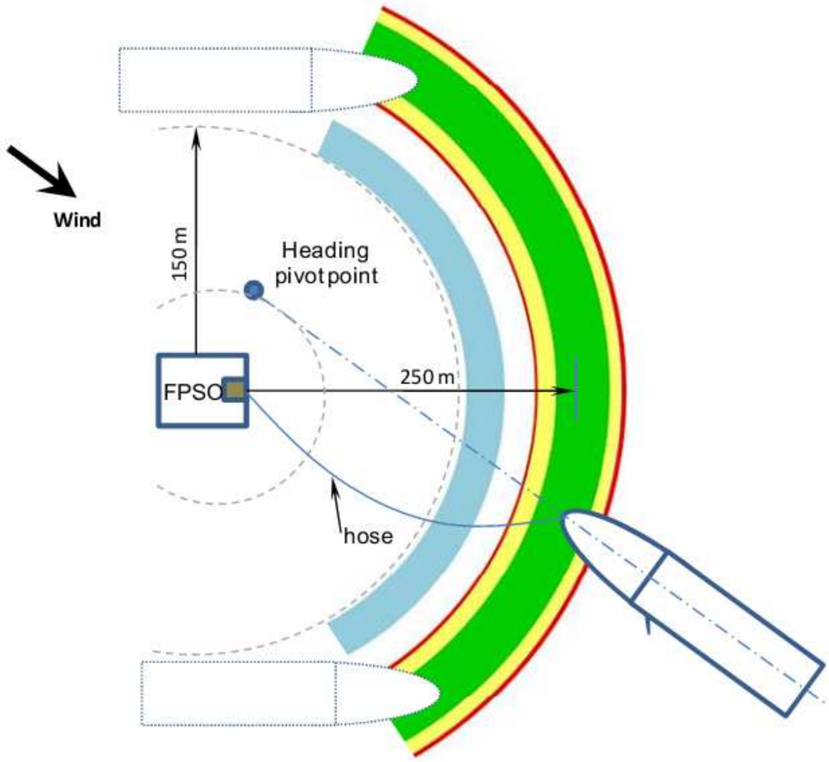
Figure 2-3: Operating sector for a SMS FPSO



Source: (Voogt and Brugts, 2010)

Chen, Lerstad and Moan (2010), present the following operating sector shown in Figure 2-4, which is used in Sevan Marine unit (spread moored cylindrical FPSO) operating in Hummingbird/Chestnut field in the North sea. Although they do not bring the information about the sector aperture angles, it is possible to see that the distance from the FPSO is 250m, that the DPST may assume a wide range of headings and that the ship always aims a pivot point which is not the FPSO's offloading station – reducing, thus, the risk of collision in case of drive-off. The blue zone is the messenger line pick-up point.

Figure 2-4: Operating sector for a SMS FPSO



Source: (Chen, Lerstad and Moan, 2010)

2.2 Offloading risk analysis

Risk analysis is an important activity for managing the health and safety of any business. They are commonly used to assess the possible hazards of the operations and decide whether the operator is implementing reasonable measures to prevent those hazards from becoming accidents.

Different techniques may be used for assessing and analyzing risks, but they are usually classified into two categories: qualitative risk analysis and quantitative risk analysis. The last alternative is usually applied when the main target is to quantify the probabilities of occurrence of a certain hazard and its consequences, when that information is important for decision-making. When it comes to offloading operations, a quantitative risk analysis targets at, for example, calculating the expected probability of collisions between shuttle tanker and FPSO as Chen and Moan (2004) did. They developed a probabilistic model based on historical statistics of collisions caused by drive-off events and on the modelling of probability of failure of recovery actions to avoid collision after drive-off has initiated.

Rodriguez (2012) has performed extensive studies on quantitative risk analysis in offloading operations introducing a method called dynamic probabilistic analysis, which considers that probabilities of failure may change over time with the come-out of new events. The method applies Bayesian and Markovian analysis to calculate the probabilities of different failure events. Other references on that subject include Rodriguez and Souza (2011a and 2011b).

Qualitative analysis, which is used in this study, is the best choice when the objective is to evaluate and rank the risks of the operation into “tolerable”, “moderate” and “not tolerable” categories and to assess recommendations for risk mitigation.

Qualitative analysis must be based, as much as possible, on professionals’ experience, historical incidents data and technical knowledge of the systems and their failure causes. Many are the authors who discuss those issues.

Vinnem, Utne and Schjølberg (2015) and Lundborg (2014) present statistics on the number of collisions and near collisions that occurred between 1996 and 2013 in FPSOs operating for Norway and the UK in the North Sea, showing that there were 7 collisions and 13 near collisions with DP shuttle tankers in that period. Chen and Moan (2004) report that among 2,000 offloading operations that were carried out by DP shuttle tankers between 1996 and 2000, 5 collisions took place, all of them caused by drive-off event, which happens when the DP system erroneously drives the ship out of position – backwards or forwards, the last one increasing the risk of collision.

Also according to Chen, the occurrence of drive-off is associated with the intense response of FPSOs to environmental conditions (surge and yaw motions), which imposes large changes in the horizontal relative distance between the vessels. These situations make the DP system of the ST constantly seek the correct distance from the target and possibly end up driving the tanker forward and against the platform. This hypothesis is not actually applicable in Brazilian fields, because SMS FPSOs do not present large fishtailing motions while single point moored FPSOs operate with conventional shuttle tankers. By PETROBRAS own experience, drive-off occurs mostly for technical or maintenance problems such as locking of the pitch of the Controlled Pitch Propeller (CPP) in an unwanted position.

Chen also estimated by time domain simulations that the Captain’s response to drive-off must take 53 seconds maximum to successfully avoid collision when operating at 80m-distance, whereas it must take 81 seconds maximum when operating ate 150m-distance. However, based on information about incidents, analysis of questionnaires given to various Captains and observation training simulator instructors, on average, an operator takes 60-90 seconds to react.

MacDonald et al. (1999), Chen and Moan (2004) and Vinnem, Utne and Schjølberg (2015) point out that the biggest risks are related to drive-off and may cause extensive damage as rupture of fuel tanks, damage to living quarters, loss of multiple anchoring lines, flooding of the machinery room, and even multiple explosions in both vessels if severe collision takes place just below the flare structure.

Several recommendations are made for mitigating risks, including use of fenders during operation (MacDonald et al., 1999), more training and better scaling of the crew (Williams et al., 1999) and better integration with the support base onshore (Easton and Falcon, 2000) - the latter being framed in the reality of drilling rigs, but not impossible to adapt to the case of DP vessels.

Vinnem, Utne and Schjølberg (2015) and Mo, Muddusetti and Cargill (2011) also propose the implementation of decision support software on the DPST that provides online information such as manuals, documents, standards, lists of equipment interdependence and failure consequences, assisting the commander in decision-making on the continuation or not of the offloading operation.

Finally, Chen and Moan (2004) propose measures to increase the time to respond to the drive-off events: more effective systems to drive-off detection, improved training of the crew to ensure greater attention during operations and the increase in operating distance between ship and platform.

This last recommendation makes perfect sense if we compare accident statistics occurred in the North Sea, where the DPST operates 80 to 100m away from the FPSO (Vinnem, Utne and Schjølberg, 2015), and in Brazil, where PETROBRAS procedures require 150m. While Vinnem, Utne and Schjølberg (2015) reports at least seven collisions between 1996 and 2013 in the North Sea, Brazil experienced only one collision event between 2002 and 2016.

Obviously, this is a very simplified comparison. Several issues may be related to fewer accidents in Brazil, including shorter history in DP offloading, type of FPSO mooring system (SPM versus SMS), shorter number of DP-aided offloadings performed per year, company's management system and other issues. However, the operating distance between vessels is a strong sign.

Literatures about predicting collision damages between ships were also researched in order to have an idea of how critical a collision between FPSO and DP shuttle tanker would be during offloading. Many authors have developed several tools and they include simple formulae, simplified analytical methods, simplified FEM, and non-linear FEM simulations.

Most part of the articles found, though, such as Sun (2015), Kitamura et al. (2002), Yamada and Pedersen (2007) and Gao et al. (2014), predict collision consequences between two ships, or between FPSO and passing ships, taking place at speeds ranging from 5 to 15 knots. The last authors conclude that right angle collision is the worst case for the struck ship.

However, MacDonald et al. (1999) claim that collision between FPSO and DP shuttle tanker during offloading might take place at a maximum of 2 knots, because such a small distance between the vessels would not allow the DPST to accelerate more than that in case of a drive-off event. No other study was found about calculating collision consequences between FPSO and DPST during offloading, but it is known that the only collision experienced in PETROBRAS' history originated structural damages only with no oil spills or personnel injury.

2.3 Offloading numerical simulations

Numerical simulations are usually applied in Naval and Marine Engineering in order to calculate vessels' motions and accelerations under the influence of weather (current, wind and waves), other vessels[2] and mooring or Dynamic Positioning system. Three types of simulations are commonly used: static analyses, fast-time dynamic analyses and real-time dynamic analysis.

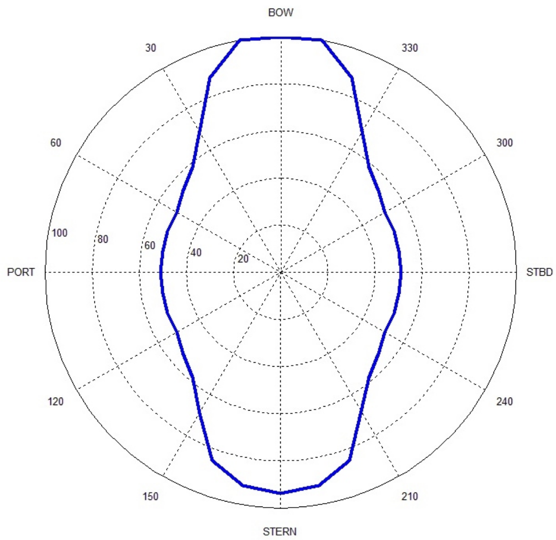
[2] Simultaneous operations with two or more vessels generally require a so-called diffraction and radiation analyses, because the presence of other hulls close to a certain vessel may affect the profiles of wave, wind and current that reach it.

Static analyses consider that environmental loads are constant forces acting on the hull. Thus, they are simple, fast and do not consume many computational resources. Although the real environmental conditions are dynamic, i.e., they change over time, static analyses are widely used in the industry since they allow that a large number of conditions are tested in minimum time. Normally, a safety margin is put into place to guarantee that the results are conservative.

When it comes to Dynamic Positioning operations, they are commonly used, for example, to evaluate the station-keeping capability of DP vessels. The simulations calculate constant environmental loads over the hull in every direction from 0 to 360° and evaluate if the available thrust is able to counteract those forces or not, and, thus, if the vessel can maintain position and heading or not. The results are usually presented as Capability Plots, which are polar plots that contain wind envelopes, where the maximum wind speed at which the vessel can maintain position and heading is plotted for each angle of attack. A plot example is shown in Figure 2-5.

IMCA (2000) specifies the requirements for generating Capability Plots based on static analyses. In order to compensate for dynamic loads, which, as already said, are not represented in static analysis, IMCA recommends using a 15-20% dynamic margin over the available thrust to guarantee the conservativeness of the results.

Figure 2-5: DP Capability Plot example



Source: (VICUSdt, 2016)

Some authors disagree with performing static analysis to determine station-keeping capability of DP vessels, which is the case of Smogeli et al. (2013). The authors of this study show that performing dynamic analysis and establishing allowable offset and heading deviations instead might be more conservative and realistic than IMCA's method and generate smaller wind envelopes. However, the dynamic analysis results depend on several factors, including thrusters' response time and DP system control parameters, which were not detailed in their study.

On the other hand, Tannuri, Saad and Morishita (2009) verified that the IMCA 20% margin for static analysis is adequate for DP vessels that do not need much offset precision such as DP shuttle tankers. Other vessels, however, such as drilling units and pipe laying vessels, which need more offset and heading precision, should be modeled with larger margins in static analysis.

Dynamic analyses, on the other hand, are simulations that take into account the fact that environmental loads are dynamic and change over time and that consequently, vessels' motions also change with time. They can be performed through either fast-time analysis or real-time analysis. Since both are time domain simulations and consider non-linear effects, they are much more complex, time-consuming and resources consuming than static analyses.

Fast-time dynamic analysis usually requires a specific software, like Dynasim, and a computer with good processing capability (or a cluster, depending on how complex the simulation is). The parameters of the simulation are input in the software and the simulation is run by itself with no further interference from the user. The results can be shown as time domain or frequency domain graphics concerning vessel's motions and accelerations, environmental loads, thruster forces or mooring lines' tensions. An animation of the vessel's movements is usually generated from the simulations as well. When it comes to analyzing DP operations, they are most commonly used, for example, when the main goal is to evaluate and test DP system behavior or parameters of the PID controller, as done by Peng and Spencer (2008) and Tannuri and Morishita (2006).

Real time simulations are the last type of simulations that are commonly used to analyze DP operations. These simulations take place in full-mission facilities, with a realistic representation of the ship's bridge – built with all the available equipment that exists in the real ship – and immerse pilots into very realistic scenarios. These simulators use the same algorithms as the fast-time dynamic analysis, but they project on the screens the animation of the operation as if it as happening in real life and the users are capable of interacting with the simulation and change parameters such as environmental condition, thruster forces and rudder direction. They can be used for a variety of applications, including crew training and skills improvement, operations planning and non-conventional operations evaluation. Currently, most of the medium to large size navigation companies, pilots and Captains, are already familiarized with this type of simulators. Some time-domain maneuvering simulators are presented by Ankudinov, Kaplan and Jacobsen (1993) and Fossen and Smodeli (2004). Other authors such as Varela and Soares (2015), Sutulo and Soares (2015), Tannuri, Saad and Morishita (2009) and Tannuri et. al (2014) have described examples of operation analyses with real time simulations.

Sutulo and Soares (2015) have compared the results from real-time maneuver simulations to sea trial full-scale data and have concluded that their simulator's numerical model is adequate to reality. Tannuri, Saad and Morishita (2009) have compared full-scale measurements of a DP offloading operation – that included vessel's motions, individual thrusters' forces, DPST and FPSO distances and environmental conditions – to the offloading simulation in the same conditions. The results also show good agreement between numerical simulations and full-scale measurements indicating that the computational simulator is an effective tool in the analysis and design of DP systems.

Tannuri et al. (2014) describe the mathematical models of the simulator used in this project and presents two examples of application. A better overview of this simulator is presented in section 7.1.

2.4 Offloading downtime analysis

Many literatures discuss improvements in the availability of offloading operations, as they are directly related to the cost of production loss due to possibility of interrupting the FPSO production.

Misund and Tveitt (1982) proposed as downtime calculation method the observation of several production units over time, counting how many oil transfer failures occurred and how long it took until the problem was resolved. Because the proposed method was difficult to put into practice, as the authors said themselves, they adhered only to cite best practices for increasing the availability of the operation, such as providing redundancy in systems or major equipment and performing periodic maintenance campaigns in key components as a hawser, hoses and oil swivel.

Yamamoto et al. (2002) studied a new technology to control the dynamic positioning system based on neural networks and shows that with this system, which is installed on the FPSO to control yaw motions, the tension in the hawser may be well controlled even under adverse conditions. Thus, the Hs limit for offloading operation can be increased from 3.5m to 4.5m, increasing thus the availability of operation.

Ballard and Evans (2014) discuss the planning of offshore operations, such as installation of subsea equipment, based on the concept of availability. The importance of his work to the present one is that he proposes using environmental conditions measures or computer modeling, like hindcast data, to predict the probability of success of each sub-task depending on its duration. This was similarly done in the present study and better described in section 5.

Tannuri et al. (2010a) present a methodology for calculating downtime of offloading operations through performance of dynamic analysis. Tannuri et al. (2010b) make a comparative analysis of calculating downtime through static and dynamic analysis and conclude that the first method is more conservative than the second one when using a 20% margin for dynamic allowance (this margin is used to compensate the dynamic loads that are neglected in static analysis as mentioned in section 2.3).

Finally, Corrêa et al. (2013) use the static analysis methodology for calculating the downtime of offloading operations, and the present work is based on the same approach proposed by them but with a more conservative approach, which is taking into account an operating window of 36h as it will be explained in section 5.2.

2.5 Environmental hindcast data

The downtime calculation was performed based on hindcast data from Campos and Santos basins. Hindcast data consist in a database of wave and swell significant heights and periods, wind and current speeds, all of them associated with their incidence direction. These data are generated using numerical models that provide accurate, localized long-term data of ocean and atmospheric conditions.

Several literatures such as Akpinar and Kömürcü (2013), Boudière et al. (2013), Chawla, Spindler and Tolman (2013), Durrant, Greenslade and Simmonds (2009) and Suursaar, Kullas and APS (2012) discuss the use, accuracy and validation of hindcast data. In general hindcast data are very reliable, have been validated through comparison with satellite altimeters and in-situ buoy measurements and have been used for different purposes, such as offshore structures design, marine energy converters, wave farms design and even for marine biology studies.

The wave and wind data for this study come from the results of BOMOSHU JIP (Oceanweather, 2016) and current data come from the HYCOM consortium (HYCOM, 2016). All data were also validated through comparison with satellite measures and oceanic buoys. The data comprehend the period of 1st of January 2004 and 31st of December 2009 because HYCOM data were available from 2004 on and the JIP finished in 2009. More recent data were not available, however they are not expected to have changed over the years. PETROBRAS oceanography specialists affirm that recent buoy measurements do not show increase in wind, wave and current intensities over the last years.

3 THEORETICAL CONCEPTS

This section presents the theoretical concepts that were used as a basis for the simulations or calculations performed in this study.

3.1 Static environmental loads over the hull

The Offloading Downtime Analysis further discussed in section 5 is accomplished by means of static analyses and uses a database of discrete environmental conditions called hindcast data (se sections 2.5 and 5.1.2). Static analysis is chosen over dynamic analysis because it is more time saving in terms of computational resources.

Static analysis only considers average loads over the hull and despises important effects such as wind gusts, first order movements and slow drift forces. Hence, they are faster than dynamic analysis. To compensate for these simplifications, a 20% margin is applied over the thrusters' maximum capability as a reserve for dynamic effects. This margin is usually known as "dynamic allowance" (IMCA, 2000).

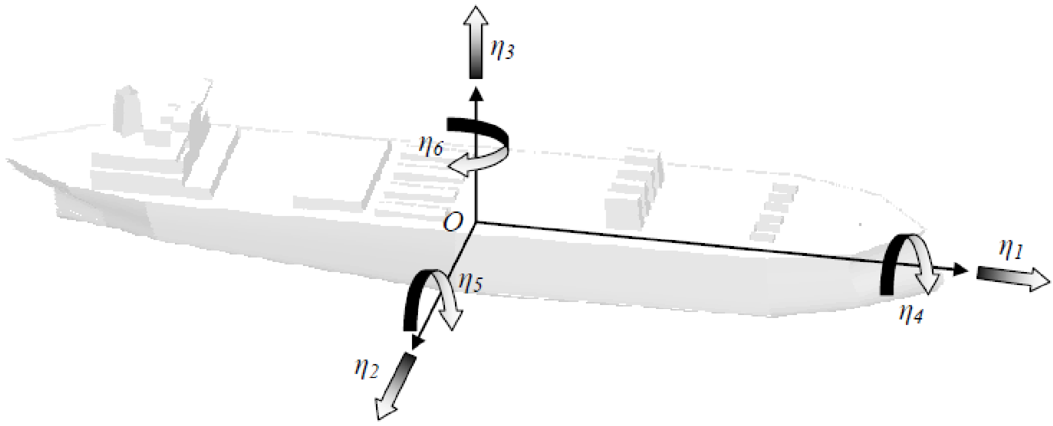
In order to perform static analyses, the first step is to calculate environmental loads over the hull of the DPST. Environmental loads comprehend current, wind and wave forces, and their calculation is described in the following sections.

The mathematical models are the same used by Tannuri, Saad and Morishita (2009) and Corrêa (2012). Current and wind moments and loads are considered constant and are described by generic equations that require drag coefficients. Wave loads and moments are also constant but are calculated based on the location's wave spectrum.

As the hindcast data is a discrete database, the formulation presented on the following sections must be applied to each of the 17,536 environmental conditions of the database to calculate the resultant environmental loads and, further on, the station keeping ability of the DPST.

Ships' dynamics is classically decomposed into six degrees of freedom, as shown in Figure 3-1. Translational movements represented by η_1, η_2 and η_3 are called, respectively, surge, sway and heave. Rotational movements represented by η_4, η_5 and η_6 are called, respectively, roll, pitch and yaw.

Figure 3-1: Ship's dynamics in six degrees of freedom



Source: (Corrêa, 2012)

As the Dynamic Positioning System is only capable of acting on the horizontal plane movements (surge, sway and yaw), only these three degrees of freedom are modeled in the static analyses.

3.1.1 Current moments and loads

Current moments and loads are calculated according to OCIMF guidelines "Predictions of wind and current loads on VLCCs" (OCIMF, 1994). Although the shuttle tanker of this study is a Suezmax type, equations (3.1) to (3.3) below are also applicable.

$$F_{1C} = \frac{1}{2}\rho_w U^2 L T C_x(\alpha_r) \quad (3.1)$$

$$F_{2C} = \frac{1}{2}\rho_w U^2 L T C_y(\alpha_r) \quad (3.2)$$

$$F_{6C} = \frac{1}{2}\rho_w U^2 L^2 T C_n(\alpha_r) \quad (3.3)$$

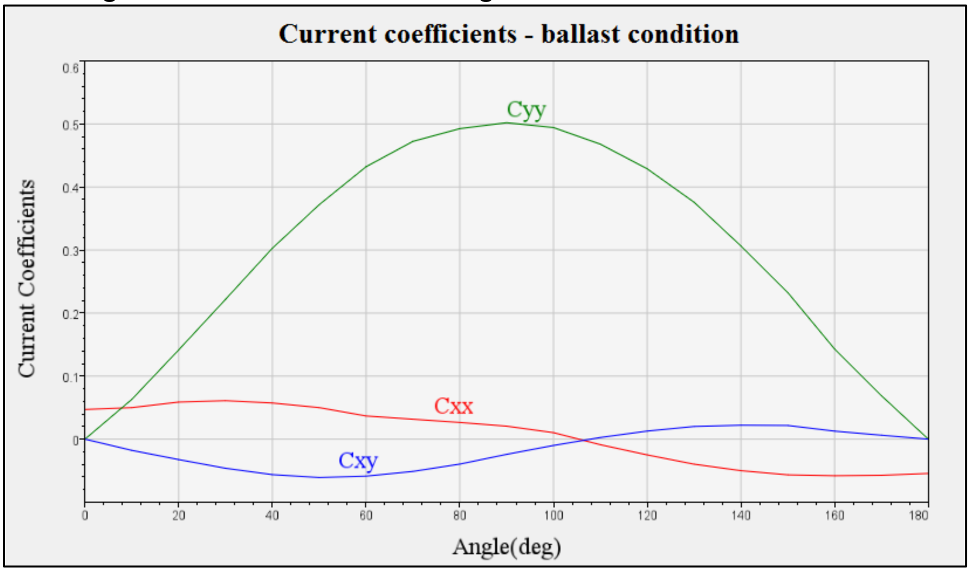
Where:

- F_{1C} is the current load in the longitudinal, or surge, direction;
- F_{2C} is the current load in the transversal, or sway, direction;
- F_{6C} is the current moment about the vertical axis, or yaw;
- ρ_w is the water density;
- U is the current speed;
- L is the shuttle's length between perpendiculars;

- T is the shuttle's draft;
- *Cx, Cy* and *Cn* are the static and dimensionless current drag coefficients in function of α_r;
- α_r is the current incidence angle (measured from the ship's stern)

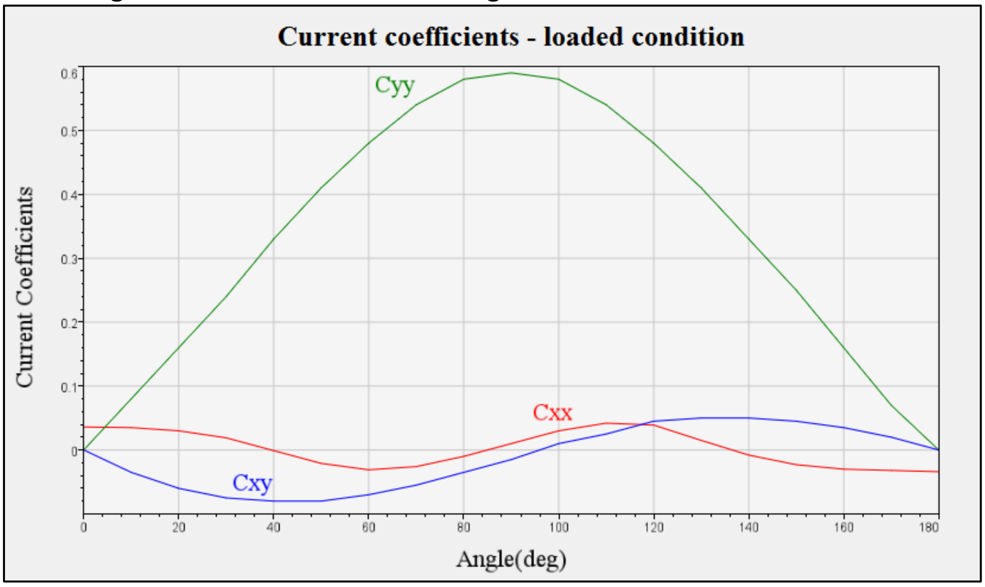
Figure 3-2 and Figure 3-3 are extracted from Dynasim software, which contains OCIMF's recommended values of current drag coefficients (*Cxx*, *Cyy*, *Cxy* represent respectively *Cx*, *Cy* and *Cn*).

Figure 3-2: OCIMF's current drag coefficients – ballast condition



Source: Author

Figure 3-3: OCIMF's current drag coefficients – loaded condition



Source: Author

3.1.2 Wind moments and loads

Wind moments and loads are also calculated according to OCIMF guidelines "Predictions of wind and current loads on VLCCs" (OCIMF, 1994). Equations (3.4) to (3.6) below are also applicable.

$$F_{1Wi} = \frac{1}{2}\rho_a V^2 A_{frontal} C_{wix}(\beta_r) \quad (3.4)$$

$$F_{2Wi} = \frac{1}{2}\rho_a V^2 A_{lateral} C_{wiy}(\beta_r) \quad (3.5)$$

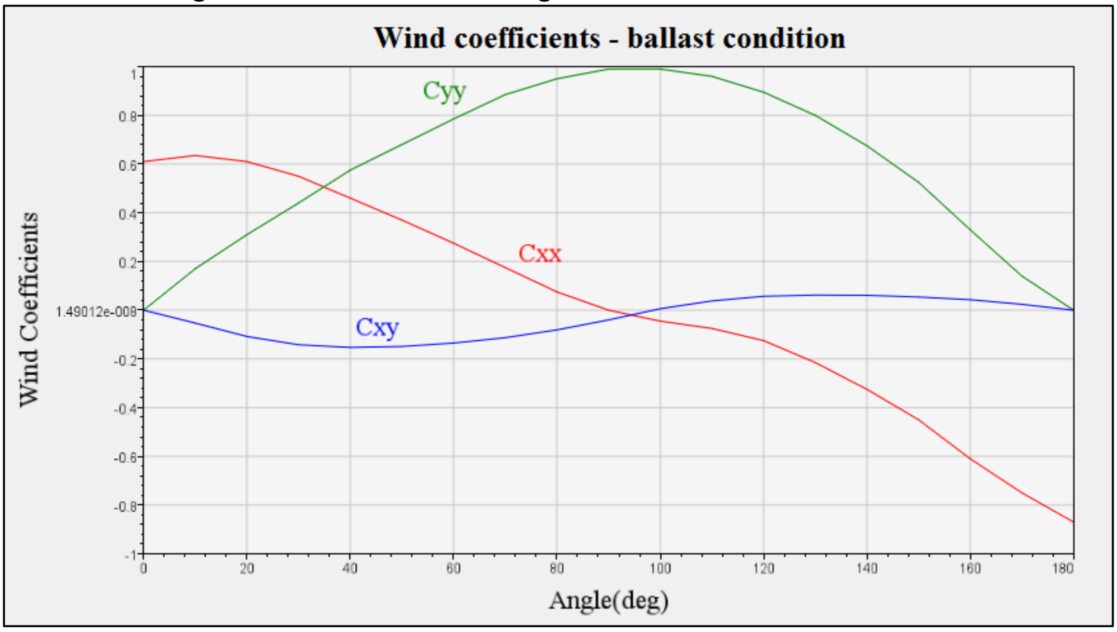
$$F_{6Wi} = \frac{1}{2}\rho_a V^2 L\, A_{lateral} C_{win}(\beta_r) \quad (3.6)$$

Where:

- F_{1Wi} is the wind load in the longitudinal, or surge, direction;
- F_{2Wi} is the wind load in the transversal, or sway, direction;
- F_{6Wi} is the wind moment about the vertical axis, or yaw;
- ρ_a is the air density;
- V is the wind speed;
- L is the shuttle's length between perpendiculars;
- *Alateral and Afrontal* are the lateral and frontal windage area ;
- *Cwix, Cwiy* and *Cwin* are the static and dimensionless wind drag coefficients in function of β_r;
- β_r is the wind incidence angle (measured from the ship's stern)

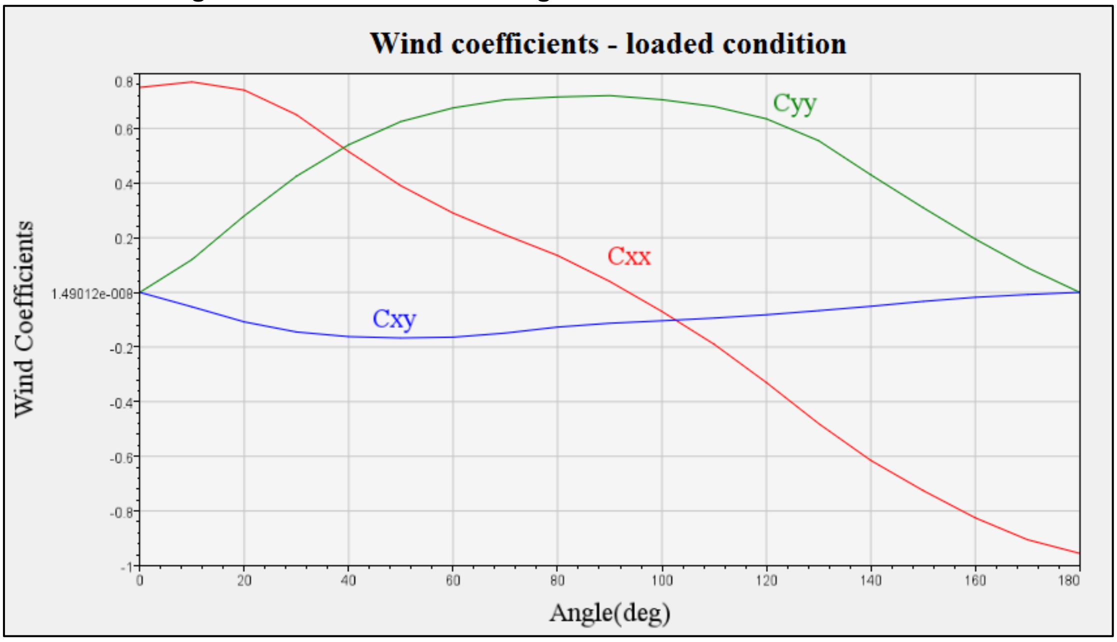
Figure 3-4 and Figure 3-5 are extracted from Dynasim software, which contains OCIMF's recommended values of wind drag coefficients (*Cxx*, *Cyy*, *Cxy* represent respectively *Cwix*, *Cwiy* and *Cwin*).

Figure 3-4: OCIMF's wind drag coefficients – ballast condition



Source: Author

Figure 3-5: OCIMF's wind drag coefficients – loaded condition



Source: Author

3.1.3 Wave moments and loads

Wave forces and moments can be decomposed into three categories: mean drift, slow drift and first order.

First order loads are proportional to the wave heights and present high frequencies. The DP system is not capable of reacting to these forces, because the thrusters' response time is too slow for that. Moreover, these forces do not interfere in the average position of the vessel in a long time observation, so they are not considered in static analysis.

Slow and mean drift loads are second order loads, i.e., proportional to the square of the wave heights. These are the loads, which the DP system is able to compensate, because of their lower frequency. Slow drift loads are dynamic, so they are also not considered in static analysis.

Mean drift loads are constant and impose large thrust demand in the DP system to compensate it. Thus, they are the only wave loads considered for static analysis and their calculation is shown further in this section.

In order to calculate mean drift forces, it is important to model the location sea state in which the DP vessel is operating through a sea spectrum. The sea spectrum represents the way irregular waves' energies are distributed in relation to their frequency. Following PETROBRAS procedures, bi-modal JONSWAP modeling is used here, whose calculation is given by Equation 3.7.

$$S(\omega) = \frac{\alpha_0 g^2}{\omega^5}.exp\left[-\frac{5}{4}\left(\frac{\omega_0}{\omega}\right)^4\right]\gamma^{exp[-(\omega-\omega_0)^2/(2\sigma^2\omega_0^2)]} \qquad (3.7)$$

Where:

- g is the gravity;
- $\sigma = \begin{cases} 0.07, & \omega \le \omega_0 \\ 0.09, & \omega > \omega_0 \end{cases}$;
- $\gamma = 6.4{T_P}^{-0,491}$
- T_P is the peak period;
- $\omega_0 = 2\pi/T_P$ is the peak frequency;
- ω is the incident wave frequency;
- $\alpha_0 = \frac{5}{16.g^2}H_S^2\omega_0^4[1 - 0.287.\ln(\gamma)]$;

After modeling the sea spectrum, it is possible to calculate mean drift forces and moments using equation 3.8 below.

$$F_{jDM} = 2\int_0^{\infty} S(\omega)D_j(\omega,\beta_0)d\omega \cong 2\sum_{i=0}^{n} S(\omega_i)D_j(\omega_i,\beta_0)\Delta\omega \tag{3.8}$$

Where:

- $D_j(\omega,\beta_0)$ is the drift coefficient in the *j* direction (j = 1, 2 or 6);
- β_0 is the wave angle of incidence (measured from the stern of the ship);

Drift coefficients are influenced by the presence of current, because they modify the frequency of encounter of refracted and generated waves. These coefficients are, thus, a function of current speed and direction and are calculated with the aid of appropriate software for computing wave loads and motions of offshore structures like WAMIT using the following equation:

$$\begin{aligned} D_{j,U}(\omega,\beta_0) \\ = D_j(\omega,\beta_0) + \frac{U}{c}[cos\alpha_r(b_{wj}cos\beta_0 + b_{rj}sen\beta_0 \\ + sen\alpha_r(b_{wj}sen\beta_0 - b_{rj}cos\beta_0)] \end{aligned} \tag{3.9}$$

Where:

- $j = \begin{cases} 1\ for\ 'surge' \\ 2\ for\ 'sway' \\ 3\ for\ 'yaw' \end{cases}$;
- U is the current speed;
- α_r is the current angle of incidence (measured from the stern of the ship);
- $c = \frac{g}{\omega}$ is the wave celerity;
- $b_{wj} = 4D_j(\omega,\beta_0) + \omega\frac{\partial D_j(\omega,\beta_0)}{\partial\omega}$;
- $b_{rj} = -2\frac{\partial D_j(\omega,\beta_0)}{\partial\beta_0}$;

The graphics of mean drift coefficients extracted from Wamit can be found in Corrêa (2012), section 4.4.3.

3.2 DP thrust allocation algorithm for static analysis

A thrust allocation algorithm is an optimization algorithm used in the Dynamic Positioning System to distribute thrusters' forces and azimuth angles to balance environmental forces.

Tannuri (2002) proposes a methodology for thrust allocation based on minimization of the total energy required from the DPS.

The modeling of the problem consists in calculating the forces and azimuth angles (if applicable) of each thruster so that the resultant force is equal but opposite to the environmental load.

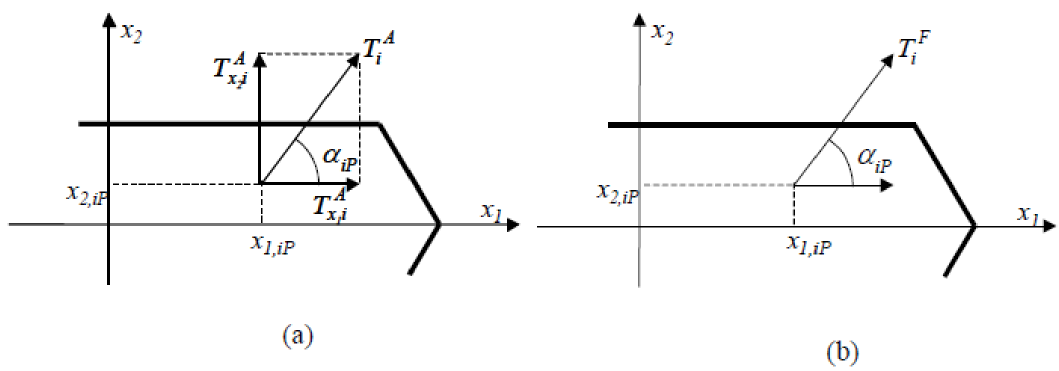
Be $F_T = (F_{1T}, F_{2T}, F_{6T})^T$ the vector of the environmental loads, where:

- F_{1T} is the load in surge direction (longitudinal);
- F_{2T} is the load in sway direction (transverse);
- F_{6T} is the moment in yaw (vertical axis);

Be $T_F = (T^A_{x_1 1}, \dots, T^A_{x_1 n_{azim}}, T^A_{x_2 1}, \dots, T^A_{x_2 n_{azim}}, T^F_{1+n_{azim}}, \dots, T^F_{n_{prop}})^T$ the vector of thruster forces (see Figure 3-6), where:

- A refers to "azimuth thruster";
- F refers to "fixed thruster";
- x_1 refers to force in surge direction (longitudinal);
- x_2 refers to force in sway direction (transverse);
- n_{azim} is the number of azimuth thrusters;
- n_{prop} is the total number of thrusters;

Figure 3-6: Definitions for (a) azimuth thrusters – *i* = *1, …,*n_{azim} and (b) fixed thrusters – *i* = *1+*n_{azim}*, …,*n_{prop}



Source: (Tannuri, 2002)

The relationship of F_T and TF is linear and depends on the position of each thruster in ship's local coordinates $(x_{1,iP}, x_{2,iP}), i = 1, \dots, n_{prop}$ and on the orientation of fixed thrusters α_{jP} $(j = 1 + n_{prop}, \dots, n_{prop})$. The relation is given by matrix *A* below:

$$A = \begin{pmatrix} 1 & . & 1 & 0 & . & 0 & c_{1+n_{azim}} & . & c_{n_{prop}} \\ 0 & . & 0 & 1 & . & 1 & s_{1+n_{azim}} & . & s_{n_{prop}} \\ -x_{2,1P} & . & -x_{2,n_{azim}P} & x_{1,1P} & . & x_{1,n_{azim}P} & m_{1+n_{azim}} & . & m_{n_{prop}} \end{pmatrix}$$

Where:

- $c_j = \cos(\alpha_{jP})$;
- $s_j = \sin(\alpha_{jP})$;
- $m_j = -c_j . x_{2,jP} + s_j . x_{1,jP}$, $j = 1 + n_{prop}, \dots, n_{prop}$

The thrust allocation problem consists in finding vector T's unknown values given vector F_T and matrix A through the following system of equations (3.10):

$$A . T_F = F_T \qquad (3.10)$$

However, this system of equations presents 3 equations and $n_{prop} + n_{azim}$ unknown values, so the solution for this system has to be found through minimization algorithms. The minimization consists in finding the combination of thruster forces that require minimum total power demand from the DP system.

It is well known that the power demand on the DP system is proportional to the sum of the modulus of thrust forces to the power of 3/2 (Tannuri, 2002, Rindarøy, 2013, and Fossen, 2002). However, the power demand can be approximated by the sum of thrust forces to the power of 2 in order to use simpler minimization algorithms without implying significant errors to the result (De Wit, 2009). The function to be minimized, $L(T)$, thus, is assumed to be proportional to the sum of squares of thruster forces following equation (3.11) below.

$$L(T) \sim \sum_{i=1}^{n_{prop}} {T_i}^2 \qquad (3.11)$$

In this study, the minimization of the power demand function is accomplished in Matlab through “Fmincon” function, which finds the minimum of a problem specified by the function to be minimized and the problem’s restraints given by the user.

In the thrust allocation problem of the present work, the only restraint is to consider that the maximum load in each thruster must be less than 80% of maximum available thrust. This is done to better distribute the thrust demand among all the thrusters and to avoid that the minimization algorithm calculates, for example, 100% power of one thruster and 10% of the others.

The present problem does not consider any forbidden zones or efficiency loss due to hull structures or thrusters interferences, but that is a fair simplification since those effects are less expected in a shuttle tanker when compared to a semi-submersible rig.

3.3 Preliminary risk analysis

As part of managing the health and safety of any business, it is important to control the risks involved in every operation or activity. Risk analysis techniques are commonly used to assess the possible hazards of the operations and decide whether the company is implementing reasonable measures to prevent those hazards from becoming accidents.

Risk analysis can be either qualitative or quantitative. The last alternative is usually applied when the main target is to quantify the probabilities of occurrence of a certain hazard and its consequences, when that information is important for decision-making. For example, if a company wants to evaluate a certain operation and determine the probability of failure and the costs involved in the event of failure, quantitative analysis is the best choice. However, this technique is usually complex, time costing and might demand the use of specific software.

Qualitative analysis, which is used in this study, is the best choice when the objective is to determine the severity and importance of the risks of the operation, to rank them and to assess recommendations for risk mitigation.

This alternative is widely used in the oil & gas industry when it comes to planning operations and activities from the simplest ones, such as welding and painting, to the most complex ones such as FPSO or subsea equipment installation. Qualitative risk analysis is so important in this sector that the International Maritime Organization

(IMO, 2002) proposes its own methodology called Formal Safety Assessment (FSA) for that.

FSA is a structured and systematic methodology for qualitative risk analysis whose main goal is to help in the evaluation of new regulations for maritime safety and protection of the marine environment, but it can also be used as a tool for routine operation risk analysis. The methodology consists in accomplishing the following five steps:

1. **Identification of hazards:** identify a list of hazards, their frequency, their severity and ranking of the risks with the help of a tolerability matrix;
2. **Risk analysis:** detailed investigation of the causes and consequences of the more important scenarios identified in step 1;
3. **Risk control options (RCOs):** propose effective and practical recommendations for risk mitigation;
4. **Cost benefit assessment:** identify and compare benefits and costs associated with the implementation of each recommendation identified and defined in step 3; and
5. **Recommendations for decision-making:** define the RCOs, which should be presented to the relevant decision makers.

It is important to highlight at this point the following terminology defined by IMO that will also be used in this study:

- “Hazard” is a potential to threaten human life, health, property or the environment;
- “Accident” is an unintended event involving fatality, injury, ship loss or damage, other property loss or damage, or environmental damage.
- “Initiating event” is the first of a sequence of events leading to a hazardous situation or accident. Here, it will be referred to as the “cause” of an accident.
- “Accident scenario” is a sequence of events from the initiating event to one of the final stages, which can be interpreted as the specific combination of a certain hazard, the events that trigger the accident (i.e., the causes), and their corresponding consequences. If an accident may

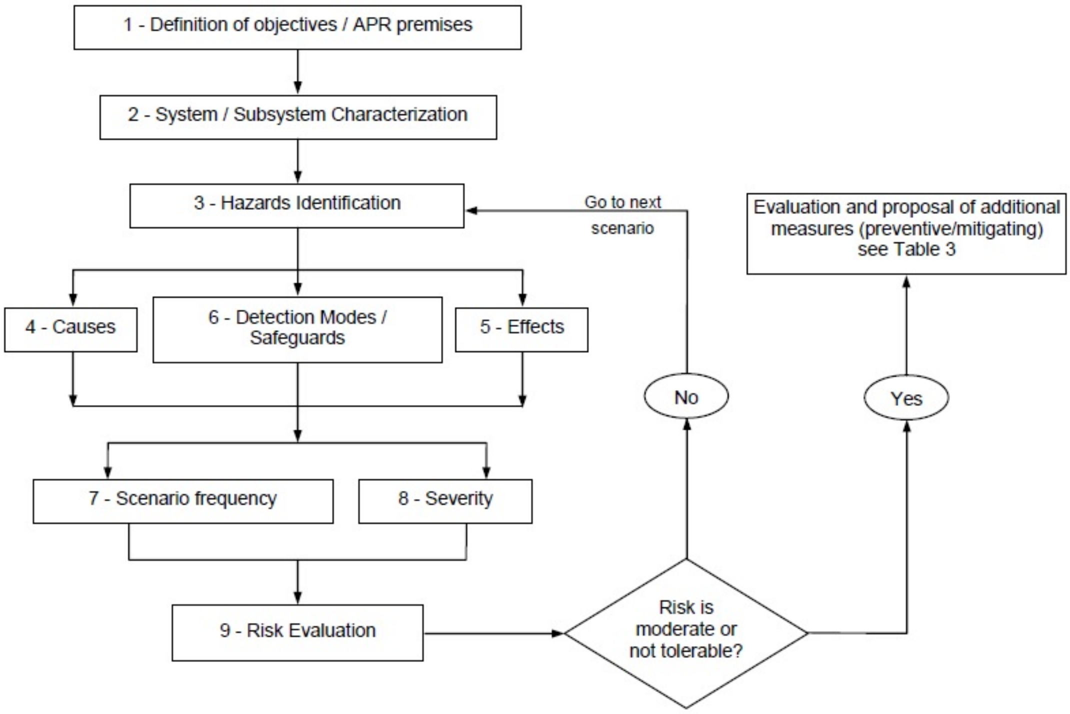
present different causes, each of them might generate a different accident scenario;

- “Consequence” is the outcome of an accident;
- “Frequency” is the number of occurrences per unit time (e.g., per year), but in this study it represents the qualitative probability of occurrence of an accident scenario (for example, “frequent”, “likely”, “not likely”, “remote”);
- “Risk” is the combination of the frequency and the severity of the consequence.

Another common technique for qualitative risk analysis is called Preliminary Risk Analysis, or simply PRA. This technique is close to FSA’s methodology, except that steps 1 and 2 do not follow this exact order and steps 4 and 5 are not necessarily accomplished. PETROBRAS has established an internal regulation for performing PRA and other qualitative techniques, which is N-2782 – Applicable Techniques for Industrial Risk Analysis (PETROBRAS, 2015b) – that can be found in ANNEX A.

Figure 3-7 below is extracted from N-2782 and shows the PRA methodology flowchart. The frequency, severity and risk evaluation follows the Risk Tolerability Matrix shown in Figure 3-8.

Figure 3-7: PRA flowchart



Source: (PETROBRAS, 2015b)

Figure 3-8: Risk Tolerability Matrix, N-2782

Consequences Severity Categories	Description / Caracteristics				Frequency Categories				
	People	Asset / Operational continuity	Environment (see Note 1)	Image	A Extremely Remote Conceptually possible but with no references in the industry	B Remote Not expected to occur although there are references in similar facilities in the industry	C Not Likely Not likely of occuring during the lifetime of a group of similar facilities	D Probable Possible of occuring once during the facility life time	E Frequent Possible of occuring many times during the facility life time
V Catastrophic	Multiple fatalities on site or off-site fatality	Catastrophic damages which can lead to the loss of the industrial facility	Catastorphic damages	International impact	M	M	NT	NT	NT
IV Critical	Onsite fatality or severe injuries off-site	Severe damage to systems/ equipment (slow repair)	Critical damages	National impact	T	M	M	NT	NT
III Medium	Severe onsite injuries or light off-site injuries	Moderate dammage to systems	Moderate damages	Regional impact	T	T	M	M	NT
II Marginal	Light injuries	Light damages to systems/ equipment	Light damages	Local impact	T	T	T	M	M
I Negligible	First aid cases or no injury	Light damage to equipment without compromising the operational	Insignificant damages	Insignificant impact	T	T	T	T	M

Source: (PETROBRAS, 2015b)

A group of specialists on the subject accomplishes this methodology in a brainstorm session. A default spreadsheet, which is shown in Figure 3-9 below, is used for supporting the team. Besides the predefined header, it contains 12 columns, which must be filled as described below.

Figure 3-9: PRA Spread Sheet Pattern

Preliminary Risk Assessment											
Name:								**Date:**		**Rev.:**	
Operational Phase:											
Hazard	**Causes**	**Safeguards**	**Consequences**	**Freq.**	**Sev.**	**Risk**	**Recommendations**	**Freq.**	**Sev.**	**Risk**	**Scenario**

Source: Author

- **1st column: Hazard.** This column describes the identified hazard for the operational phase under review.

- **2nd column: Causes**. The possible causes of each accident are identified in this column. These causes can involve both intrinsic equipment failures, human errors in operation or maintenance, or external causes.

- **3rd column: Detection / Safeguards**. This column lists all the resources available at the facility to ensure the safe operation or to detect abnormal occurrences, thus minimizing the consequences of any accident.

- **4th column: Consequences**. The potential harmful effects for the safety of people, environment, facilities / production and company's image of each hazard are listed in this column.

- **5th column: Frequency Category**. In this column, the accident scenarios are classified into categories of frequency as requires the Risk Tolerability Matrix shown in Figure 3-8. For classifying the frequency, the existing effective safeguards must be considered.

- **6th column: Severity Category**. The categories of severity of the consequences are filled in column 7 following the Risk Tolerability Matrix shown in Figure 3-8.

For classification of the consequences, existing safeguards and detection systems can be considered for mitigation.

- **7th column: Risk Category**. Combining the categories of frequency with the severity, the risk category is obtained through the Risk Tolerability Matrix. Three risk categories are used: ‘Tolerable’, ‘Moderate’ and ‘Not Tolerable’.

- **8th column: Recommendations / Observations**. This column contains the recommendations for mitigating risks – which aim to reduce the frequency of the scenario or to minimize the severity of the consequences – and any relevant comments to the accident scenario under study.

- **9th column: Residual Frequency Category**. This column shows the reclassification of the frequency of the accident scenario considering the implementation of the recommendations listed in column 8.

- **10th column: Residual Severity Category**. This column shows the reclassification of the severity of the consequences of the accident scenario considering the implementation of the recommendations listed in column 8.

- **11th column: Residual Risk Category**. This column shows the reclassification of the risk of the accident scenario considering the implementation of the recommendations listed in column 8.

- **12th column: Accident Scenario Identification**. This column contains an identification number of the accident scenario for easy reference if needed. The accident scenario is defined as the ensemble formed by phase, hazard, its causes and its consequences.

The PRA methodology is the most used in PETROBRAS, and offloading operations are commonly evaluated through this technique. When the operations take place in normal conditions, i.e., following offloading guidelines, they are already covered by a generalist analysis that is applicable to all the FPSOs and DPSTs in Brazil.

However, if one parameter is changed – like the operating sector angles, a simultaneous operation with a rig, harsh environments, DPST degradation and others – a specific risk analysis must be carried out. That is why the Preliminary Risk Analysis is important to be done in order to validate the new operating sector. The results of this analysis are described in section 4.

4 PRELIMINARY RISK ANALYSIS

Preliminary risk assessment was the first task to be done in this study because it was important to analyze the expansion of the operating sector among other PETROBRAS specialists before investing in other time and cost consuming activities.

As explained in section 3.3, offloading operations in normal conditions are already covered by a generalist risk analysis that is applicable to all the FPSOs and DPSTs in Brazil. However, when one parameter is changed – like the operating sector angles in this case – a specific risk analysis must be carried out.

Corrêa (2012) presents Preliminary Risk Analyses for offloading operations comparing the use of conventional and DP shuttle tankers. The conclusion is that conventional STs present a greater number of non-tolerable risks than DPSTs. However, his study is focused in normal offloading operations and does not discuss the additional risks associated with operating in the extended sector. Hence, the main goal of the PRA presented in this section is to analyze these additional risks.

The following sections explain the methodology used, the participating team, the premises taken and finally the results, which were summarized from the technical report that was issued at the time (DNV, 2014).

4.1 Methodology

As mentioned in section 3.3, the Preliminary Risk Analysis followed recommendations of PETROBRAS norm N-2782, Applicable Techniques for Industrial Risk Analysis.

The first step was to identify the different phases of the offloading operations – approach, connection, offloading, disconnection and departure – and to assess all the operating procedures for them. Then, for each phase, the group of specialists assessed a list of hazards, and, for each hazard, its causes, safeguards, existing means of detection and the possible consequences. The consequences' severity were classified following the most serious effect that an accident scenario presents, e.g., if a collision implied light injuries to people (category II following the risk matrix) and catastrophic oil spill (category V), the scenario severity was classified in category V – catastrophic.

The ensemble formed by phase, hazard, its causes and its consequences constitutes an accident scenario. Thus, the same hazard, e.g. DPST drive-off, can unfold in more than one accident scenario, e.g., collision caused by drive-off, collision caused by blackout, collision caused by human error. For each accident scenario, the frequency of occurrence and severity of its consequences were evaluated qualitatively, and the risk was classified as Risk tolerability matrix established by N-2782 standard is shown in Figure 3-8.

For each scenario, whose risk was classified as “Moderate” or “Not Tolerable” recommendations for risk reduction were proposed and the residual risk was evaluated considering the implementation of these recommendations.

The Preliminary Risk Analysis (PRA) was conducted through meetings with staff from PETROBRAS E&P division, TRANSPETRO and DNV GL, using a standard spreadsheet (shown in Figure 3-9) where the analysis of the hazards of the activities and tasks of each phase of DP offloading operation in the extended sector were filled.

In the case of the offloading operation, the main hazards refer to events such as collision, incidents during cable or hose handling, oil leaks, man lost at sea, etc. In this analysis, though, only collision scenarios were analyzed because it was considered that other types of risk are independent of the operational sector and were therefore already analyzed in other risk analyzes.

One last observation is important to highlight at this point. Considering the formal definition of “hazard” (see section 3.3), in the offloading scenario, a hazard would be, for example, the great proximity between DPST and FPSO. The concretion of this hazard, i.e., the accident, would be the collision of the two vessels caused by human error and its consequences would be oil leak from cargo tank. However, to facilitate the analysis and the filling of the spreadsheet, the definitions of “hazard” and “accident” are mixed together and the hazard in this example scenario becomes the collision itself, the cause is human error and the consequence is oil leak.

4.2 Team

The Preliminary Risk Analysis was performed by a group of offloading specialists: two DPST Captains, four naval engineers, two risk analysis consultants and a professor from University of São Paulo (USP), which gathered for two days in PETROBRAS office in Rio de Janeiro.

4.3 Premises

The main premises regarding the risk analysis study are listed below:

- Location: Non-defined basin – the group agreed that environmental conditions would not interfere on the frequency and consequences of the hazards, since the DPST only operates within contractual limits; the results are valid both for Campos and Santos basins;
- Contractual environmental limits – follow PETROBRAS offloading procedures (PETROBRAS, 2009);
- Conditions for mooring, unmooring and operating follow PETROBRAS offloading procedures (PETROBRAS, 2009);
- FPSO unit: typical ship-shaped FPSO whose characteristics are shown in Table 4-1;
- DPST: Cartola, DP 1 Enhanced, whose characteristics are shown in Table 4-2;
- No tug is used to aid the operation;
- Emergency shut-down conditions follow PETROBRAS offloading procedures (PETROBRAS, 2009);
- Offloading operating sector: the group evaluated that extending the operating sector up to 90° (as proposed in Corrêa, 2012, Figure 1-12) wouldn't be possible because of hawser interference with FPSO structures. Hence, the group proposed analyzing a different sector instead, shown in Figure 4-1 on page 72. The difference is that green sector is extended to 75° at starboard only, and a conditional green sector (hatched one) is established between 75° and 80°. Within this area, the DP shuttle tanker is allowed to stay during the offloading operation as long as the environmental conditions are mild and power demand is low – which is considered by the team to be less than 50% of rated power.

Table 4-1: FPSO premisses

Premise	Detail
Mooring	Spread Mooring System
Length over all	327.5 m
Breadth	57.237 m
Stern thrusters or propulsion	None
Heading	211 degrees from true north; maximum heading variation of 5 degrees to each side
Risers	14 production wells e 8 injection wells, 36 risers on the riser balcony
Storage capacity	252,800m^3 (1,600,000 barrels)
Inert gas system	Operational
Maximum production	28,440m^3 or 180,000bpd (barrels per day)
Offloading stations	Both operational
Offloading normal flow	6,000m^3/h
Offloading maximum flow	7,000m^3/h
People on board (POB)	110 people
Facility's service life	25 years
Hose string	237 m-length, double carcass hoses
Hawser length	180 m

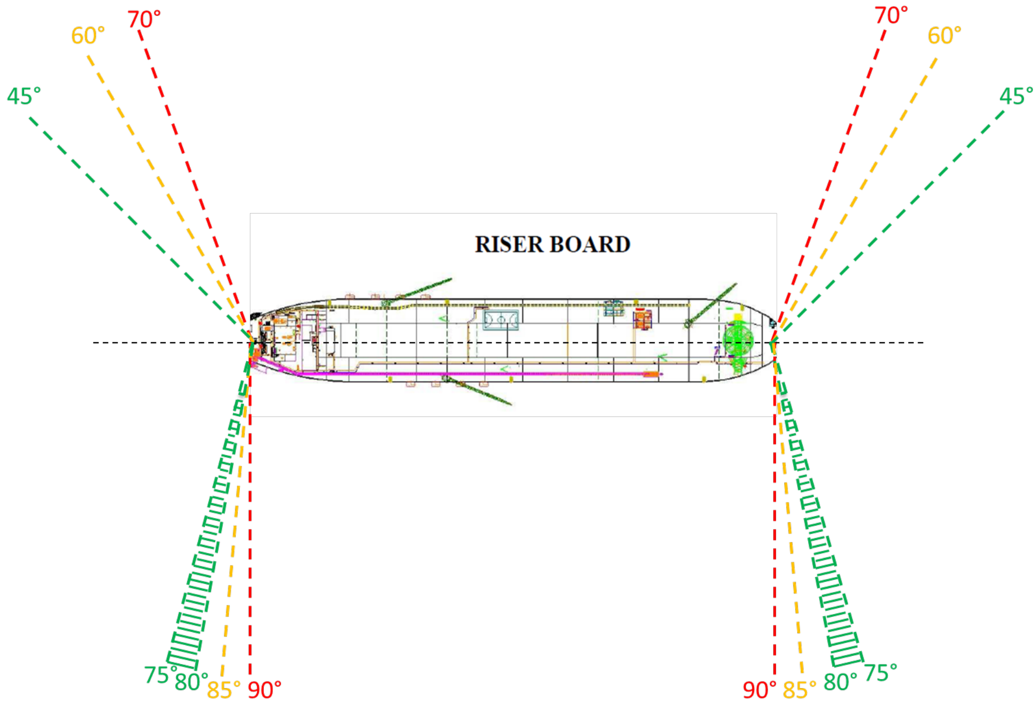
Source: Author

Table 4-2: Shuttle Tanker premises

Premise	Detail
Vessel	Cartola, DP 1 Enhanced
Breadth	46 m
Length overall	279 m
Summer draft	16 m (full)
Light draft	8 m (with 40.000ton ballast)
Double hull structure	N.A.
Main propeller	Controllable pitch
Thrusters configuration	2 tunnel thrusters (bow and stern) and 1 bow azimuth thruster;
Storage capacity	166,000m^3 (1.050.633 barrels);
Offloading through Bow Loading System (BLS) only	N.A.
Reference position systems adjusted between shuttle and FPSO	N.A.
No automatic oil leak detection, visual detection only	N.A.
Radio communication in exclusive band	N.A.
Fixed foam cannon system on deck	N.A.
Inert gas system	Operational
People on Board	26 people
Two slop tanks (one clean and one with hoses' wash water), capacity: 2.000 m^3 each	N.A.
Segregated ballast system	N.A.
Lighting on deck;	N.A.
Leak containment on the deck with relief valve to the slop tank;	N.A.
Chain stopper, with hawser tension monitoring available;	N.A.
Pelican hook (easy to release cable) and bollard (250 ton) for tug connection available on board;	N.A.
Antipollution kit (SOPEP) available on board;	N.A.

Source: Author

Figure 4-1: Extended operating sector final proposal



Source: (PETROBRAS, 2015c)

4.4 Operating procedures

The procedures for Approaching, Mooring, Offloading, Unmooring and Departing from FPSO are described in detail in PETROBRAS Offloading Guidelines (PETROBRAS, 2009).

The procedures determine system checklists, verification of environmental and operational conditions, speed and direction of approach, hawser and hose string connection, hose string wash, cargo transfer, hawser and hose string disconnection and departure from location.

4.5 Results for bow station

In total, 41 accident scenarios have been identified in the operation on the bow station within the extended sector, using a DP 1 Enhanced shuttle tanker without auxiliary tug. These hazards have consequences for the safety of personnel, environment, facilities and for the company's image.

In total, eleven accident scenarios were classified as not tolerable risks to the environment because they are a combination of a catastrophic consequence, which is large-scale oil leak from a FPSO cargo tank in case of collision, with a “not likely” probability of occurrence. These scenarios are related to human error, blackout events, sudden change in weather conditions and drive-off event, which is the most dangerous situation during offloading operations, since the DPST might collide with the FPSO at a higher speed if compared to a blackout scenario. Table 4-3 below shows the most relevant accident scenarios for the operation by the bow, and the recommendations to mitigate them are shown in Table 4-4.

It is important to notice that the author disagrees with the conclusion of the group concerning the frequency category of the scenarios of human error, blackout and sudden change in weather conditions, because they should be classified as “remote” (B) instead of “not likely” (C). The justification for that is: (1) there is no reference in Petrobras’ history that human error has ever caused a collision during offloading with DP shuttle tankers (while drive-off events, on the contrary, have) and (2) blackout events and sudden change in weather conditions will probably not lead to a collision with enough impact energy to cause the rupture of the side shell of the FPSO.

Table 4-3: Relevant accident scenarios in the operation through the bow station

Phase	Hazard / Consequence	Cause	Freq.	Sev.	Risk
Approach	Collision / Consequences: 1. Severe damage to systems – slow repair (facilities) 2. Large-scale oil leak (environment), 3. Light injuries (people), and 4. National impact on the media (image)	Human error (high speed)	C	V	NT
		Drive-off	C	V	NT
		Blackout	C	V	NT
Connection/ mooring		Drive-off	C	V	NT
		Blackout	C	V	NT
		Sudden change in weather or beam current	C	V	NT
Offloading		Drive-off	C	V	NT
		Sudden change in weather or beam current	C	V	NT
Disconnection/ unmooring		Drive-off	C	V	NT
		Blackout	C	V	NT
		Sudden change in weather or beam current	C	V	NT

Source: Author

Table 4-4: Recommendations for risk mitigation in the operation through bow station

Id.	Recommendation
R1	Approach the shuttle with a heading out of collision route with FPSO.
R2	DP operators must be trained for several accident scenarios.
R3	Follow procedures from shuttle's safety management system.
R4	In the hatched green sector – 75 to 80 degrees to starboard –, the shuttle must operate with low power demand and mild weather.
R5	Do not approach with more than 50% power demand.
R6	Keep shuttle tanker maintenance plans updated.
R7	Keep Controllable Pitch Propeller (CPP) hydraulic oil always clean to avoid unwanted clamping of the pitch.
R8	Perform real time simulations for analyzing escape route in case of shuttle's drive-off.
R9	Use of DP 2 shuttle.
R10	Perform annual inspections of DP system.
R11	Keep both offloading stations operational to guarantee operation through preferential station.
R12	Perform periodical OESD I and II tests according to the ST safety management system and follow offloading procedures.
R13	Constant monitoring of the operation, including verification of alarms, relative distances between DPST and FPSO and weather forecasts.
R14	Telemetry system must be operational.

Source: Author

After considering the implementation of the recommendations listed in Table 4-4 the 11 not tolerable risks were re-classified into "Moderate" category because the frequency of the scenarios was reduced from C to B.

4.6 Results for stern station

Results for stern station are the same of bow station, except for 11 extra scenarios, in which the collision between shuttle tanker and FPSO causes flooding of the platform's machinery room, damage to the hull girder and consequent sinking of the vessel. These accident scenarios were conceived from the observation of emergency documents of some FPSO units, where, depending on the unit's loading condition, the flooding of the engine room generates shear forces and bending moments that exceed the design limits. However, it is important to highlight that **these scenarios should be revised by the PRA group and re-classified into Moderate category**. FPSO projects already consider the flooding of the machinery room scenario as required by MARPOL Convention (IMO, 1973); hence, it is unlikely that a FPSO may sink due to this scenario. Moreover, shear forces and bending moments' envelopes are applicable to intact stability analyses only. After consulting several PETROBRAS and Bureau Veritas specialists on the subject, the author concluded that these scenarios present an extremely remote probability of occurrence.

Table 4-5 below presents those 11 scenarios, which were classified as "not tolerable" by the PRA team. The recommendations for mitigating those risks are the same as shown in Table 4-4 for operation at the bow station and may also reduce the risks to Moderate category.

Table 4-5: Not tolerable accident scenarios in the operation through the stern station

<table>
<tr><th>Phase</th><th>Hazard / Consequence</th><th>Cause</th><th>Freq.</th><th>Sev.</th><th>Risk</th></tr>
<tr><td rowspan="3">Approach</td><td rowspan="11">Collision
/
Consequences: Flooding of the machinery room, hull girder damage, sinking of the FPSO resulting in:
1. Loss of the industrial facility,
2. Large-scale oil leak (environment),
3. Light injuries (people), and
4. National impact on the media (image)</td><td>Human error (high speed)</td><td>C</td><td>V</td><td>NT</td></tr>
<tr><td>Drive-off</td><td>C</td><td>V</td><td>NT</td></tr>
<tr><td>Blackout</td><td>C</td><td>V</td><td>NT</td></tr>
<tr><td rowspan="3">Connection/ mooring</td><td>Drive-off</td><td>C</td><td>V</td><td>NT</td></tr>
<tr><td>Blackout</td><td>C</td><td>V</td><td>NT</td></tr>
<tr><td>Sudden change in weather or beam current</td><td>C</td><td>V</td><td>NT</td></tr>
<tr><td rowspan="2">Offloading</td><td>Drive-off</td><td>C</td><td>V</td><td>NT</td></tr>
<tr><td>Sudden change in weather or beam current</td><td>C</td><td>V</td><td>NT</td></tr>
<tr><td rowspan="3">Disconnection/ unmooring</td><td>Drive-off</td><td>C</td><td>V</td><td>NT</td></tr>
<tr><td>Blackout</td><td>C</td><td>V</td><td>NT</td></tr>
<tr><td>Sudden change in weather or beam current</td><td>C</td><td>V</td><td>NT</td></tr>
<tr><td colspan="6">Note: these scenarios should be revised by the PRA group and re-classified into Moderate category, because FPSO projects already consider the flooding of the machinery room as required by MARPOL Convention (IMO, 1973). Moreover, shear forces and bending moments envelopes are applicable to intact stability analyses only and should not be used to make any conclusions for damaged stability.</td></tr>
</table>

Source: Author

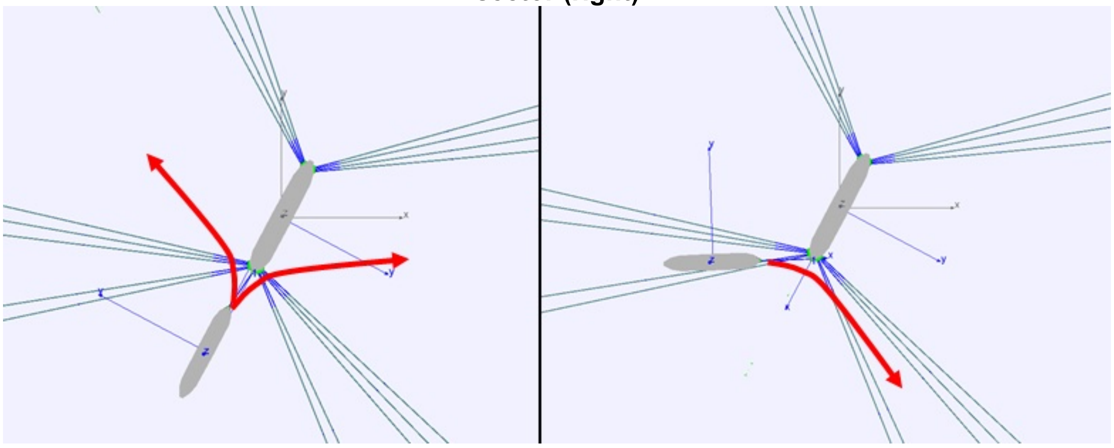
4.7 Conclusions

The Preliminary Risk Analysis was divided into two steps to separately consider the bow and stern offloading stations, because the operation by the stern can result in more accident scenarios than the operation by the bow. The following conclusions are considered valid for both Campos and Santos Basins:

- The “Not Tolerable” risks, both at the bow and stern stations, are mainly related to the occurrence of drive-off;
- These not tolerable risks involve large-scale oil leak from and FPSO cargo tank when offloading by either bow or stern;
- The recommendations assessed by the group of specialists were considered sufficient to reduce the risk of these scenarios to “Moderate”;
- The use of a DP Class 2 shuttle tanker with adequate power can reduce the risk of collisions during offloading in the extended sector both at the bow and at the stern;
- With the increase of the operational sector limit from 60 to 80 degrees, without increasing the red sector limit of 90 degrees, the yellow sector span was reduced from 20 degrees to 5 degrees and red sector span of 10 degrees to 5 degrees. With these reductions, the available time for reaction becomes smaller. Therefore, during offloading in the extended sector, attention must be doubled to changing environmental conditions and shuttle heading;

When comparing the results from the present risk analysis to the ones given by Corrêa (2012), it is possible to notice that the frequency of some scenarios was more conservative (higher) in this study than in Corrêa’s one (while here the expected frequencies for operating with DPSTs are “Not Likely”, Corrêa indicates “Remote” and “Extremely Remote”). This is because the PRA team feared that by operating in the extended sector, in case of drive-off event, the DPST Captain would have fewer options to perform an escape maneuver to avoid collision with the FPSO, if needed, and the chances of running into the platform would be higher. Figure 4-2 illustrates the escape maneuver routes to avoid collision in each operating sector. That would be the greater difference between operating in the extended and original sector: the risk of collision can be higher if no recommendations are put into place.

Figure 4-2: Escape maneuver routes when operating in original sector (left) and extended sector (right)



Source: Douglas Gustavo Takashi Yuba

5 OFFLOADING DOWNTIME ANALYSIS

This chapter describes the calculation methodology and results of the availability of the offloading operation in Campos and Santos basins, comparing the values to the original operating sector and the extended one.

The term "availability", or “uptime”, must be understood as the percentage of time in which an offloading station (or both) is available for performing offloading. This availability is based on the operational sector and the position-keeping capacity of the DPST and should not be confused with the availability of offloading equipment (reel, HPU, pumps and cargo valves, etc.), which is defined by reliability engineering.

This term can also be understood as the probability of success of offloading, which represents the chance of a shuttle tanker getting to the location and being able to accomplish the offloading operation during 36h (6h connection + 24h operation + 6h-off) without interruptions.

The opposite of "availability" – "unavailability" or “downtime” –, is the mostly used term in the following sections.

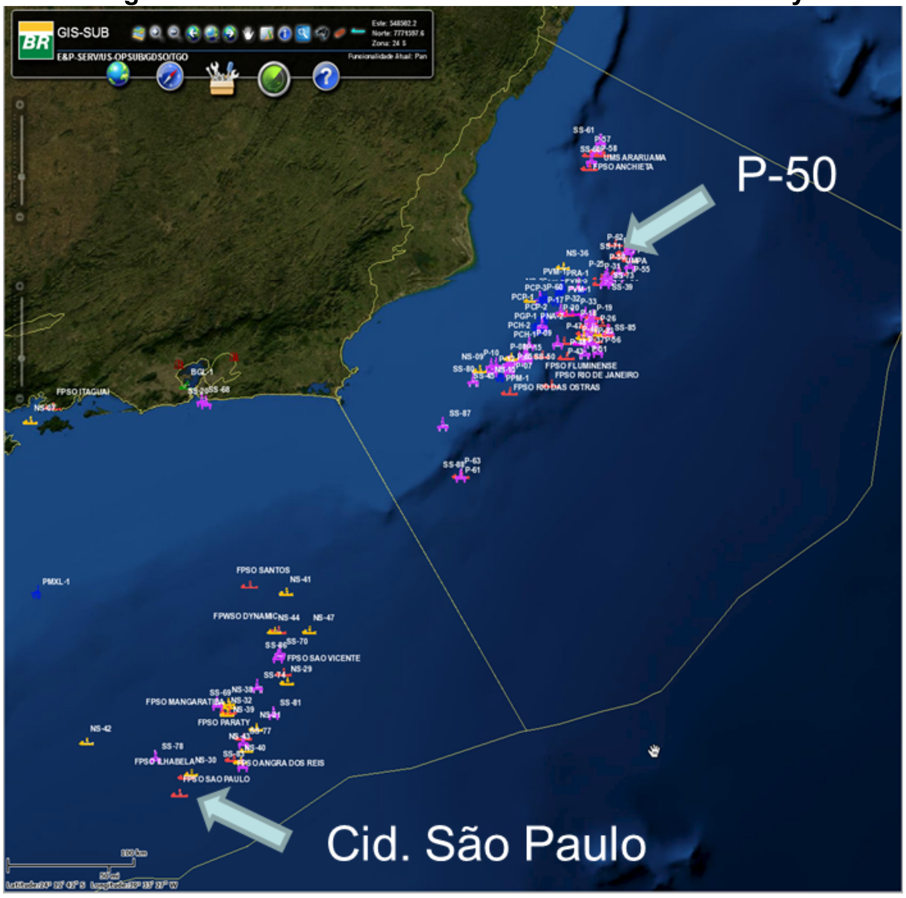
5.1 Premises

The following sections describe the premises used in this study regarding location, environmental conditions, vessel and operating limits.

5.1.1 Basins

Two FPSO´s are used as case studies in this section. The FPSO P-50 is located in Albacora Leste field, in Campos Basin. The FPSO Cidade de São Paulo is located in the Lula field (Santos Basin). Figure 5-1 shows the location of both fields.

Figure 5-1: Location of the FPSOs chosen for this study



Source: (PETROBRAS, 2015c)

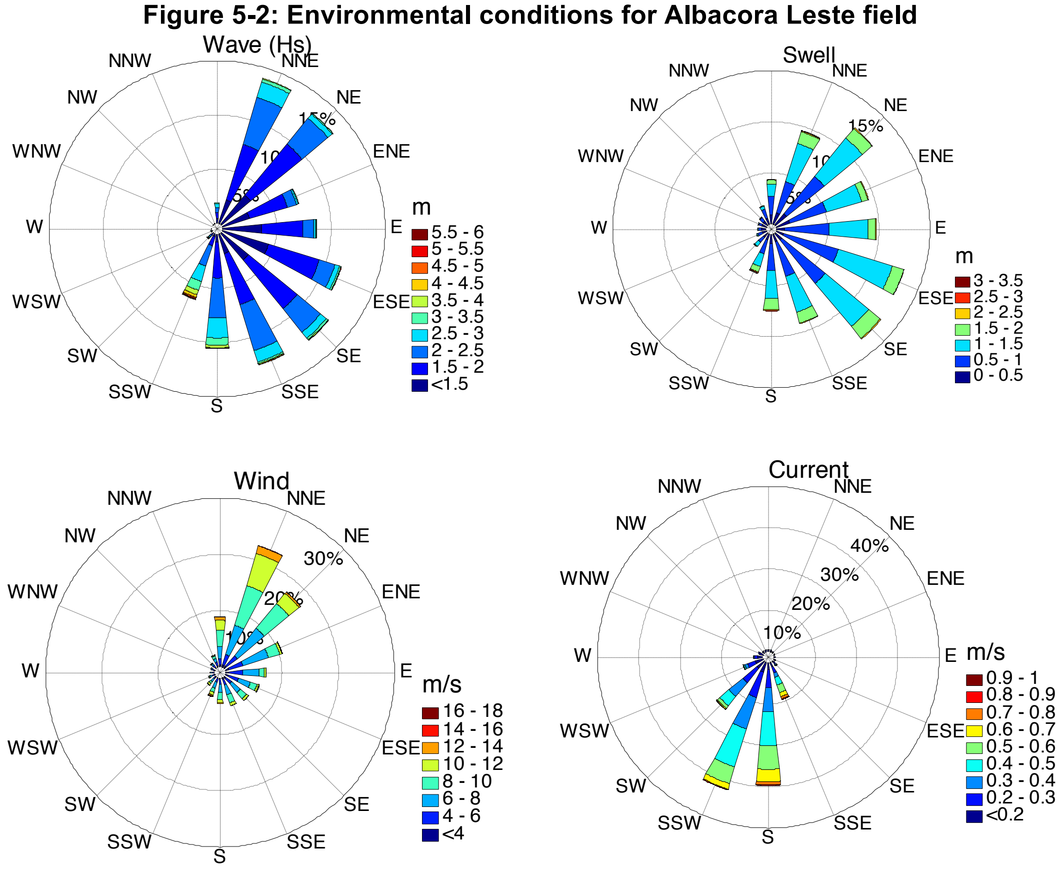
5.1.2 Environmental conditions

The occurrence of simultaneous environmental agents as bi-modal wave, wind and current were considered in this analysis.

Hindcast data was available for both locations. The data consisted in the modelling of environmental conditions in the period of 6 years between 01/01/2004 and 31/12/2009 with 3 intervals in 3h totaling 17,536 cases for each field. The long-term computation of the environmental agents is based on numerical models validated/calibrated by some sparse monitoring campaigns in specific locations of Campos and Santos Basin as explained in section 2.5. The environmental data used in the present project are based on the same used for defining the official Metocean of Campos and Santos Basin adopted by PETROBRAS. A detailed description of the mathematical model adopted is presented by Andrioni et al. (2012).

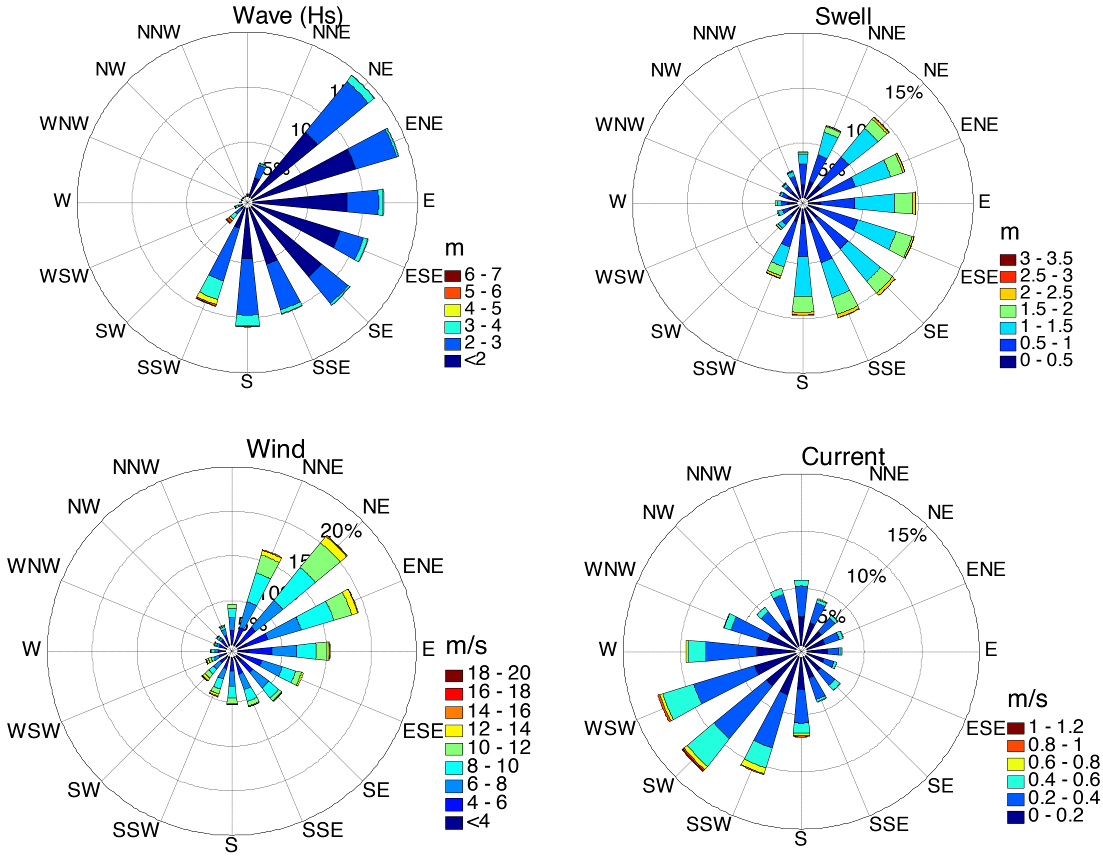
Figure 5-2 shows the frequency, direction and intensity of each environmental agent for the Albacora Leste field and Figure 5-3 shows the environmental data for Lula field. It should be noted that environmental data for wind, wave and swell show the direction of incidence, while the current data show the direction of propagation.

Figure 5-2: Environmental conditions for Albacora Leste field



Source: (PETROBRAS, 2015c)

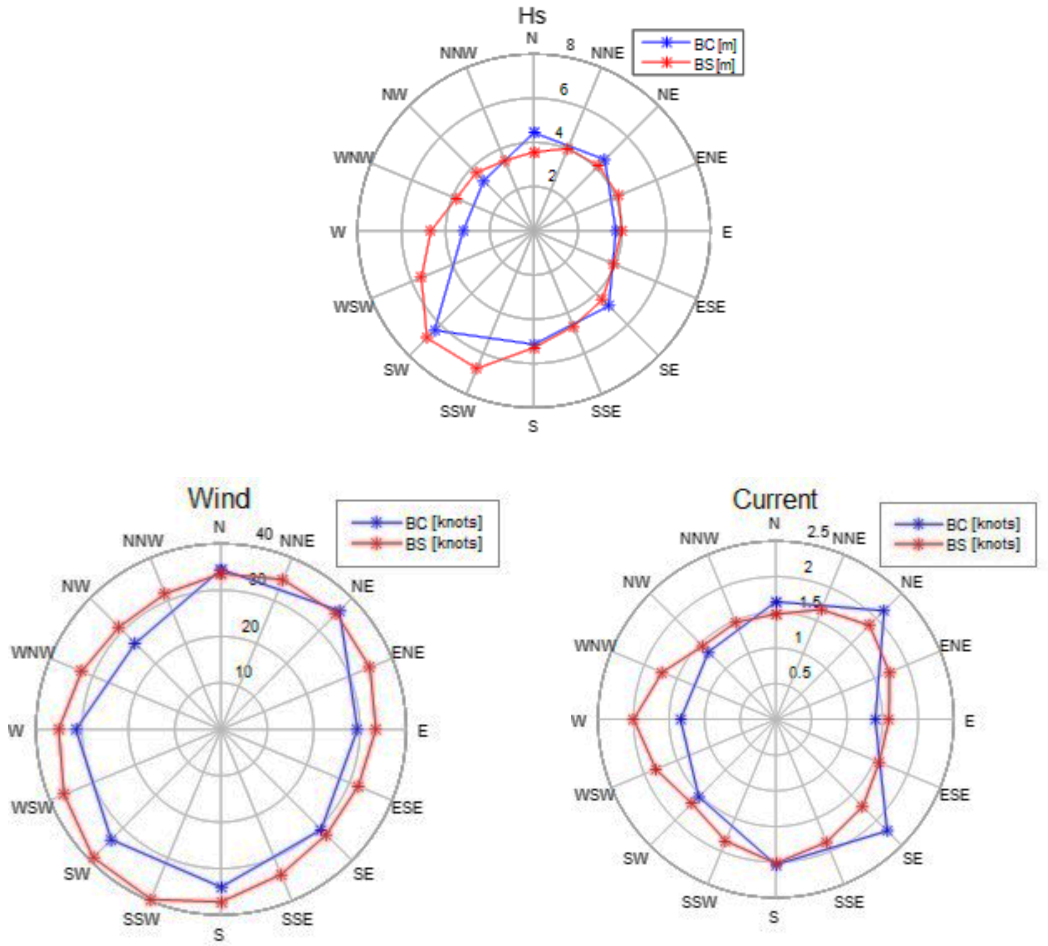
Figure 5-3: Environmental conditions for Lula field



Source: (PETROBRAS, 2015c)

Figure 5-4 shows a comparison of annual environmental conditions of the two locations. It may be observed that for most directions the environmental agents in Lula field (BS) feature higher intensities than Albacora Leste (BC).

Figure 5-4: Annual conditions comparison for Campos and Santos basins



Source: (PETROBRAS, 2015c)

5.1.3 Shuttle tanker

The DPST chosen for this work was Navion Stavanger (Figure 5-5). It is a Suezmax tanker with Dynamic Positioning System Class 2, as recommended by the Preliminary Risk Analysis, whose characteristics are shown in Table 5-1. Thrusters' layout is shown in Table 5-2.

Figure 5-5: Navion Stavanger shuttle tanker

Source: (PETROBRAS, 2015c)

Table 5-1: DP shuttle tanker's main characteristics

Property	Full-Loaded	Ballasted
Length Overall LOA (m)	278	
Length between Perp. LPP (m)	262	
Breadth (m)	46	
Draft (m)	15.85	8.0
Displacement (ton)	170,000	80,000
Wind Lateral Area (m²)	2668	4842
Wind Frontal Area (m²)	929	1290

Source: (PETROBRAS, 2015c)

Table 5-2: DP shuttle tanker's thrusters arrangement

Actuator	Position (related to the midship)	Max. Thrust	Power
Bow Tunnel Thruster	x = 127m y = 0m	+/- 31tonf	2200kW
Bow Azimuth Thruster	x = 122m y = 0m	+38tonf; -24 tonf	2200kW
Stern Tunnel Thruster	x = -111m y = 0m	+/- 29tonf	1935kW
Stern Azimuth Thruster	x = -91m y = 0m	+38tonf; -24 tonf	2200kW
Main Propeller	x = -125m y = 0m	+211tonf; -135 tonf	18.881kW
Rudder	Not used in the analysis		

Source: (PETROBRAS, 2015c)

5.1.4 Operating limits

Table 5-3 shows the environmental limits for oil transfer operations from SMS FPSO to DP shuttle tankers adopted by PETROBRAS. It may be observed that approach and connection/mooring phases have more restrict limits because of the greater proximity of the ST to the platform. Thus, these limits were adopted in the downtime study as the trigger for offloading interruption or non-start.

Table 5-3: Operating limits for offloading from FPSOs with DPST

Phase	Criterion	Accepted value
Approach/Connection Disconnection/Depart	Wind	40 knots
	Wave (Hs)	3,5 m
Offloading	Wind	50 knots
	Wave (Hs)	3,5 m

Source: Author

5.1.5 Operating sector

After performing Preliminary Risk Analysis – discussed in section 4 –, Kongsberg specialists were consulted in order to check the possibility of implementing in the existing software the hatched green sector as suggested by the PRA team.

Instead of creating the hatched green sector, Kongsberg specialists suggested creating a “Bow Rotation” zone in which the DP operation mode is changed from “Normal” to “Bow Rotation” when the shuttle tanker attaints the green sector limits (-50°[3] or +75°) and to a Heading Restriction mode when the stern of the shuttle attains grey sector limit (-60° or +85°) as shown in Figure 5-6 on the next page.

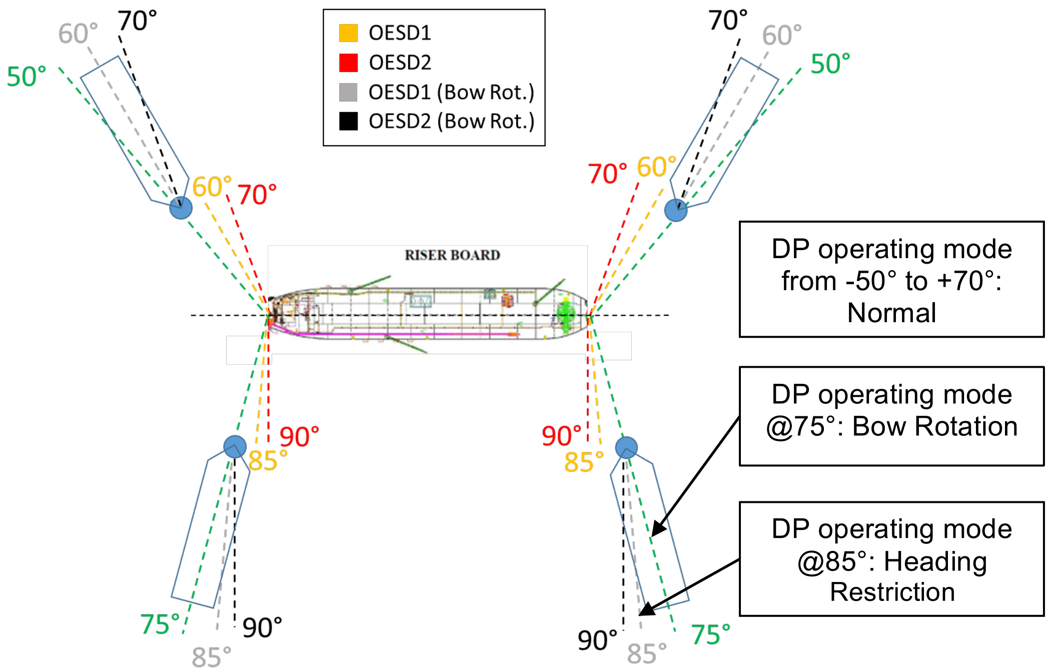
Normal mode is the most commonly used DP mode in offloading operations. In this mode, the ship operates with a fixed reference point (center of rotation), which is the shuttle’s midship section, and in weathervane mode, which means that the shuttle automatically aligns with the resultant of environmental conditions to minimize thrusters’ demand. The Bow Rotation mode is also a weathervaning mode, but in which the fixed reference point is the bow of the shuttle, not the midship section. The Heading Restriction mode is a Bow Rotation mode added to a one-side-only heading restriction, which forbids the shuttle’s heading to surpass the grey limit on one side but allows the shuttle to freely weathervane between grey and green limits.

Changing from Normal Mode to Bow Rotation mode on the green sector limit would be a good solution, because this would allow a significant decrease in power demand. Originally, when the DPST attaints the green sector limit, the Captain tries to hold the shuttle in position changing the DPS to Auto Position Mode – which is a fixed position and fixed heading mode – so that the operation is not interrupted. This

[3] This is due to technical restrictions on the software only. The fact that the sector is increased by 5° on portside is not a concern, since yellow and red sectors are kept the same, i.e., 60° and 70° respectively.

situation usually increases the power demand on the thrusters. The inclusion of the Bow Rotation mode allows the shuttle to continue in weathervane mode as the bow continues inside the green sector, thus, reducing the power demand from the original alternative.

Figure 5-6: Operating sector final proposition



Source: (PETROBRAS, 2015c)

As this alternative greatly approaches the hatched green sector proposition and complies with the PRA recommendation of operating in a misaligned heading so that the escape route is facilitated in case of drive-off, this was the final operating sector considered in the following calculations.

5.2 Calculation methodology

To calculate the offloading downtime, static analyses were used, programmed in MatLab software. It is based on an adaptation of computer code simulation TPN/Dynasim (Nishimoto, Fucatu and Masetti, 2002), (Nishimoto et al., 2003). This program performs a static evaluation of the available thrust on the DP system, to verify if the shuttle is able to counter the resulting environmental forces and keep position for each environmental condition of the hindcast data. The equations for calculating environmental forces over the hull are described in section 3.1.

The application of dynamic simulations would be more complete than static simulations, but that would require a very high computational time due to the large number of environmental conditions and headings to be analyzed.

For static analysis, the geometry of the FPSO hull is not used, since the program is not able to account for hulls interference. Only the relative heading between vessels is considered in order to check the possible positions for the shuttle within the extended sector. That is considered a conservative hypothesis, because in most cases the shadow effect reduces the forces acting on the DPST, since it is on the downstream position. There are some few cases, however, where the environmental force is amplified due to the change on current/wind flow direction by the FPSO (see for example Illuminati et al., 2009), but they are exceptions. Hence, for downtime calculation, it is expected that the shadow effect will increase the uptime that is calculated with the hypothesis of no-shadow effect.

In the first step, the routine creates a three-dimensional vector of boolean values and verifies if the vessel has enough power to maintain position or not for all the 17,537 environmental conditions, 71 DPST headings and 2 loading conditions (loaded and ballast). The routine assigns zero to the cells if the shuttle cannot maintain position and one if it can.

The logical structure of this part of the routine is as follows:

```
For each loading condition (l = 0 to 1) (Loaded and Ballast)
    For each shuttle tanker heading (h = 1 to 71) (0° to 355° with 5 deg
    increments[4])
        For each environmental condition (e = 1 to 17 537 cases)
            Get static forces and momentum from wave, wind and current
            (attribute to Fenv vector)
            Perform thrust allocation of -Fenv on the vessel and check if
            it is feasible
            If not feasible, vector_feasilibity [l, h, e] = 0
            If feasible, vector_feasilibity [l, h, e] = 1
        End_for
    End_for
End_for
```

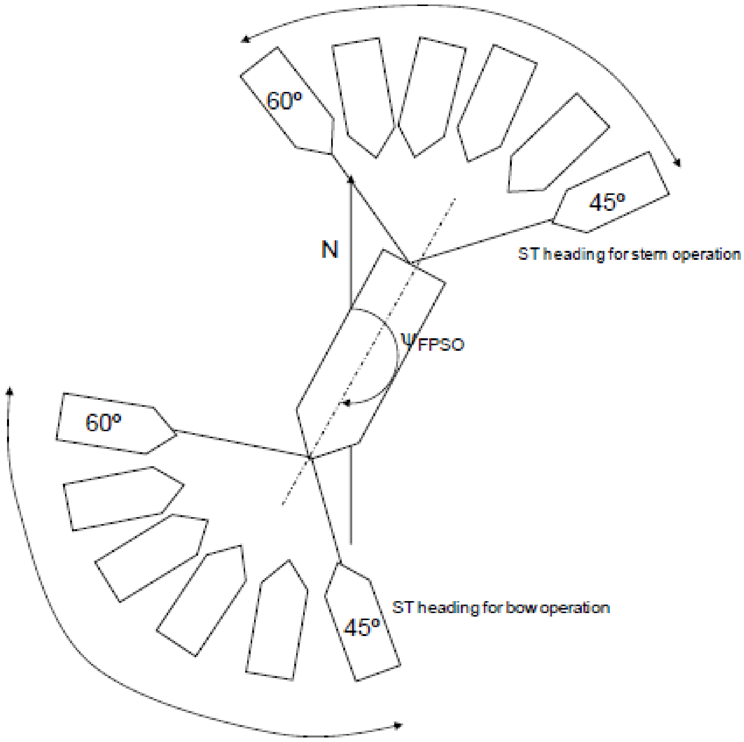
[4] Although the DPTS will only operate inside the green sector limits, the calculation of environmental forces and thrust allocation is performed from 0° to 360° in order to give more flexibility to the availability analysis. Having the data of all the possible headings allows the user to choose a wide range of operating sector angles on the following step to calculate their uptime and later compare the results.

Next, in possession of the feasibility vector and probabilities of occurrence of each environmental condition (which is 1/17,537), the routine calculates the uptime and downtime of the offloading operations by the bow station, by the stern, and by both (bow and stern) as follows:

```
Given the heading of FPSO and operational sector limit angles

For each environmental condition (e = 1 to 17 537 cases)

    Check if there is at least one heading inside the green sector for
    which it is possible to carry out the offloading in loaded condition by
    the bow
          If possible, check if there is at least one heading inside the
          green sector for which it is possible to carry out the offloading
          in ballast condition by the bow
               If possible, verify if the next 12 environmental conditions
               also meet the previous two criteria
                   If true, increase the bow uptime by Prob[e]:
                   Uptime_bow = Uptime_bow + Prob[e]
                   and count_upbow[e]=1
                   **this last counter helps later to calculate uptime of
                   bow-stern

    Check if there is at least one heading inside the green sector for
    which it is possible to carry out the offloading in loaded condition by
    the stern
          If any, check if there is at least one heading inside the green
          sector for which it is possible to carry out the offloading in
          ballast condition by the Stern
               If possible, verify if the next 12 environmental conditions
               also meet the two previous criteria
                   If true, increase the Stern uptime by:
                   Uptime_stern = Uptime_stern + Prob[e]
                   and count_upstern[e]=1
                   **this last counter helps later to calculate uptime of
                   bow-stern


     If count_upbow[e] = 1 OR count_upstern[e] = 1 then increase the uptime
     of the bow-stern
          Uptime_bowstern = Uptime_bowstern + Prob[e]

End_for
```

Figure 5-7 illustrates how the routine works, testing for all possible headings within the bow and stern sectors, if there is at least one solution for a given environmental condition.

Figure 5-7: MatLab routine logic – evaluation of the existence of at least one solution for a given environmental condition



Source: (Corrêa et al., 2013)

The acceptance criteria for an environmental condition to be accounted for as uptime for a particular offloading station are as follows:

1. Hs is less than 3.5m (contractual limit)
2. Wind speed is less than 40 knots (contractual limit)
3. If environmental forces tends to push the ship towards the FPSO, this force must be less than 22 kN (which is equivalent to a wind of 10 knots and 1m Hs wave, to ensure that the shuttle is not operating at the unfavorable station)
4. The thrust of the most requested propeller is less than 80% (dynamic allowance, explained in sections 2.3 and 3.1)
5. Shuttle's roll amplitude is less than 6° (to guarantee comfort on board of the ST, according to Captains' experience)
6. Operating window of 36 hours is met (6h for connection, 24 hours for offloading and 6h for disconnection).

The above-described routine can be used to calculate the availability of the offloading given the heading of the FPSO and the operating sector limit angles. Thus, it is possible to calculate the downtime for both basins (because FPSO headings are different) and for both sectors – original (-45°/+60°) and extended one (-45°/+75°).

This allows to calculate the uptime gain due to the extension of the operating sector and to compare the results of both basins.

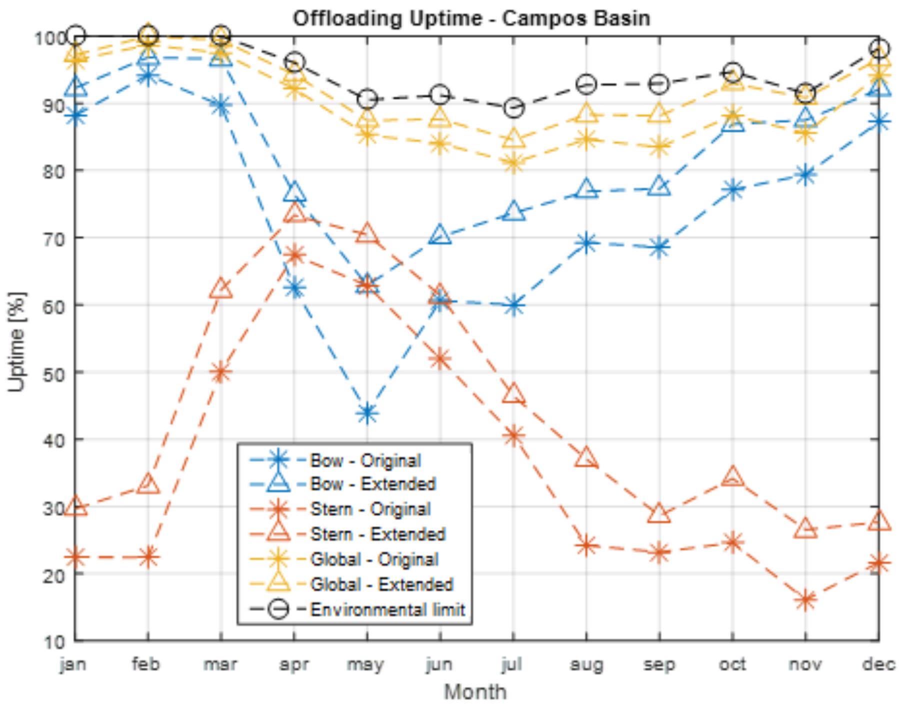
5.3 Seasonal uptime results

Since the environmental data from Campos and Santos Basins show that summer and winter present very different conditions, it is important to present seasonal (monthly based) uptime results.

Figure 5-8 presents the results of offloading seasonal uptime comparing the original sector of 60° and the extended sector of 75° for Campos Basin, and Figure 5-9 shows the results for Santos Basin. The blue lines represent bow station, red lines represent stern station, yellow lines represent global system (bow and stern) and black line represent maximum uptime due to contractual limits. Triangles represent extended sector and asterisks represent original sector.

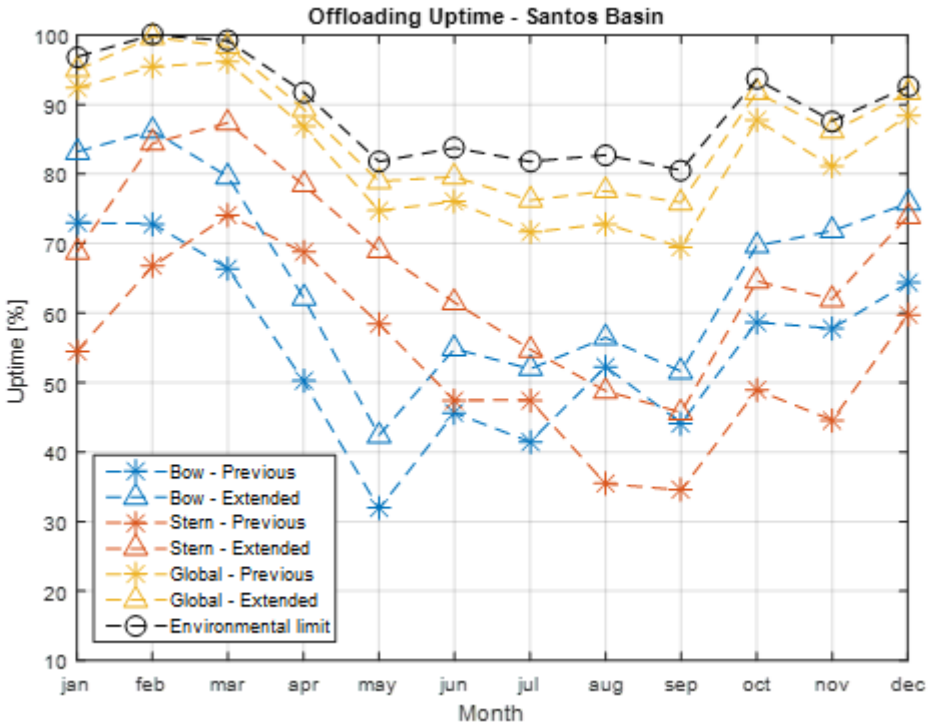
It can be seen that extending the green sector from 60 to 75 degrees is beneficial for both offloading stations in every season of the year and that the global operation uptime approaches even more from the maximum uptime due to contractual limits.

Figure 5-8: Offloading uptime (Campos Basin)



Source: (PETROBRAS, 2015c)

Figure 5-9: Offloading uptime (Santos Basin)



Source: (PETROBRAS, 2015c)

One interesting point to be noted from the previous graphics is that, in Campos Basin, the bow station is more advantageous than the stern station in most months of the year except for the month of May. In some months of the year, it was found a difference of 60% more availability for bow station than for stern station. Even though, the stern station plays an important part for the global uptime, which remains very close to the contractual limits' uptime.

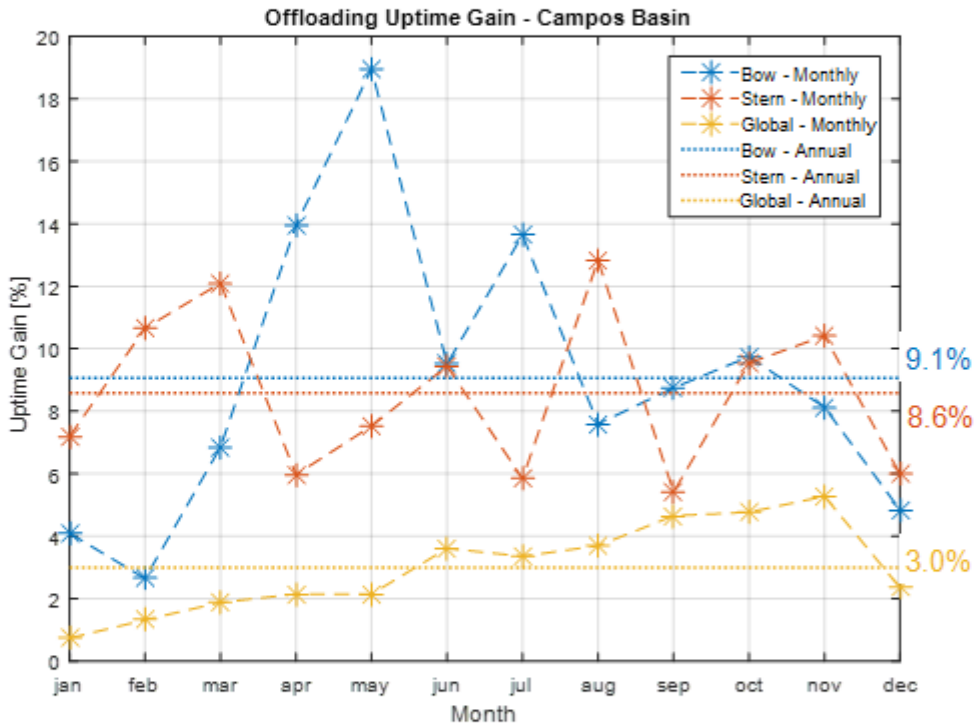
Results for Santos Basins, however, show that stern station is preferable during 5 months of the year and that availability differences between the two stations are smaller than in Campos Basin.

The following graphics, Figure 5-10 and Figure 5-11, show the actual uptime gain on each station and on the global system for both basins. This graphic is done by subtraction of the triangles lines by the asterisks lines on Figure 5-8 and Figure 5-9.

It can be seen that for Campos Basin an annual uptime gain of 9.1% was found for bow station and 8.6% for stern station. The global system presents an annual availability gain of 3.0%. By analyzing each month individually, it is noticed that some months may present uptime gains of up to 19% (bow station, month of May) or as low as 4% (bow station, month of February).

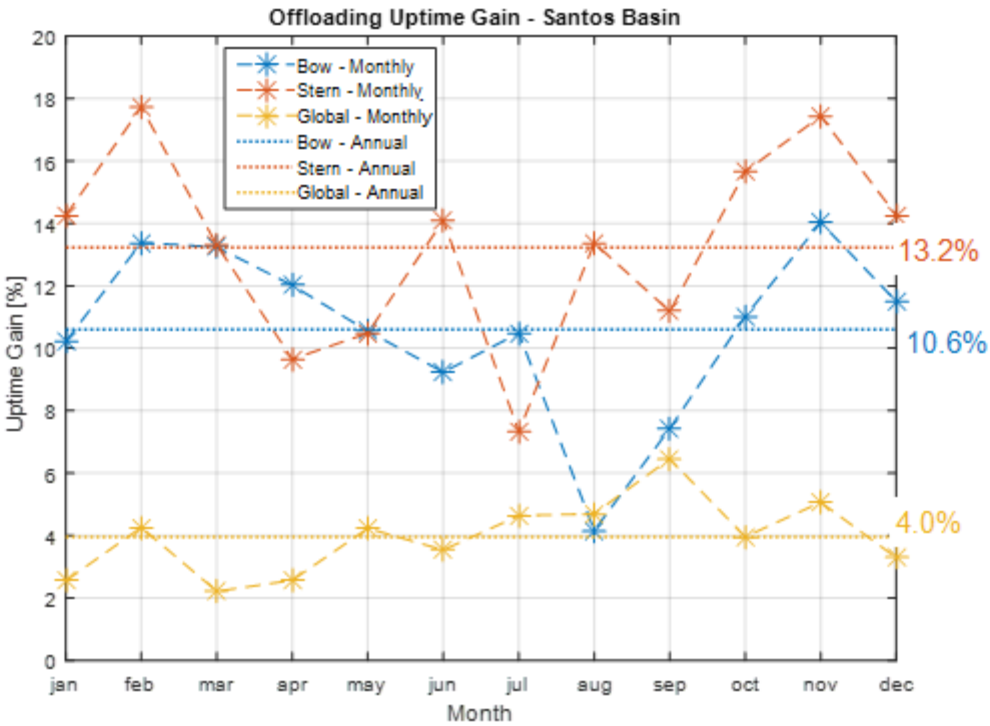
As for Santos Basin, the uptime gain is even more significant, around 10.6% for bow station, 13.2% for stern station and 4% for the global system (annual average). By analyzing each month individually, it is noticed that some months may present uptime gains of up to 18% (stern station, month of February) or as low as 2.5% (bow station, month of August).

Figure 5-10: Offloading uptime gain for Campos Basin



Source: (PETROBRAS, 2015c)

Figure 5-11: Offloading uptime gain for Santos Basin



Source: (PETROBRAS, 2015c)

5.4 Probability of disconnections during offloading

It is important to notice that even if the 36-hour window is not met in real life, the shuttle may be able to start the offloading in one station and change stations if the weather changes. Changing stations represent an important loss of time, since the ST has to disconnect from one station and re-connect to the other one. However, it gives the operator more flexibility to offload, especially if the FPSO is close to top.

The probability pf disconnection during offloading would be an interesting information to calculate, however, no specific methodology was developed in this study for that. Nonetheless, it is possible to assess this issue in a simplified manner.

Since the probability of finding a 36h window on a single station is higher for the extended sector than for the current sector, it is clear that the probability of not meeting the required window and perform a disconnection is smaller, though this probability is not quantified.

Thus, it is possible to say that, by operating in the extended green sector, it is less likely that the DPST has to change stations to continue with the oil transfer.

6 DP SYSTEM POWER DEMAND

This section presents the discussion about another advantage of extending the offloading operating sector. As previously mentioned in the Introduction, section 1.6, by operating in the extended sector, the shuttle tanker can better align with environmental conditions which would decrease the power demand on the thrusters and hence the risk of blackout. The comparison between the optimized power demand on the DP system when the vessel operates in original and extended sectors is shown below.

6.1 Calculation methodology

In order to compare the power demand on both sectors, the results from downtime analysis routine were used. As explained in section 5.2, the MatLab routine determines for all environmental conditions and all shuttle headings if it is able to keep position or not by calculating environmental loads over its hull and allocating thrust on the propellers.

With this information, it is possible to find for each environmental window of 36h the optimized DP power demand to the operation. This can be done both for normal and extended sectors. By comparing the optimized power demand, it is possible to conclude if the extended sector helped the shuttle to find a more comfortable heading, with less power demand.

The logic of the routine is as follows:

1. For the original green sector, find every environmental window that allows the offloading operation to take place;
2. For each of these windows, find the optimized DP power demand as follows:
    i. For every environmental condition within the 36hour-window, find the optimum heading inside the sector which requires the minimum DP power demand;
    ii. The optimized power demand for the window, i.e., the whole operation, will be the highest power demand found in item i.
3. Keep the optimized power demand value on a specific vector;

4. Do steps 1 to 3 for extended sector;
5. Compare results through histograms.

This methodology is applied for bow station, stern station and global system for each month of the year.

An important point to be noted is that the environmental conditions that had solution in the extended sector only were not considered for the comparison of DP power demand. Only the conditions that had solutions in both sectors were taken into account, otherwise the comparison would be unfair, since the ultimate goal here is to understand what is the gain in terms of safety when extending the green sector.

After calculating the optimized DP system utilization for all environmental windows for both sectors, several histograms were generated showing how many cases (environmental windows) request the following ranges of power on the DP System:

- 0 to 10%
- 10 to 20%
- 20 to 30%
- 30 to 50%
- 50 to 80% (maximum utilization, discussed in 5.2)

The histograms were generated for Campos and Santos Basins, for original and extended sectors, and for bow and stern stations, to facilitate comparison, each one showing the power demand in every month of the year.

6.2 Results

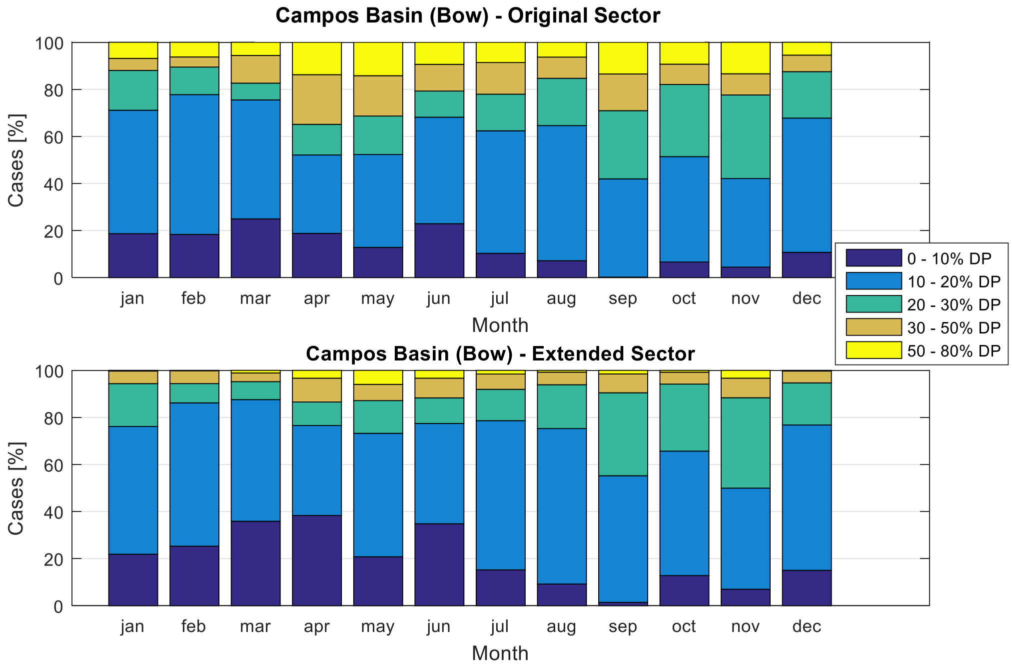
The next sections present the results for Campos and Santos Basins.

6.2.1 Power demand in Campos Basin

Figure 6-1 and Figure 6-2 below show the results for bow and stern stations respectively. The y-axis represents all the cases (environmental windows) where the DPST can operate in both sectors (previous and extended sectors). The length of the color bars represents the percentage of cases where the DPST presents the average power demand corresponding to its color. The total sum of color bars corresponds to

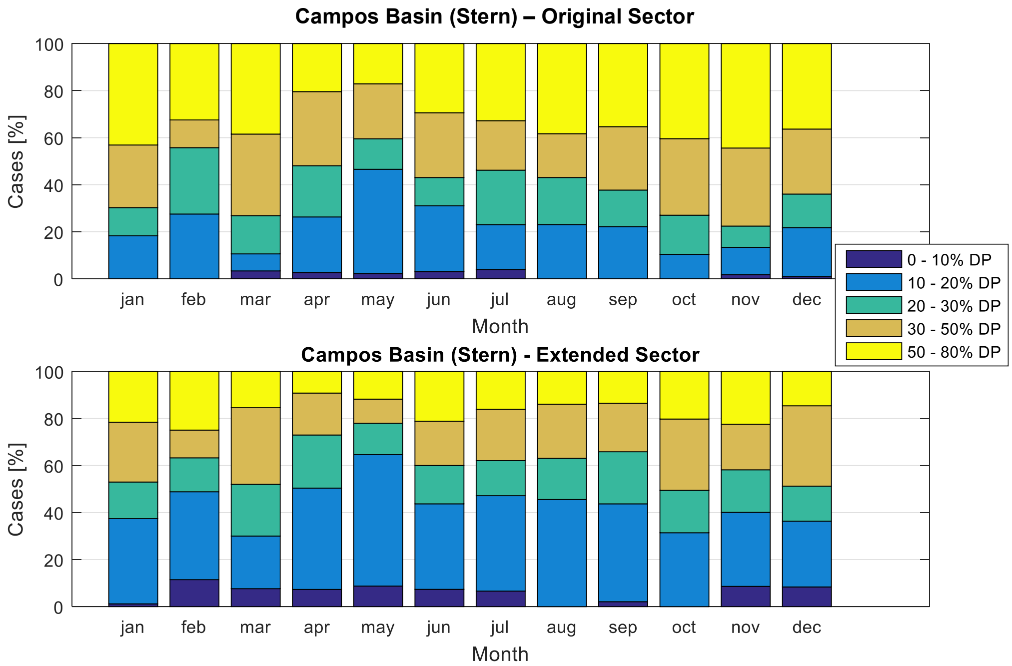
100% of the cases, and the total number of cases is the same for previous and extended sectors.

Figure 6-1: Average utilization of DP System for Bow Station (Campos Basin)



Source: (PETROBRAS, 2015c)

Figure 6-2: Average utilization of DP System for Stern Station (Campos Basin)



Source: (PETROBRAS, 2015c)

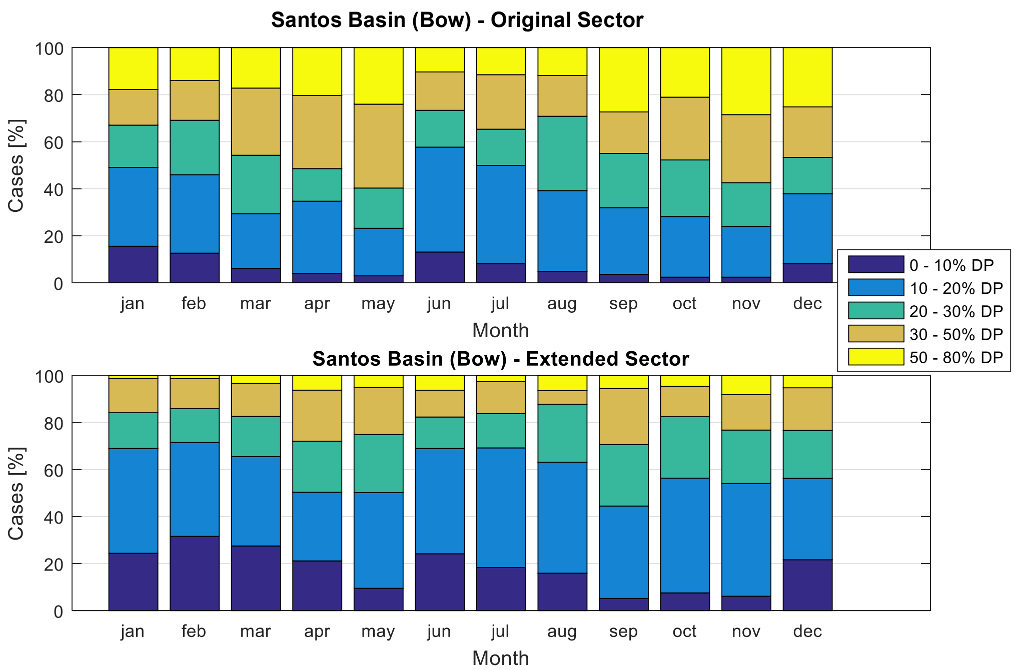
Firstly, it is possible to verify that the average utilization of the DP system is always lower in the bow station compared to the stern station, regardless of operating sector. This is due to more favorable environmental conditions to offload by the bow, as seen in section 5.1.2.

Regarding the operating sector, it is clear that for the extended sector there is a power demand reduction at both bow and stern stations. For example, for the stern station in January, if the shuttle operates in the original sector the chances that the power demand is lower than 50% are less than 60%. However, if the shuttle operates in the extended sector, this chances increase to almost 80%. This indicates that the sector's extension could make the operation safer in terms of stress on the DP system and risk of blackout.

6.2.2 Power demand in Santos Basin

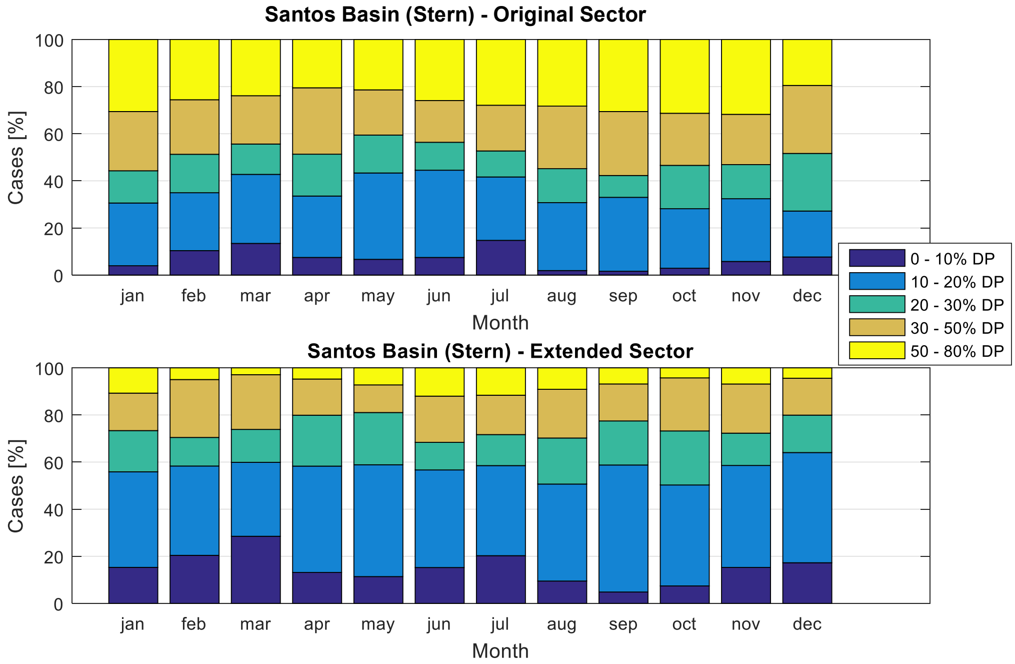
Figure 6-3 and Figure 6-4 show the results for bow and stern stations respectively.

Figure 6-3: Average utilization of DP System for Bow Station (Santos Basin)



Source: (PETROBRAS, 2015c)

Figure 6-4: Average utilization of DP System for Stern Station (Santos Basin)



Source: (PETROBRAS, 2015c)

As well as observed for Campos Basin, it is possible to see that the average utilization of the DP system is lower in the bow station than in stern station, regardless of operating sector. This is also due to more favorable environmental conditions to offload by the bow.

Regarding the operating sector, it is possible to see that power demand reduction also occurs when operating within the extended sector and it is even more significant for the bow in Santos Basin than for Campos.

7 REAL TIME SIMULATIONS

The last part of this study consisted in performing real time simulations with the participation of experienced DPST Captains so they could give their impression on how safe the operation in the extended sector would be in real life. The simulations were performed in the Maritime and Waterway Simulator, or *Simulador Marítimo Hidroviário* (SMH-USP) in Portuguese, available at the University of São Paulo inside the Numerical Offshore Tank Laboratory of the University of São Paulo (TPN-USP) facilities.

These simulations had three main objectives. First, to assess the opinion of experienced Captains on the operation's safety in a realistic simulator. Second, to compare DP System power demand in the original and extended sectors to confirm that the extended sector may allow the shuttle tanker to consume less fuel. Third and most importantly, to analyze if drive-off events during the operation in the extended sector were safely overcame by performing escape maneuvers to avoid collision with the FPSO. As explained in section 4.7, this was one of the main concerns of the group of specialists of the Preliminary Risk Analysis.

7.1 The maneuvering simulator SMH-USP

The SMH is a simulator for analysis and training of waterway, port and offshore operations, which was developed by the University of São Paulo, TRANSPETRO and PETROBRAS, with the technical collaboration of Brazilian Pilots Association (CONAPRA) in 2012.

The software is based on the TPN (Numerical Offshore Tank) numerical code (Nishimoto et al., 2002), which had several modifications, in order to perform real-time simulations. It helps in performing various maneuverings in extreme conditions, with different types of ship and in damaged conditions and/or command failures. Non-conventional operations, such as ship-to-ship berthing and maneuvering of hulls of future FPSO platforms (without propulsion), can also be examined beforehand using simulation.

The simulator is equipped with 25 flat screen TVs giving a 360° view of the operation, 10 command screens, levers to control tunnel, azimuth thrusters, main propeller (fixed or variable pitch) and rudder, and DP system control station (in-house code and/or Kongsberg DP system code). See Figure 7-1.

Figure 7-1: TPN-USP's Full-Mission Simulator

Source: (TPN, 2015)

The simulator is capable of considering the following variables:

- Calculation of movement in six degrees of freedom;
- Hydrodynamics of the vessel in open water considering external wave and current;
- Shallow water effects (bathymetric bottom) on the potential and viscous hydrodynamic efforts and on propulsion and maneuvering system;
- Bank effects and interaction with other vessels;
- Thrusters modeling (fixed or variable pitch), autopilot and dynamic positioning system;
- Fenders, anchor and cables for docking and mooring simulations.

As the simulations are performed, the simulator outputs are recorded in a particular hardware. These outputs comprehend videos, images of the vessel's trails, time history graphics of vessels' motions (heave, roll, pitch, surge, sway and yaw), power demand on each thruster, hydrodynamic forces and others.

7.2 Team

According to Tannuri et al. (2014), "the simulators are never perfect, since mathematical models are simplifications of reality. Therefore, they must always be used in conjunction with the knowledge and experience of local conditions". Based in this same idea, the team that participated in the real time simulations was composed by two experienced DPST Captains (one of whom had participated in the PRA sections), four naval engineers from PETROBRAS and three simulator specialists from TPN (Figure 7-2 and Figure 7-3).

Before the simulations took place, a calibration test was done a few weeks before, in the presence of another experienced Captain in order to adjust any items or parameters that he found necessary. On this day, a drive-off situation was tested. After discussing with the Captain about his perceptions, TPN staff provided a DARPS screen to the facility and programmed the code so it would be possible to easily change the thrusters command from the DP console to the manual levers.

Figure 7-2: Petrobras, TPN and Transpetro teams on the calibration simulations

Source: (TPN, 2015)

Figure 7-3: Transpetro and TPN teams during the actual simulations

Source: (TPN, 2015)

7.3 Simulation Cases

Amongst the environmental hindcast data from Campos and Santos Basins, the most significant conditions were chosen to be input into the simulations. These conditions were chosen because they represented either typical conditions from each basin or intense conditions that would tend to push the DPST out of the original green sector.

In total, twelve simulations were performed with different shuttle tanker's draft and different environmental conditions, as shown in Table 7-1. All of them included drive-off simulations to verify if the escape maneuvers would be successful and safe – which was assessed as an important concern in the Preliminary Risk Analysis detailed in section 4. The focus was to compare thrusters demand in original an extended sector and to evaluate possible drive-off escape maneuvers in the extended sector.

Table 7-1: Simulation Cases

Case	DPST Draft	Current (dir. / knot)		Wind (dir. / knot)		Wave (dir. / Hs / Tp)			Swell (dir. / h / t)		
1	Ballast	W (266°)	0.74	SSE (103°)	21	SSE (113°)	3m	7.6s	-	-	-
2	Ballast	S (185°)	0.8	SE (134°)	20	SE (133°)	3.3m	7.6s	-	-	-
3	Full	S (202°)	0.74	SSW (206°)	15	SSW (192°)	3m	16s	-	-	-
4	Full	S (202°)	0.74	SSW (206°)	15	SSW (192°)	3m	16s	-	-	-
5	Full	SW (241°)	1	S (181°)	10	S (196°)	1.8m	9s	-	-	-
6	Full	SW (241°)	1	S (181°)	10	S (196°)	1.8m	9s	-	-	-
7	Interm.	S (190°)	1.2	SE (135°)	20	SE (135°)	3.4m	10s	-	-	-
8	Interm.	S (190°)	1.2	SE (135°)	20	SE (135°)	3.4m	10s	-	-	-
9	Interm.	S (190°)	1.2	NE (45°)	20	NE (45°)	1.5m	7s	SE (135°)	3m	10s
10	Interm.	W (270°)	1.2	SE (135°)	20	SE (135°)	3m	10s	-	-	-
11	Interm.	W (270°)	1.2	SE (135°)	20	SE (135°)	3m	10s	-	-	-
12	Full	W (270°)	1.5	NE (45°)	20	NE (45°)	1.5m	7s	SE (135°)	2m	10s

Notes:
1) Cases 1, 2, 3, 5, 7, 9, 11 and 12 were simulations that compare original and extended sectors followed by drive-off simulation.
2) Cases 4 and 6 were drive-off simulations only. No comparison between operating sectors.
3) Case 8 was a blackout simulation.
4) Case 10 was an unsuccessful approach simulation.

Source: (TPN, 2015)

7.4 Results

The following sections show the results of real time simulations concerning power demand and drive-off scenarios. The results are summarized in Table 7-2 below. A detailed description of each of the simulated cases can be found in Appendix A. As the results show, most scenarios indicated that the extended sector is not only possible but also advantageous in terms of power demand. During the simulations of these scenarios, the Captains felt comfortable all the time and concluded that operating in this sector would be safely accomplished in real life.

Table 7-2: Results of real time simulations

Case	Operating in extended sector is possible	Extended sector is more advantageous in terms of power demand	Drive-off maneuver is successful	Notes
1	Yes	Yes	No	[1]
2	Yes	Yes	Yes	[2]
3	Yes	No	Yes	[2]
4	-	-	Yes	[1] [3]
5	Yes	Yes	Yes	[2]
6	-	-	No	[1] [3]
7	Yes	Yes	Yes	[2]
8	Yes	-	-	[4]
9	Yes	No	Yes	[1]
10	-	-	-	[5]
11	Yes	Yes	Yes	[2]
12	Yes	Yes	Yes	[1]

Notes:
[1] Drive-off escape maneuver performed using main propeller and rudder only.
[2] Drive-off escape maneuver performed using main propeller, rudder and all the thrusters.
[3] Drive-off simulation only. No comparison between operating sectors.
[4] Blackout simulation. No comparison between operating sectors or drive-off results.
[5] Unsuccessful approach simulation. Vessel did not keep position because of inertia.

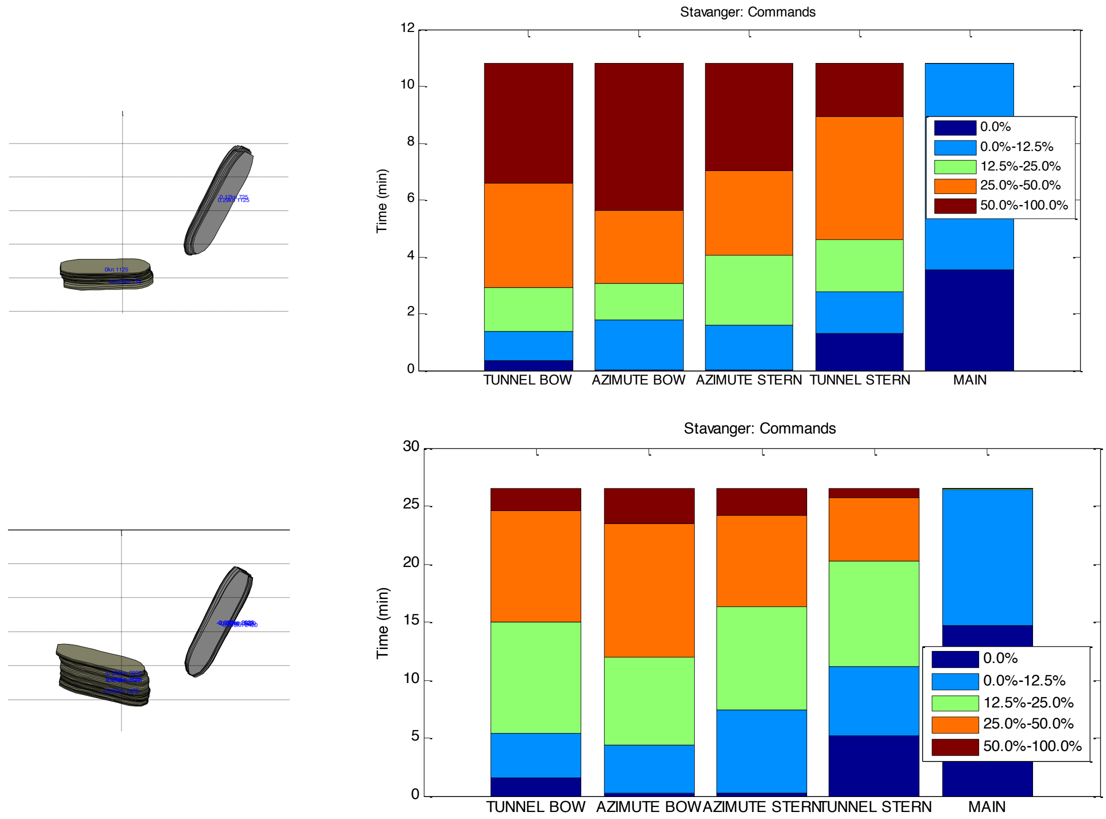
Source: Author

7.4.1 Power demand

The evaluation of power demand on each simulation is done through power histograms, which are provided by the simulator and show for how many time during the simulation each thruster attained the different levels of power demand. Dark red color represents the time a certain thruster worked between 50% and 100% of its nominal power, and dark blue color represents the time that this thruster was not used. Light blue, green and Orange colors represent, respectively, the time that a thruster was used at very low demand (from 0% to 12.5%), low demand (from 12.5% to 25%) and moderate demand (from 25% to 50%). So the more dark red areas on the histogram, the more that thruster was demanded at full power. The more blue and green colors on the histogram, the more time the thruster had low demand.

As a summary from all the simulations, it can be said that extended sector generally showed to be less power demanding than original sector. This happens mostly for environments where wave and wind come from East and South East, or when strong currents come from the East (cases 1, 2, 7, 11 and 12). Figure 7-4 below shows the power histogram of Case 2. It is possible to notice a significant power reduction when the DPST changes position from original sector limit to extended one.

Figure 7-4: Case 2 – Power demand comparison between operation in original (top) and extended (down) sectors.

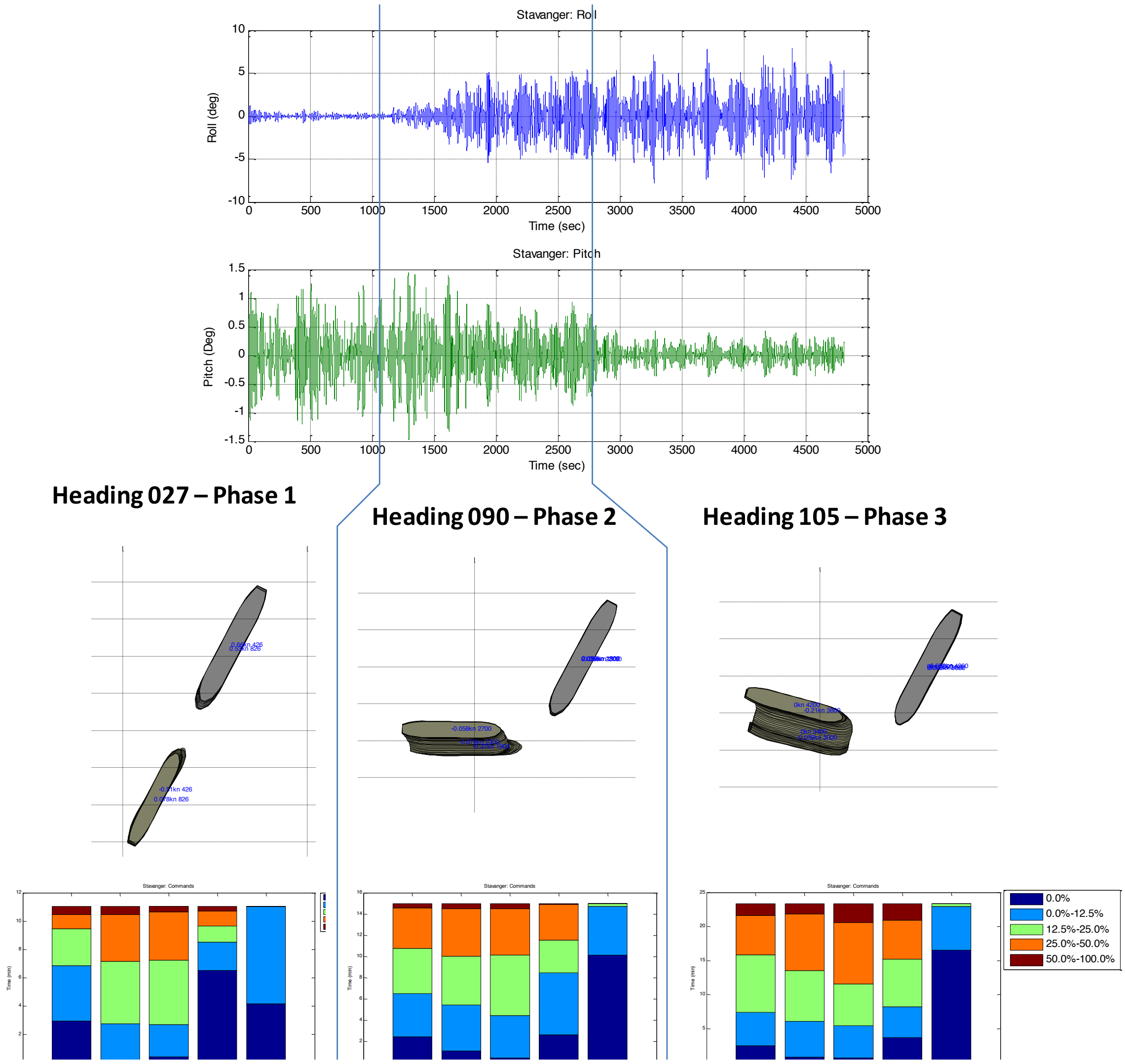


Source: (TPN, 2015)

Two simulations (cases 10 and 11) also showed the importance of the hatched green sector. In these simulations, the DPST was only able to keep position at 80^{o} in relation to the FPSO. This confirms the uptime gain in extending the operating sector.

Finally, two simulations (cases 3 and 9) did not show power consumption advantages for the extended sector. Instead, case 3 even showed that the extended sector might be disadvantageous depending on the wave height and period coming from the South. In this simulation, the shuttle was positioned inside the extended green sector, it was submitted to beam sea and presented excessive roll motions (see Figure 7-5). This would have hindered the operation in real life. This does not happen when Hs and Tp are lower but still coming from the south as it was observed in case 5.

Figure 7-5: Case 3 – Power demand and motions comparison between operation in original and extended sectors



[Order of thrusters in the histograms from left to right: Tunnel Bow, Azimuth Bow, Azimuth Stern, Tunnel Stern, Main propeller]

Source: (TPN, 2015)

The other simulation that showed no advantage of the extended sector, case 9, presented wave, wind and current coming from North-Northeast and the swell coming from Southeast. In this case, the best relative heading for the shuttle tanker was found to be 30 degrees in relation to the FPSO. Obviously, the fact that the extended sector is not always advantageous is not a surprise, because since the beginning it was seen as a solution for performing offloading under specific environmental conditions that push the shuttle out of the original green zone.

7.4.2 Drive-off escape maneuvers

Drive-off events were simulated in the worst-case scenario, with pitch of the Controllable Pitch Propeller clamped at maximum forward position, which means that the main propeller would drive the DPST towards the FPSO at maximum thrust. The escape maneuvers were performed in two different ways. First and most common way was using the rudder and all the thrusters to apply a moment to starboard on the shuttle to make the curve and escape from the FPSO. Second, which is a more conservative approach, was using only the ruder to turn the DPST away from the FPSO. It is important to notice that the main propeller is fully actuated forward on both cases.

The performance and success of the escape maneuver can be analyzed through a series of images that show the vessel’s trail through time. They give an idea of the DPST’s trajectory during escape maneuver and how far from the FPSO unit it went by.

Most drive-off scenarios were successfully handled in the extended sector and there were no collisions. Case 1 and 6 were exception. In these simulations, the Captains performed the escape maneuver using main propeller and rudder only. The thrusters were not used to aid just as a conservative approach. In Case 1, a collision took place and in case 6, although there was no collision, the DPST came too close to the FPSO.

Drive-off simulations showed that it is always recommended to perform escape maneuvers using all available thrusters to minimize the risk of collision. When the weather tends to push the shuttle away from the FPSO, however, the maneuver can be safely done with the main propeller and rudder only (this was possible in cases 4, 9 and 12). Although most of the escape manoeuvers were successfully performed, the Captains highlighted that it is safer that the shuttle’s bow never points towards the offloading station as usually done so it is easier to avoid collision in case of drive-off.

Figure 7-7 and Figure 7-6 below show the comparison between drive-off escape manoeuvers performed in cases 1, 2, 3 and 4. It is possible to notice through the DPST trajectory that the use of thrusters to aid the escape manoeuver is safer because it increases the distance to the FPSO.

Figure 7-6: Cases 3 and 4 – Drive-off escape manoeuver using rudder and thrusters (left) and rudder only (right).

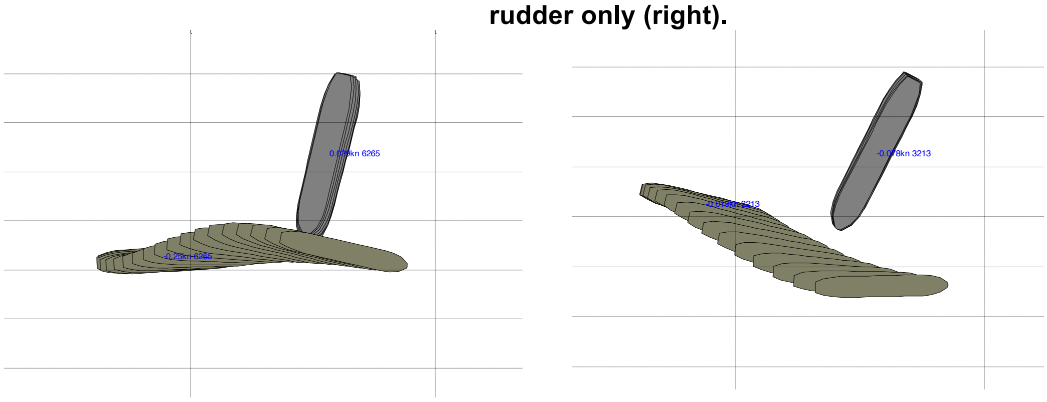
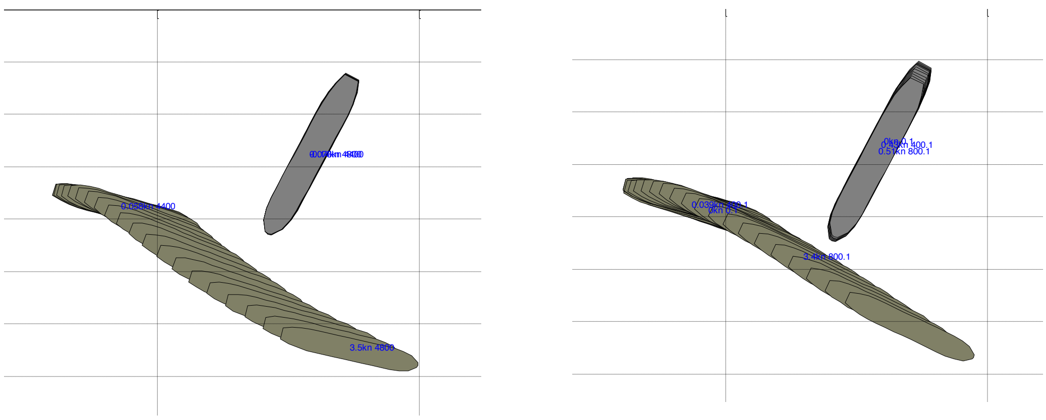


Figure 7-7: Cases 1 and 2 – Drive-off escape manoeuver using rudder only (left) and rudder and thrusters (right).



Source: (TPN, 2015)

8 FIELD TESTS

After completing the previous steps proposed by the methodology of this work, it was possible to gain confidence to test the operation with the new sectors in real life. The main objective of performing the field tests was to evaluate the DP software update on an existing shuttle tanker, to test the transition between Normal and Bow Rotation modes, between Bow Rotation and Heading Restriction Modes, and to have the Captain's impression on the operation safety.

For this test to be possible, it was firstly necessary to choose the location, the FPSO and DPST to be used and to negotiate with Kongsberg the implementation of the new sector on the shuttle tanker.

The chosen location was Santos Basin, as this is the location with greater concern since the beginning of the study. The choice of the vessel is merely a matter of respecting the premises of the Risk Analysis – DP Class II, following the recommendations – and of choosing a shuttle that has operated several times at the chosen location. The chosen vessel was Brasil 2014, a Suezmax type, DP Class 2 vessel that had already good experience in Santos Basin. Finally, the choice of the FPSO depended only on the DPST schedule, since no set-ups needed to be done on the FPSO side for this field test.

The test was performed in August 2015 and required 72 hours in total to be accomplished – 36h of primary testing and 36h of offloading operation. Two experts from PETROBRAS and one expert from Kongsberg boarded the shuttle tanker in São Sebastião port to proceed to FPSO Cidade de Mangaratiba located in Santos Basin. The DP software update was performed during the trip to the offloading location and it only took half an hour to be completed[5].

The shuttle arrived at the destination on time and connected to the FPSO's bow station following the normal procedures and approached the FPSO inside the extended sector. The offloading started and was entirely carried out under calm weather conditions that would have allowed the shuttle to operate even inside de original sector.

At a certain point, the shuttle's Captain was asked if he could position the vessel closer to the limit of the extended sector (75°) in order to force the situation were the

[5] The software update took one week of preparation onshore, and 30 min for installation onboard.

DP software would change from Normal to Bow Rotation mode and then to Heading Restriction mode. As this manoeuver would not put into risk the operation, he promptly agreed and re-positioned the shuttle.

As the shuttle overcame the limit of 75°, the DP software changed to Bow Rotation mode as expected and it was possible to see that thrusters' power demand immediately dropped down. This confirmed that the Bow Rotation mode requires less power from the DP system when the shuttle is operating at the limits of the green sector, as explained in section 5.1.5. Later, the shuttle finally attained the Heading Restriction limit and the software promptly altered the operation mode not to allow the shuttle to surpass the limit of 85° shown in Figure 5-6 on page 85.

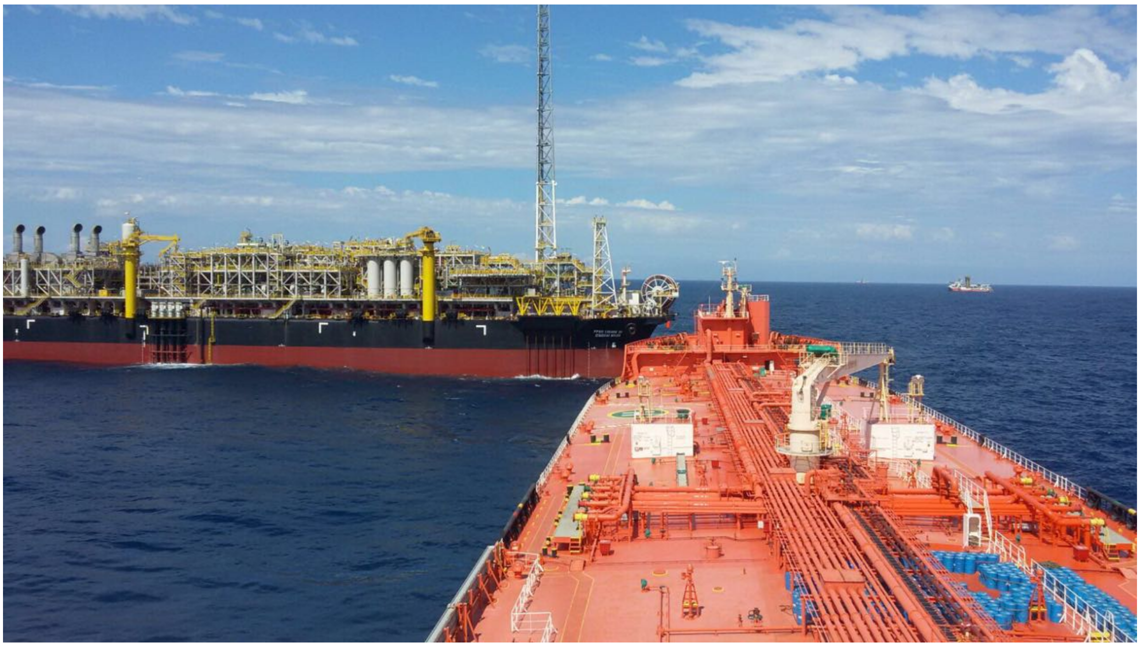
As no adversities took place and the Captain of Brasil 2014 perceived no safety issues in operating inside the extended sector, the tests were considered successful and it was decided that it was possible to move on to the next stage, i.e., definite implementation of the technology on the whole fleet (PETROBRAS, 2015c).

This stage involved official validation of the new sector inside PETROBRAS, modification of offloading procedures and implementation on all DP Class II shuttles of the fleet – which means performing set-up of every DPST shuttle with every FPSO in the fleet, what roughly makes 748 set-ups to be completed (17 DP Class II shuttle's times 22 FPSOs times 2 offloading stations).

The official validation of the new sector was done by the department in charge of offloading operations and procedures inside PETROBRAS E&P division after extensive discussions and participation of TRANSPETRO specialists.

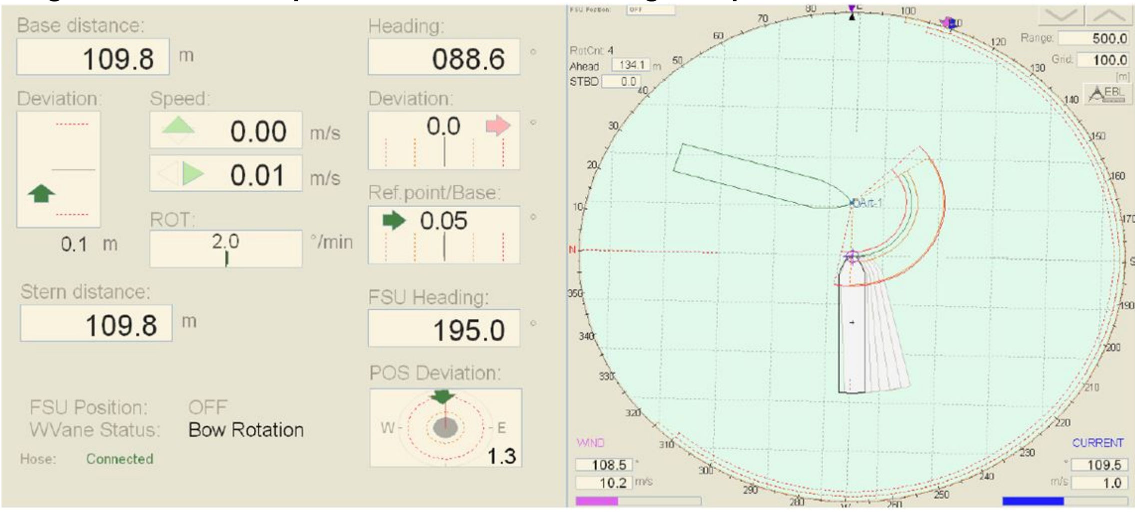
The new sector is already in operational in about 12 shuttle tankers in PETROBRAS and positive feedback has been received both by DPST Captains and by Kongsberg specialists. Figure 8-1 and Figure 8-2 show the images of Eagle Paraiba shuttle tanker operating in the extended sector and a screen capture of his DP console showing the operation mode set to "bow rotation".

Figure 8-1: DPST Eagle Paraiba operating inside the extended sector



Source: Kongsberg Maritime

Figure 8-2: Screen capture of DP console showing the operation in bow rotation mode



Source: Kongsberg Maritime

9 CONCLUSIONS

The results presented in section 5 – Offloading Downtime Analysis – and in section 6 – DP System Power Demand – show that the extended operating sector is advantageous for increasing the offloading uptime, decreasing the probability of disconnection during the operation and decreasing the average of thrusters' utilization of the DP shuttle tanker.

The Downtime Analysis shows that for Campos Basin an annual average uptime gain of 9.1% is found for bow station and 8.6% for stern station. The global system presents an annual availability gain of 3.0%. By analyzing each month of the year individually, it is noticed that some months may present uptime gains of up to 19% (bow station, month of May) or as low as 4% (bow station, month of February). As for Santos Basin, the uptime gain is even more significant – around 10.6% for bow station, 13.2% for stern station and 4% for the global system (annual average) – and by analyzing each month individually, some of them present uptime gains of up to 18% (stern station, month of February) or as low as 2.5% (bow station, month of August).

It is important to highlight that availability gain is eventually translated as economical gains to the operator, since it reduces the probability of offloading delays and top events. The delay in offloading operations generates extra costs of demurrage of the shuttle tanker. The current daily rate of these DP shuttle tankers is about US$ 55,000. Moreover, a top event may cost about 5,5 million dollars a day (considering a 100,000 barrels production plant with the crude oil brent price at US$ 55).

The Power Demand study shows that, when operating within the extended sector, there is a power demand reduction at bow and stern stations for both Campos and Santos Basin. This indicates that the sector's extension could make the operation safer in terms of stress on the DP system and consequent lower risk of blackout.

The Preliminary Risk Assessment presented in section 4 shows that the non-tolerable risk scenarios assessed are mainly caused by drive-off events. These scenarios' consequences are mainly associated with collision between the two vessels, representing risks for the personnel, environment, facilities and company's image. When offloading by the bow or stern within the extended sector, a collision on the side of the FPSO can cause large-scale oil leak of a cargo tank. When offloading by the stern, a collision may cause flooding of the machinery room and severe damage to facilities. However, the PRA group assessed several recommendations, which, when implemented, are considered sufficient to reduce the risk of these scenarios to “Moderate” category.

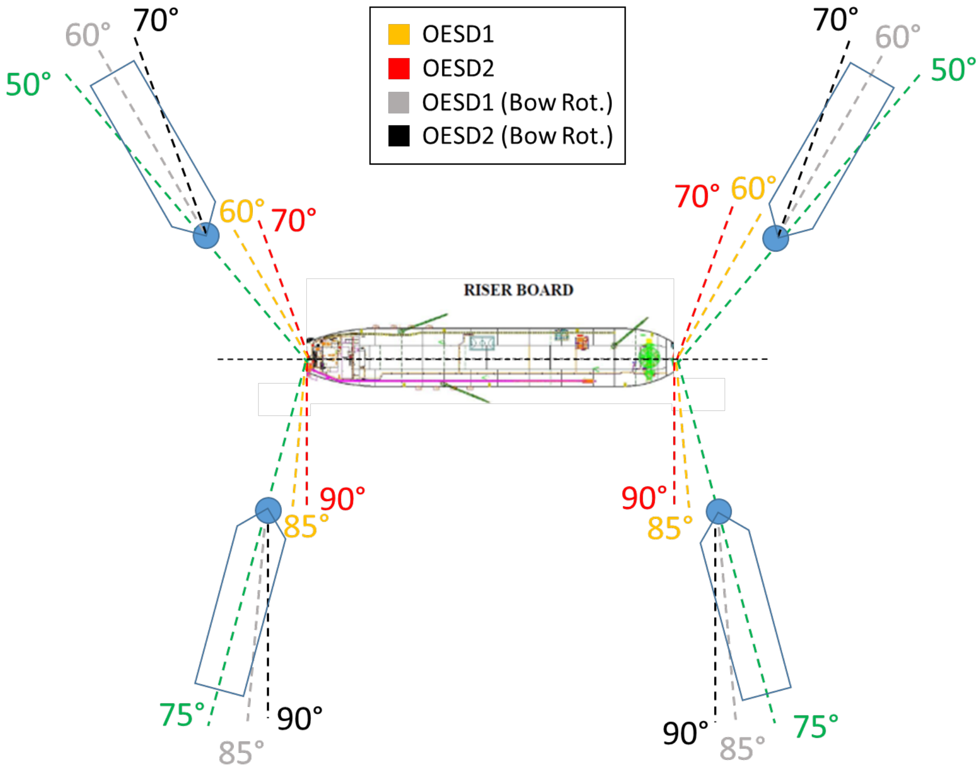
The Real Time Simulations presented in section 7 complement all the other analysis showing that:

- for some environmental conditions, where the DPST cannot keep position inside original sector, the extended sector allows the operation to continue normally,
- for most of the simulated cases, even if the DPST is able to keep position inside original sector, the extended one allows the shuttle to keep position in a more comfortable way, with reduced thrusters’ power demand,
- in case of drive-off event when operating in extended sector, it is possible to avoid collision with the FPSO by using all the thrusters, main propeller and rudder to aid the escape maneuver, and
- the experienced Captains that participated in the simulations felt comfortable all the time and concluded that operating in this sector would be safely accomplished in real life.

After all the simulations were completed, a field test was carried out to evaluate the implementation of the new sectors in real life. As no adversities took place and the Captain of the tested DPST perceived no safety issues in operating inside the extended sector, the tests were considered successful and it was decided that it was possible to implement the new sector on the whole fleet.

The final operating sector, which was validated through all the simulations and field-testing, is the one shown in Figure 9-1. The new sector presents a “Bow Rotation” zone, in which the DP operation mode is changed from “Normal” to “Bow Rotation” when the shuttle tanker attaints the green sector limits (-50° or +75°) and to a “Heading Restriction” mode when the stern of the shuttle attains grey sector limit (-60° or +85°) as explained in section 5.1.5.

Figure 9-1: Validated operating sector



Source: (PETROBRAS, 2015c)

As a general and final conclusion, this study verified that the extension of the green operating sector can be incorporated into PETROBRAS' offloading procedures without increasing any risks to the safety of people, environment, facilities and company's image and represents good advantages in terms of uptime gain and power demand reduction. The new sector is already in operational in about 12 shuttle tankers in PETROBRAS and positive feedback has been received both by DPST Captains and by Kongsberg specialists.

As a suggestion for future work, it is recommended to perform DP System reliability study together with quantitative risk analysis to determine the expected frequency of collision between shuttle tanker and FPSO. Along with these studies, Finite Element analyses can be performed to determine the exact consequences of collision and check if the severities of the scenarios assessed in PRA sessions are realistic or too conservative.

Another suggested activity is monitoring the DPST fleet to calculate the real offloading downtime and the frequency of use of the extended zone to compare with static analysis results and validate them.

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GLOSSARY

Chain stopper

fitting used to secure the anchor chain, relieving the strain on the windlass (winch), and also for securing the anchor in the housed position.

Christmas tree

assembly of valves, spools, pressure gauges and chokes fitted to the wellhead of a well to control production.

Demurrage

financial penalty that the charterer pays to the ship owner due to the delay of loading/unloading of a shuttle tanker or shipping vessel and the consequent extra use of the vessel from what was agreed by contract

Drive-off

failure event that happens when the DP system erroneously drives the ship out of position – backwards or forwards, the last one increasing the risk of collision

Floating Production Storage and Offloading (FPSO) unit

oil platform that produces the oil extracted from the well (see definition for “production plant”), stores it in cargo tanks inside its hull and performs the offloading (see definition for “offloading”)

Floating Storage and Offloading (FSO) unit

oil platform that stores the oil produced by other platforms and exports it to a ship called shuttle tanker – in an operation called offloading

F(P)SO

term used when referring to FPSO or FSO

Hawser

nautical term for cable or rope used in mooring or towing a ship.

Offloading

operation in which the oil is exported from the FPSO to a shuttle tanker through a system of flexible hoses

Offloading station

located at the bow or stern of the F(P)SO, it is where the hose reel, HPU and hawser winches are installed; Spread Moored F(P)SOs present two offloading stations and Single Point moored F(P)SOs present one offloading station

Preferential station

offloading station in which the shuttle tanker must operate to guarantee that environmental conditions are pushing the vessel away from the F(P)SO

Production plant

group of equipment installed on the topsides of a production platform that treats the oil that comes from the well, separating water, gas and other components from the oil

Production platform

oil platform that is capable of producing the oil that comes from the well through its production plant

Riser

rigid or flexible duct that connects a production platform to a subsea pipeline (that transfers oil to onshore terminals) or flowline (that connects the wells to subsea manifolds)

Riser balcony

fixed structure installed on the side shell of the FPSO, at portside, in which risers are connected

Safety management system

mandatory safety policy for avoiding oil pollution that every ship owner must provide as required by ISM Code (IMO, 2014)

Slop tank

tank into which cargo residues and oily water are pumped.

Suezmax

naval architecture term for the largest ship measurements capable of transiting the Suez Canal in a laden condition.

Telemetry system

automated communication system between shuttle tanker and F(P)SO, which is able to alert both sides in case of malfunction of offloading equipment (valves, pumps, inert gas and others)

Topsides

the upper half of a platform’s structure, above the sea level, on which equipment is installed; this includes the oil production plant (for production units), drilling rig (for drilling units) and the accommodation block; they are often designed as several modules that can be changed out if necessary allowing platforms to be more readily updated with newer technology

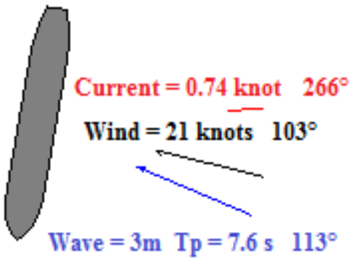
APPENDIX A – RESULTS OF REAL TIME SIMULATIONS

This appendix presents the details of the real-time simulations described in section 7.

A.1. Case 1

The first case was a connection with the FPSO under environmental conditions from Santos Basin. Wave, Wind and current coming from SSE with moderate to high intensity (see Figure A-1).

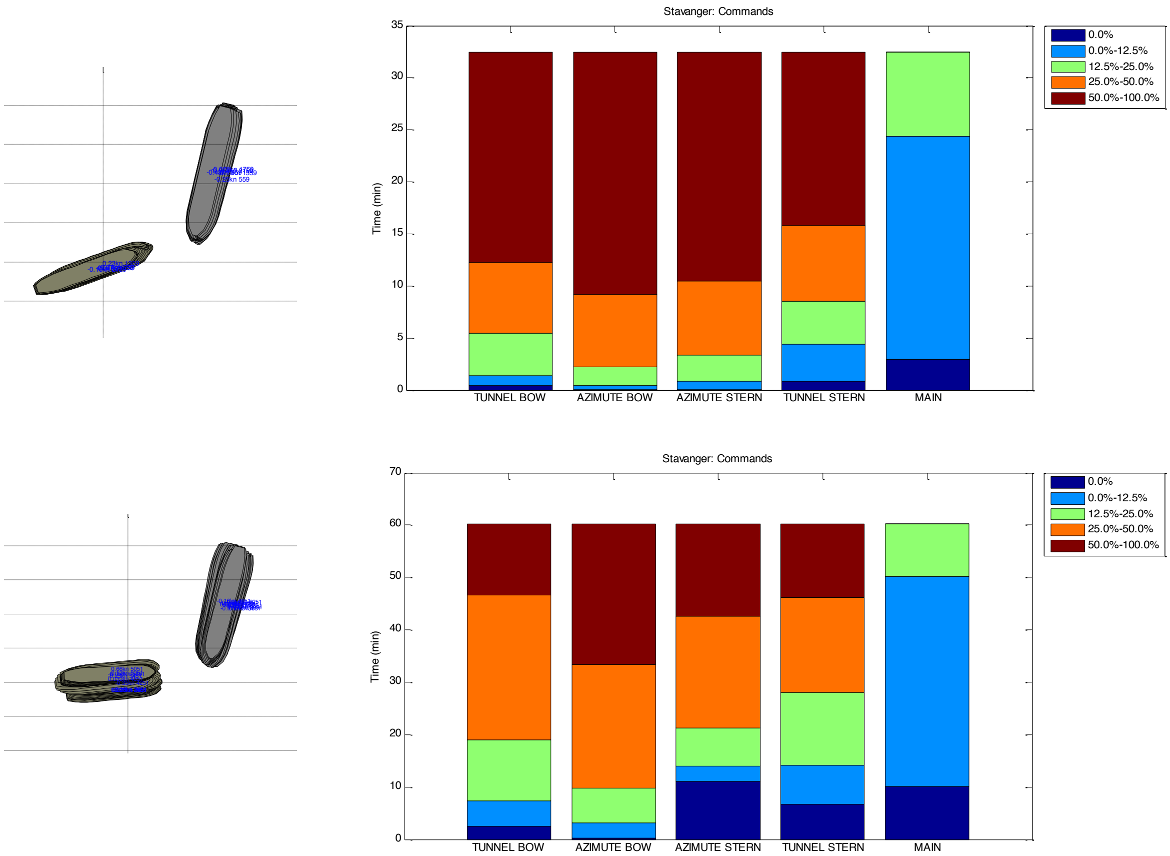
Figure A-1: Case 1 – Environmental conditions



Source: (TPN, 2015)

This simulation started with a shuttle tanker heading of 6 degrees in relation to the FPSO. It was noticed the difficulty to keep position with this heading, so the shuttle was then brought to the limit of original green sector 70 degrees (60 degrees in relation to the FPSO). At this point, the shuttle was able to keep position, but the thrusters were too much demanded, which according to the Captains was not recommended because of equipment's heat-up. The heading was adjusted again, now to the extended sector limit 80 degrees (70 degrees in relation to the FPSO) and it was possible to see that thrusters demand was reduced as expected. Figure A-2: shows the comparison of power histograms for both headings (70 and 80 degrees).

Figure A-2: Case 1 – Power demand comparison between operation in original (top) and extended (down) sectors



Source: (TPN, 2015)

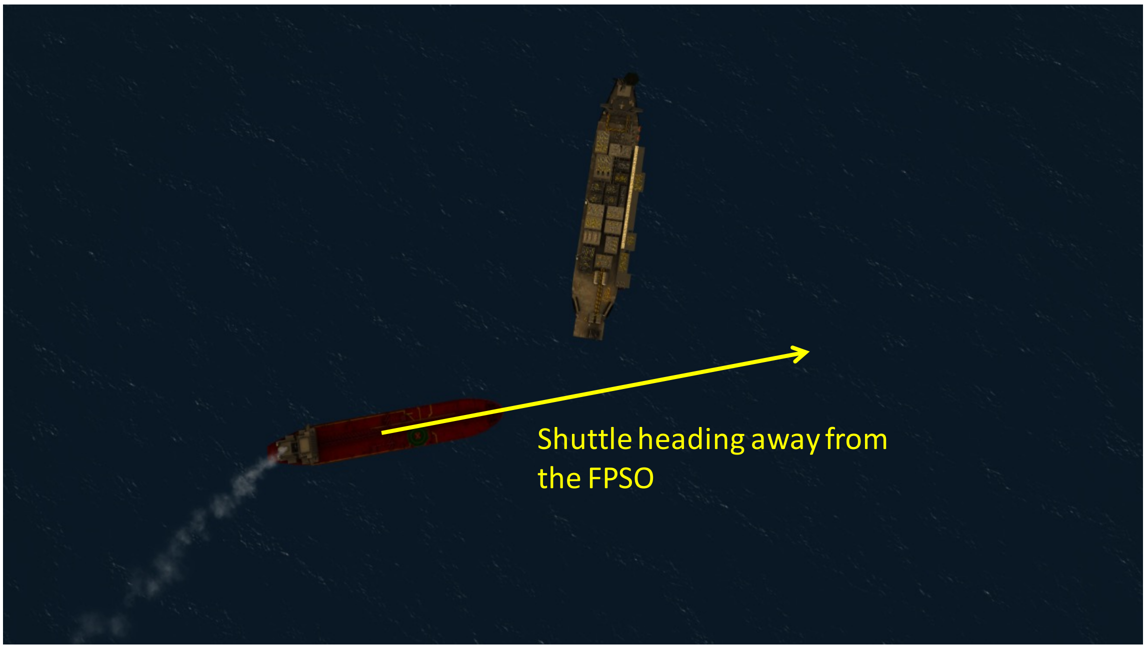
Drive-off was then simulated as if the pitch of the main propeller had locked on full thrust ahead position. The Captains performed the escape maneuver as if all the other thrusters were unavailable to aid, so only the rudder was used. The Captains wanted to try this way because it is possible that together with drive-off the thrusters will become unavailable. As it can be seen in Figure A-3, this maneuver was not successful because the two vessels collided.

Figure A-3: Case 1 – Drive-off escape using rudder only.

Source: (TPN, 2015)

At this point, the Captains highlighted that it is safer that the shuttle's bow never points towards the offloading station as usually done so it is easier to avoid collision in case of drive-off, as shown in Figure A-4.

Figure A-4: Heading suggestion during offloading in order to avoid collision in case of drive-off.

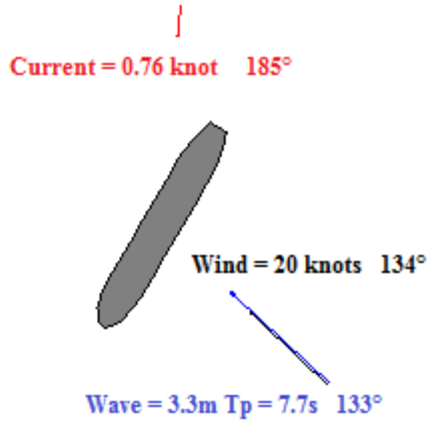


Source: (TPN, 2015)

A.2. Case 2

The second case was a connection with the FPSO under environmental conditions from Campos Basin, after the arrival of a cold front. The current runs to South and wave and wind, after turning because of the cold front, stabilize coming from Southeast (see Figure A-5). This is another situation favorable to the extended sector.

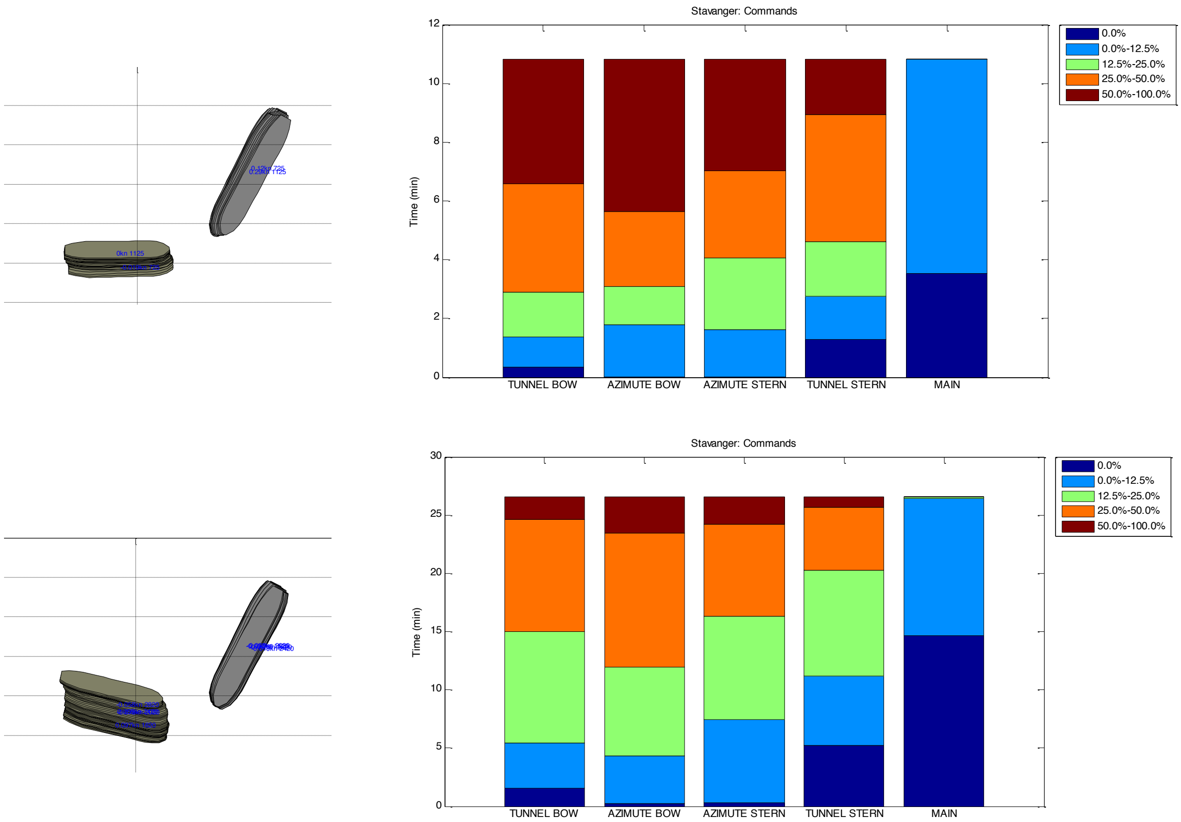
Figure A-5: Case 2 – Environmental conditions



Source: (TPN, 2015)

This simulation started with a shuttle tanker heading of 10 degrees in relation to the FPSO. It was noticed the difficulty to keep position with this heading, so the shuttle was then brought to the limit of original green sector 90 degrees (60 degrees in relation to the FPSO). At this point, the shuttle was able to keep position and power demand on the thrusters was reduced. The heading was adjusted again, now to the extended sector limit 100 degrees (70 degrees in relation to the FPSO) and it was possible to see that thrusters demand was reduced even more. Figure A-6 shows the comparison of power histograms for both headings (90 and 100 degrees).

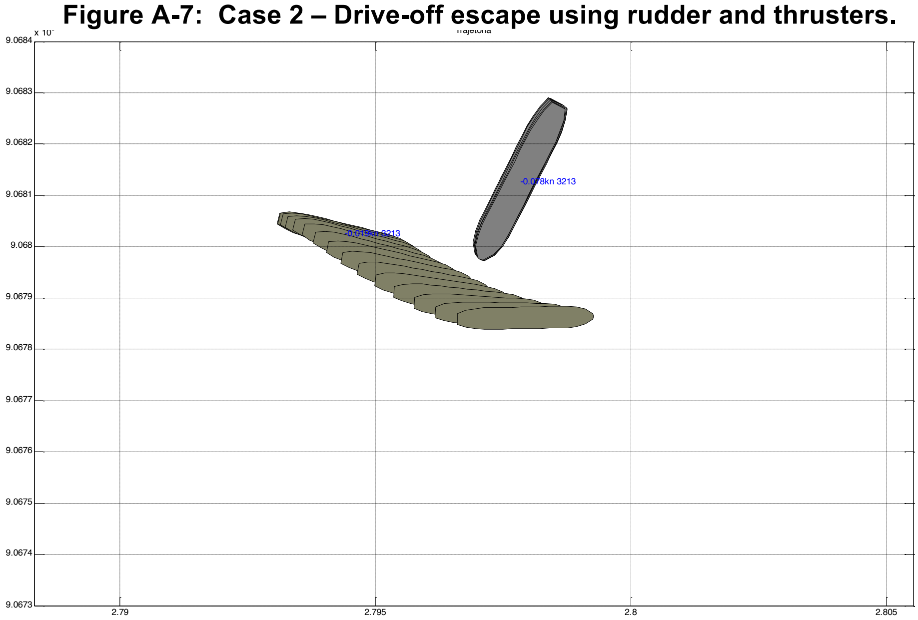
Figure A-6: Case 2 – Power demand comparison between operation in original (top) and extended (down) sectors



Source: (TPN, 2015)

Drive-off was then simulated as if the pitch of the main propeller had locked on full thrust ahead position. The escape maneuver was performed this time considering all thrusters available to work together with the rudder to avoid collision. As it can be seen in Figure A-7, this was a successful maneuver.

Figure A-7: Case 2 – Drive-off escape using rudder and thrusters.

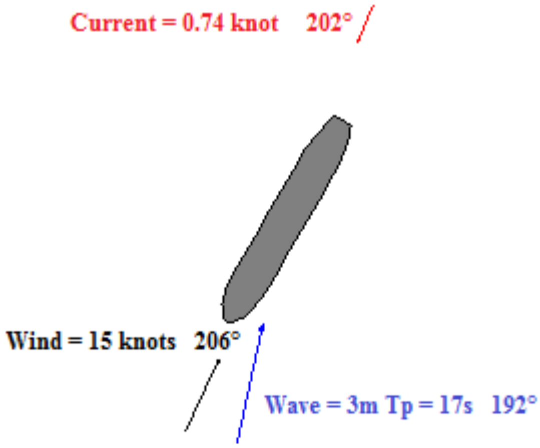


Source: (TPN, 2015)

A.3. Case 3

The third case was a connection with the FPSO under environmental conditions from Campos Basin, also associated to the arrival of a cold front. The current runs to Southwest, and wave and Wind come from South-Southwest (see Figure A-8). The Captains observed that it would be not recommended to perform offloading in these conditions since the typical period of the waves is well beyond contractual limits, which is 9s. Too long waves may cause extreme pitch motions and hawser consequent whips and stress. Moreover, these conditions tend to push the shuttle towards the FPSO, increasing the risk of collision in case of blackout. Although it was a typical case were the offloading by the Stern would me much more recommended (regardless of the period problem), the simulation was performed anyway for analysis.

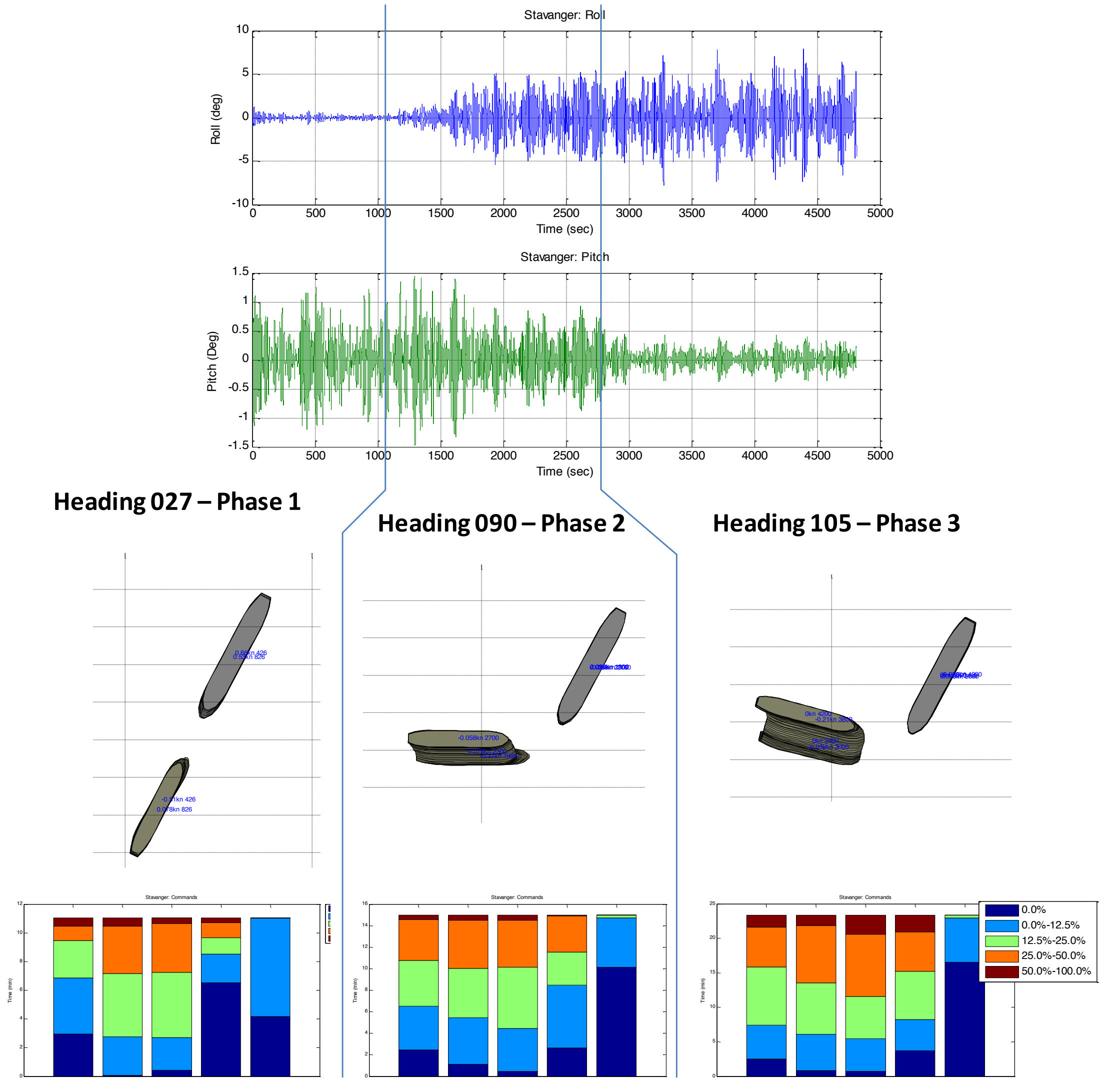
Figure A-8: Case 3 – Environmental conditions



Source: (TPN, 2015)

This simulation began with a shuttle tanker heading of 27 degrees (-3 degrees in relation to the FPSO). It was noticed that the power demand was not very high, and the vessel could easily keep position although it was being pushed towards the FPSO. The pitch motion however was accentuated, going up to ±1,2°. Next, the shuttle was brought to the limit of original green sector 90 degrees (60 degrees in relation to the FPSO). The pitch motions were reduced to ±0,8°, but the roll increased from almost zero to ±5,0°. When the heading was adjusted again, now to the extended sector limit 105 degrees (75 degrees in relation to the FPSO), it was possible to see that roll response increased even more to ±7,0°, which is actually expected because in this situation the vessel is submitted to beam sea. Figure A-9 shows the comparison of power histograms and motions for the three tested headings (27, 90 and 105 degrees). The conclusion is that for this environmental condition, the extended green sector brings no advantages.

Figure A-9: Case 3 – Power demand and motions comparison between operation in original and extended sectors



[Order of thrusters in the histograms from left to right: Tunnel Bow, Azimuth Bow, Azimuth Stern, Tunnel Stern, Main propeller]

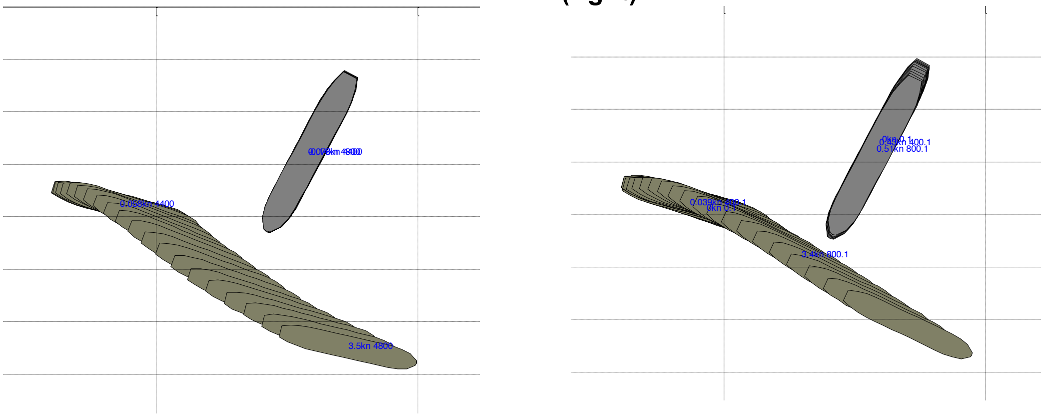
Source: (TPN, 2015)

Drive-off was then simulated and the escape maneuver was performed considering all thrusters available to work together with the rudder to avoid collision. The maneuver was successful, and the results can be seen on Figure A-10 on the next section.

A.4. Case 4

This case was just a repetition of the drive-off scenario of Case 3, but this time the escape maneuver was performed using the rudder only. As it can be seen on Figure A-10, the maneuver was also successful, although the shuttle went by closer to the FPSO than in Case 3.

Figure A-10: Case 3 and 4 – Drive-off escape using rudder and thrusters (left) and rudder only (right).

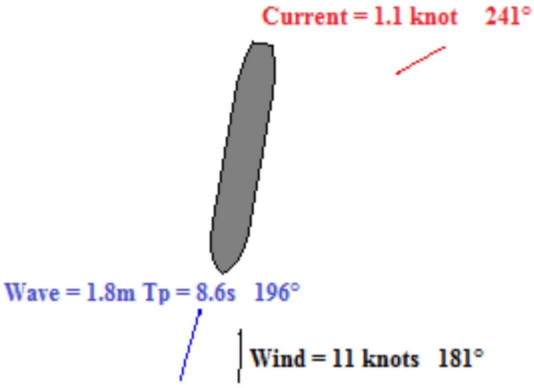


Source: (TPN, 2015)

A.5. Case 5

This represents environmental conditions from Santos Basin, after the arrival of a cold front. The current runs to Southwest and wave and wind, after turning because of the cold front, stabilize coming from South-Southeast (see Figure A-11). This situation was shown favorable to the extended sector.

Figure A-11: Case 5 – Environmental conditions

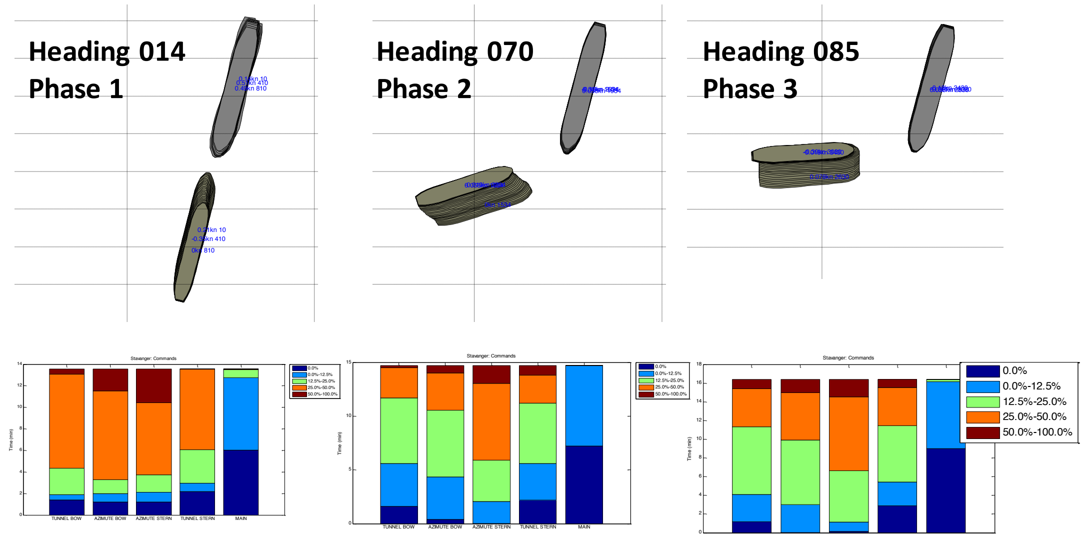


Source: (TPN, 2015)

This simulation began with a shuttle tanker heading of 14 degrees (4 degrees in relation to the FPSO). It was noticed that the power demand was not very high, and the vessel could easily keep position although it was being pushed towards the FPSO. Next, the shuttle was brought to the limit of original green sector 70 degrees (60 degrees in relation to the FPSO), showing that the power demand was reduced. When the heading was adjusted again, now to the extended sector limit 85 degrees (75 degrees in relation to the FPSO), it was possible to see that power demand decreased a little more. Figure A-12 shows the comparison of power histograms for the three tested headings (14, 70 and 85 degrees).

Unlike Case 3 simulations, the pitch and roll motions did not come up as a problem, because Hs and Tp are not as high as in case 3. In this case, roll motions did not go over ±1.5 degrees and pitch did not go over ±0.5.

Figure A-12: Case 5 – Power demand comparison between operation in original and extended sectors



[Order of thrusters in the histograms from left to right: Tunnel Bow, Azimuth Bow, Azimuth Stern, Tunnel Stern, Main propeller]

Source: (TPN, 2015)

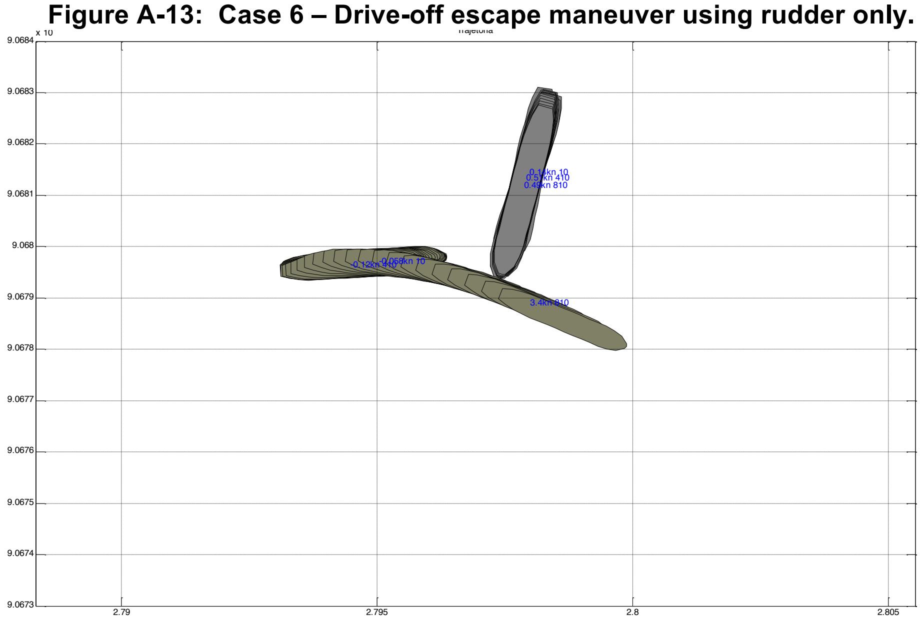
When simulating drive-off in this case, the Captains tried a different type of maneuver, this time using the azimuth thrusters backwards and the tunnel thrusters to starboard. As they saw this was not going to work, they put the azimuth thrusters also to starboard and the vessel could escape safely from collision.

A.6. Case 6

This case was just a repetition of the drive-off scenario of Case 5, but this time the escape maneuver was performed using the rudder only. As it can be seen on Figure A-13, it was a very risky maneuver, because the shuttle came too close to the FPSO although they did not collide. Again the Captains highlighted the importance of this simulation, because not only the thrusters can become unavailable during drive-off, but also other vessels, different from Stavanger, might have less azimuth thrusters and thus less escape capability.

Once more, the recommendation of never pointing the shuttle's bow to the offloading station was made, and the recommendation of always using all thrusters to escape from collision.

Figure A-13: Case 6 – Drive-off escape maneuver using rudder only.

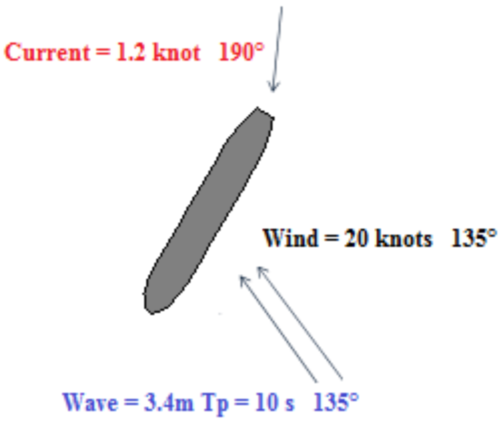


Source: (TPN, 2015)

A.7. Case 7

The seventh case was a connection with the FPSO under environmental conditions from Campos Basin, also associated to the arrival of a cold front. The current runs to South, and wave and Wind come from Southwest (see Figure A-14).

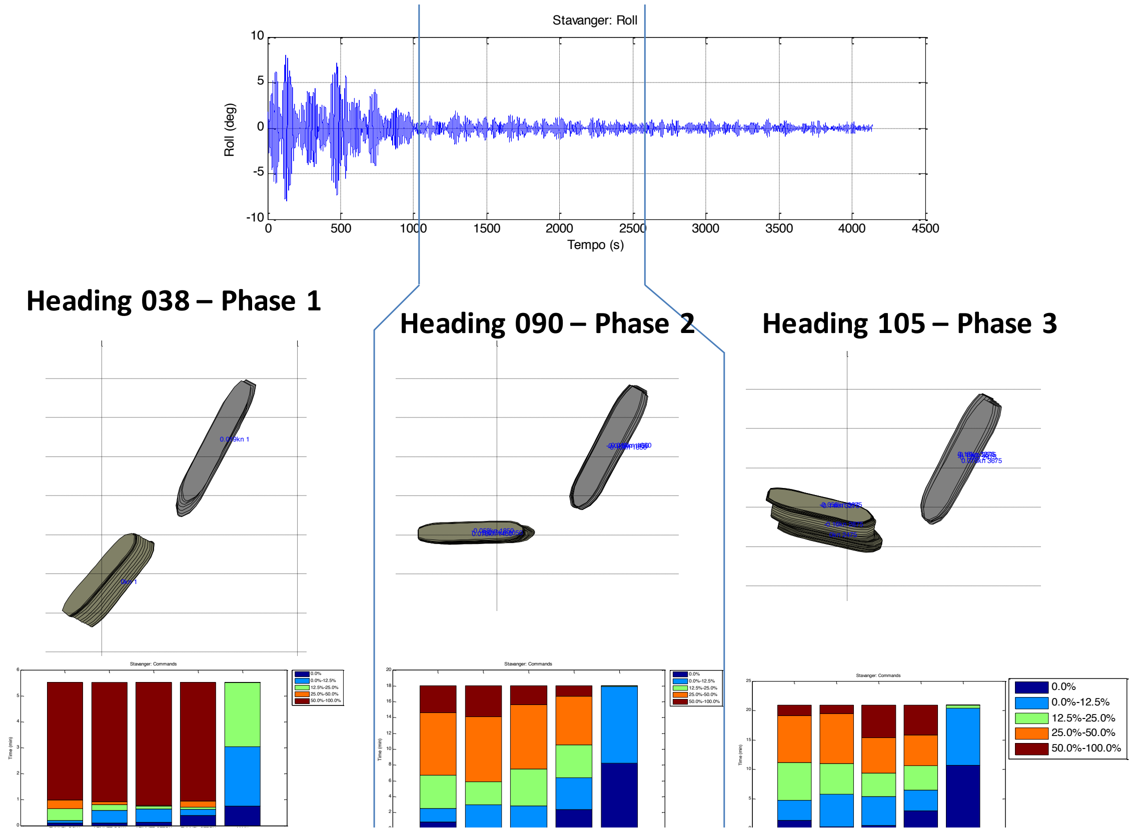
Figure A-14: Case 7 – Environmental conditions



Source: (TPN, 2015)

This simulation began with a shuttle tanker heading of 38 degrees (8 degrees in relation to the FPSO). It was noticed that the power demand was very high, and the roll motions as well. Next, the shuttle was brought to the limit of original green sector 90 degrees (60 degrees in relation to the FPSO) and the roll motions as well as the power demand were greatly decreased. When the heading was adjusted again, now to the extended sector limit 105 degrees (75 degrees in relation to the FPSO), it was possible to see that roll response continued low as expected and that power demand decreased a little more. Figure A-15 shows the comparison of power histograms and motions for the three tested headings (38, 90 and 105 degrees). The conclusion is that for this environmental condition, the extended green sector brings power reduction advantage.

Figure A-15: Case 7 – Power demand and motions comparison between operation in original and extended sectors



[Order of thrusters in the histograms from left to right: Tunnel Bow, Azimuth Bow, Azimuth Stern, Tunnel Stern, Main propeller]

Source: (TPN, 2015)

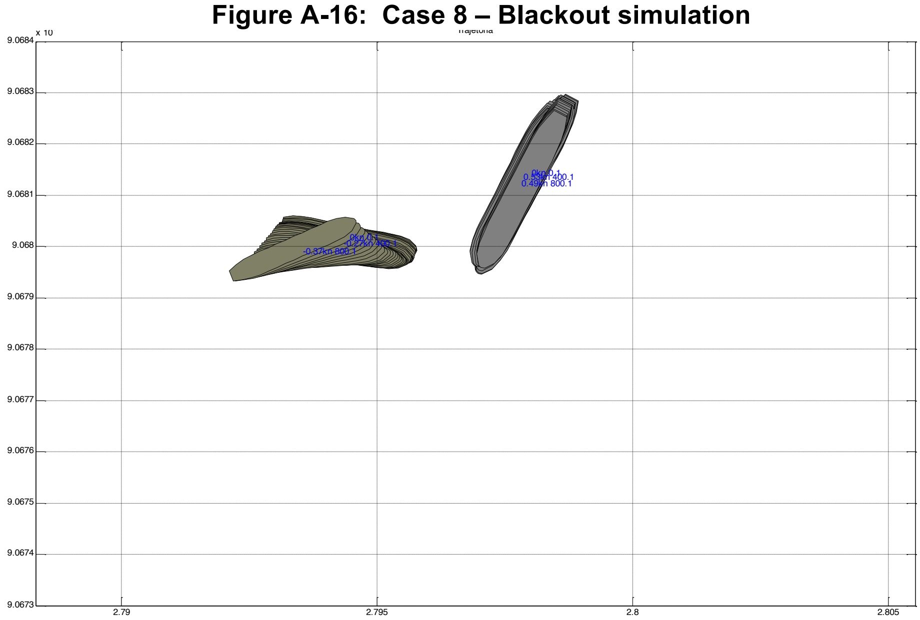
Drive-off was then simulated and the escape maneuver was performed considering all thrusters available to work together with the rudder to avoid collision.

The maneuver was successful, and the results are similar to Case 3, shown in Figure A-10.

A.8. Case 8

This case was requested by the Captains to check, under the same environmental conditions from Case 7, what it would happen in case of a blackout event if the ship was on the extended sector limit. Thus, all the thrusters were disabled at some point, and as expected, the vessel started to distance from the FPSO, giving no risk of collision (see Figure A-16).

Figure A-16: Case 8 – Blackout simulation

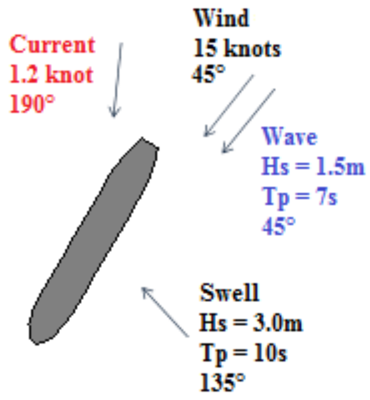


Source: (TPN, 2015)

A.9. Case 9

This case corresponds to the arrival of a swell coming from SE associated to typical environmental conditions from Campos Basin (Current to S, wave and Wind from NE) during connection with the FPSO. See Figure A-17.

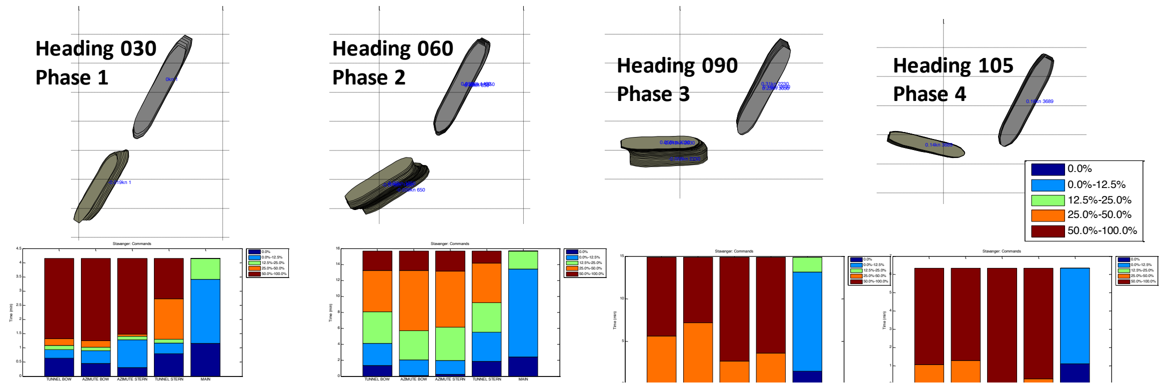
Figure A-17: Case 9 – Environmental conditions



Source: (TPN, 2015)

This simulation began with a shuttle tanker heading of 30 degrees (0 degree in relation to the FPSO). It was noticed that the power demand was very high and the vessel was not able to keep position. Next, the shuttle was brought to 60 degrees (30 degrees in relation to the FPSO), the power demand decreased and the shuttle position was stabilized. Then it was brought to the limit of original green sector, 90 degrees (60 degrees in relation to the FPSO), and then again to the extended sector limit, 105 degrees (75 degrees in relation to the FPSO). It was possible to see that power demand increased repeatedly for both limits. Figure A-18 shows the comparison of power histograms for the four tested headings (30, 60, 90 and 105 degrees). The conclusion is that for this environmental condition, the extended green sector brings no advantage.

Figure A-18: Case 9 – Power demand comparison between operation in original and extended sectors



[Order of thrusters in the histograms from left to right: Tunnel Bow, Azimuth Bow, Azimuth Stern, Tunnel Stern, Main propeller]

Source: (TPN, 2015)

Drive-off was then simulated and the escape maneuver was performed considering the use of the rudder only, because, according to the Captains, as the environmental conditions would push the ship towards starboard, i.e. far from the FPSO, the risk of collision would be lower and that proved to be true during the successful maneuver. Figure A-19 shows the screens of the simulator during drive-off simulation.

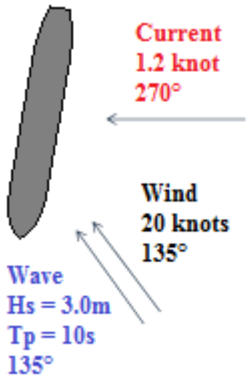
Figure A-19: Case 9 – Drive-off simulation – bridge view

Source: (TPN, 2015)

A.10.Case 10

This case corresponds to the approach towards the FPSO under typical Santos Basin conditions (Current to W, wave and Wind from SE). See Figure A-20.

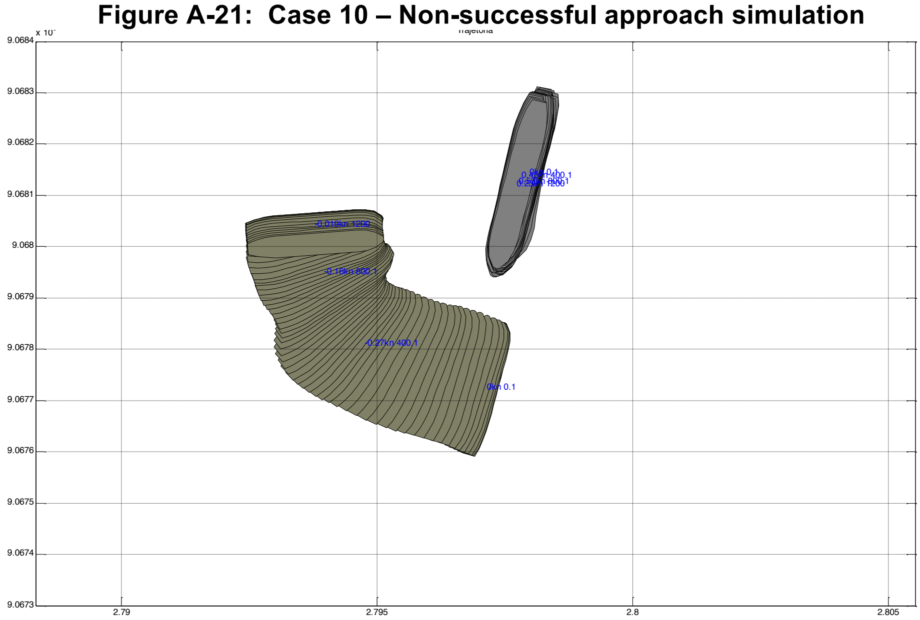
Figure A-20: Case 10 – Environmental conditions



Source: (TPN, 2015)

This simulation started with a shuttle tanker approaching with a heading of 17 degrees (7 degrees in relation to the FPSO). It was noticed that the power demand was very high and the vessel was not able to keep position. The Captains were then forced to position the shuttle to the extended sector limit (heading 85 degrees - 75 degrees in relation to the FPSO), because even in original limit (heading 70 degrees - 60 degrees in relation to the FPSO) the tanker could not keep position. Even for this heading, the shuttle continued to drift off and the simulation was aborted. Figure A-21 shows the trail of the ship’s drift-off.

Figure A-21: Case 10 – Non-successful approach simulation



Source: (TPN, 2015)

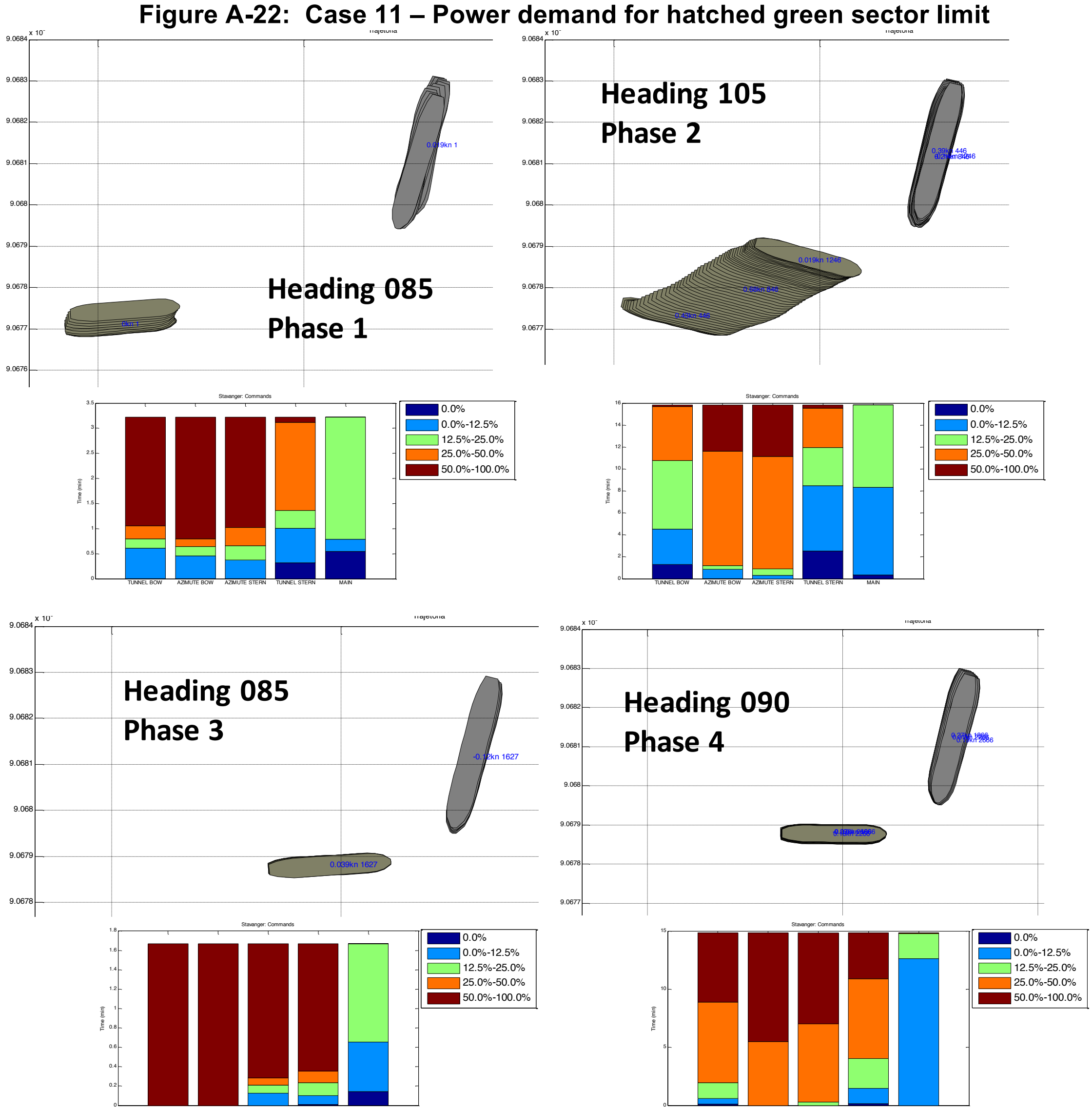
The Captains highlighted that for this environmental condition the shuttle should not approach with heading 17 degrees (7 degrees in relation to the FPSO) but already headed to the East. The problem in this simulation was that when the weather started drifting the ship away from initial position, it gained too much inertia and when he was finally positioned on the most favorable heading, it still was not able to keep position. Case 11 was further done to repeat the approach, now with the recommended heading.

A.11.Case 11

This case is a repetition from Case 10, but this time approaching with the recommended heading of 85 degrees (75 degrees in relation to the FPSO), which is the extended sector limit. The approach is performed with the DP system, because according to the Captains the distance from the FPSO already allowed that.

Due to environmental conditions, the power demand on the thrusters was very high and the Captains decided to change the heading to 105 degrees (95 degrees in relation to the FPSO), which is on the red sector. Although this would not be permitted in real life, the Captains decided to do that only for analyzing the ship's behavior. At this heading, the shuttle approached the FPSO safely. When it got to the operation distance of 150m, the heading was adjusted to 85 degrees (75 degrees in relation to the FPSO - extended green sector limit) but it was possible to see the power consumption increased too much. Thus, the heading was adjusted again to 90 degrees (80 degrees in relation to the FPSO - hatched green sector limit) and in this position the thrusters demand dropped into an acceptable level. Figure A-22 shows the power demand comparison on these four phases.

Figure A-22: Case 11 – Power demand for hatched green sector limit



[Order of thrusters in the histograms from left to right: Tunnel Bow, Azimuth Bow, Azimuth Stern, Tunnel Stern, Main propeller]

Source: (TPN, 2015)

Drive-off was then simulated and the escape maneuver was performed considering the use of all thrusters and rudder (

Figure A-23). This was necessary because the wave and wind coming from SE push the shuttle against the platform, increasing the risk of collision. The escape maneuver was successful and the shuttle went by the FPSO at a 44m distance.

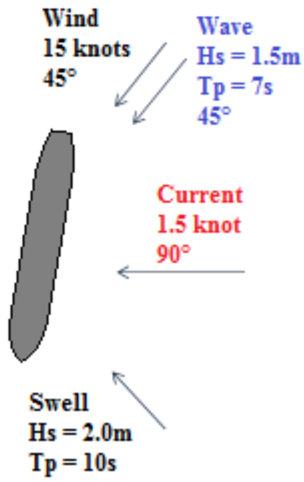
Figure A-23: Case 11 – Drive off escape simulation

Source: (TPN, 2015)

A.12.Case 12

This case corresponds to the arrival of a swell coming from SW associated to typical environmental conditions from Santos Basin (Current to W, wave and Wind from NE) during connection with the FPSO. See Figure A-24.

Figure A-24: Case 12 – Environmental conditions

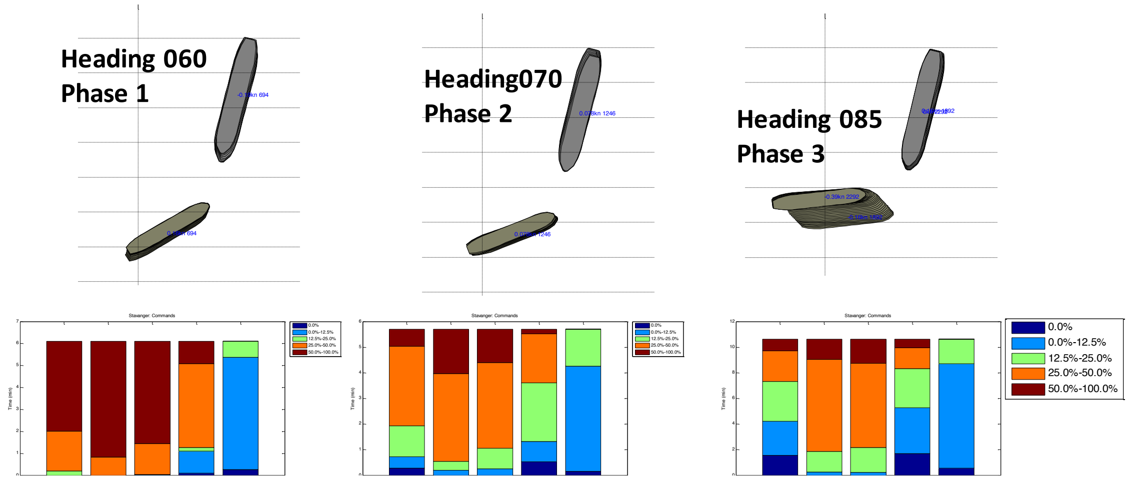


Source: (TPN, 2015)

This simulation started with the shuttle tanker fully loaded with a heading of 60 degrees (50 degrees in relation to the FPSO). It was noticed that the power demand was very high although the vessel was able to keep position. Next, the shuttle was brought to the limit of original green sector, 60 degrees (60 degrees in relation to the FPSO), and then again to the extended sector limit, 85 degrees (75 degrees in relation to the FPSO). It was possible to see that power demand decreased repeatedly for both limits.

Figure A-25 shows the comparison of power histograms for the three tested headings (60, 70 and 85 degrees). The conclusion is that for this environmental condition, the extended green sector presents good advantage for power consumption.

Figure A-25: Case 12 – Power demand comparison between operation in original and extended sectors



[Order of thrusters in the histograms from left to right: Tunnel Bow, Azimuth Bow, Azimuth Stern, Tunnel Stern, Main propeller]

Source: (TPN, 2015)

Drive-off was then simulated and the escape maneuver was performed considering the use of the rudder only because the conditions tend to push the shuttle away from FPSO. The maneuver showed to be effective to escape from collision.