

ANALYSIS OF OFFSHORE TRANSPORTATION LOGISTICS BY DISCRETE-EVENT SIMULATION

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Dissertação apresentada ao Programa de Pós-graduação em Engenharia Oceânica, COPPE, da Universidade Federal do Rio de Janeiro, como parte dos requisitos necessários à obtenção do título de Mestre em Engenharia Oceânica.

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Rio de Janeiro Setembro de 2017

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DISSERTAÇÃO SUBMETIDA AO CORPO DOCENTE DO INSTITUTO ALBERTO LUIZ COIMBRA DE PÓS-GRADUAÇÃO E PESQUISA DE ENGENHARIA (COPPE) DA UNIVERSIDADE FEDERAL DO RIO DE JANEIRO COMO PARTE DOS REQUISITOS NECESSÁRIOS PARA A OBTENÇÃO DO GRAU DE MESTRE EM CIÊNCIAS EM ENGENHARIA OCEÂNICA.

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RIO DE JANEIRO, RJ - BRASIL SETEMBRO DE 2017

Silva, Rafael Basílio da Analysis of Offshore Transportation Logistics by Discrete-Event Simulation / Rafael Basílio da Silva. -Rio de Janeiro: UFRJ/COPPE, 2017. XV, 91 p.: il.; 29,7 cm. Orientador: Jean-David Job Emmanuel Marie Caprace Dissertação (mestrado) --UFRJ/ COPPE/ Programa de Engenharia Oceânica, 2017. Referências Bibliográficas: p. 90-91. 1. Offshore Supply Chain 2. Offshore Supply Vessel. 3. Discrete-Event Simulation. 4. Vessel Sizing. 5. Simulation Model. I. Caprace, Jean-David Job Emmanuel Marie. II. Universidade Federal do Rio de janeiro, COPPE, Programa de Engenharia Oceânica. III. Título.

"I am wiser than this man, for neither of us appears to know anything great and good; but he fancies he knows something, although he knows nothing; whereas I, as I do not know anything, so I do not fancy I do. In this trifling particular, then, I appear to be wiser than he, because I do not fancy I know what I do not know."

Socrates

ACKNOWLEDGMENTS

To my mother and my wife, for their wholeheartedly support and love dedicated to me.

To my uncles, especially Uncle Félix, for their incentive to get ahead in life and the knowledge handed over to me.

To my parents-in-law, Esperança and Geraldo, for their support with household chores and comprehension whenever I needed to dedicate to my thesis.

I would also like to thank specially my thesis advisor PhD Jean-David Caprace. The door of Prof. Jean-David office has been always open whenever I ran into a trouble spot or had a question about my research or writing. He consistently allowed this paper to be my own work, but steered me in the right the direction whenever he thought I needed it.

To the examination board for taking part in this evaluation and UFRJ/COPPE for the structure provided and the excellent academic staff.

To all the colleagues from Petrobras who helped me to understand a little about offshore logistics, especially to (in alphabetical order): Estêvão Teodoro, Marcio Stiel, Marcos Camelo and Saulo Pimenta.

Lastly, I would like to thank to Petrobras for this opportunity.

Resumo da Dissertação apresentada à COPPE/UFRJ como parte dos requisitos necessários para a obtenção do grau de Mestre em Ciências (M.Sc.).

ANÁLISE DA LOGÍSTICA DE TRANSPORTE OFFSHORE POR MEIO DE SIMULAÇÃO POR EVENTOS DISCRETOS

Rafael Basílio da Silva

Setembro/2017

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Programa: Engenharia Oceânica

A logística desempenha um papel fundamental na indústria de petróleo e gás, uma vez que grandes distâncias entre unidades offshore e bases terrestres demandam uma eficiente cadeia de suprimento. Neste cenário, as empresas de pétroleo utilizam uma enorme infra-estrutura para atender, manter e desenvolver operações de unidades offshore, composta por aeroportos, portos, hubs, armazéns, navios especializados, entre outros recursos. As condições meteorológicas, as taxas de inoperância da frota e o tempo de espera das embarcações para operar com a unidade offshore são as variáveis mais sensíveis que afetam as operações de fornecimento offshore. Neste contexto, o presente trabalho tem como finalidade encontrar a quantidade ideal de embarcações supridoras necessárias para que a logística de transporte offshore de cargas possa cumprir sua função sem prejudicar o nível de serviço demandado. Neste estudo, a perspectiva de custos de recursos será incorporada para fins de análise. Abstract of Dissertation presented to COPPE/UFRJ as a partial fulfillment of the requirements for the degree of Master of Science (M.Sc.)

ANALYSIS OF OFFSHORE TRANSPORTATION LOGISTICS BY DISCRETE-EVENT SIMULATION

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September/2017

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Logistics plays a fundamental role in the petroleum and oil industry, since large distances between offshore units and its onshore supply base demand an efficient supply chain. In this scenario, oil companies use huge infrastructure to service, maintain and develop operations of offshore units, composed by airports, ports, hubs, warehouses, specialized vessels, among other resources. Weather conditions, vessels off-hire rates and vessel waiting time to operate offshore units are the more sensitive variables that affect offshore supply operations. In this context, the present work aims to find the ideal amount of supply vessels necessary for the logistics of offshore cargo transportation to fulfill its function without affecting the service level demanded. In this study, resource cost perspective will be incorporated for analysis purposes.

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List of Abbreviations

AHTS - Anchor Handling Tug Supply Vessel

WOW - Waiting-on-Weather Time

WOP - Wait-on-Platform Time

PSV - Platform Supply Vessels

PETROBRAS – Petróleo Brasileiro S.A.

UMS - Unit for Maintenance and Safety

UT – Utility Vessel

OSRV - Oil Spill Recovery Vessel

P – Passenger Vessel

LH – Line Handling Vessel

SL – Service Level

WOCP - Waiting-on-Cargo-Programming Time

WOPC - Waiting-on-Port-Calling Time

PLAT - Oil Platform Cluster

SOND - Drill Rig Cluster

ESP – Special Unit Cluster

AIS - Automatic Identification System

NQ – Number in Queue

NR - Number of Busy Resource Units

1. INTRODUCTION

1.1 PURPOSE

This study aims at presenting a simulation-based model of logistics operations to support offshore units focusing mainly on setting up the number of supply vessels required to perform a suitable level of service with a minimum cost.

More specifically, the present study focuses on simulating the offshore transportation of general deck cargo from the Port of Macae to offshore units in Campos Basin (loading logistics), considered to be one of the Brazil's most important oil province.

For the purpose of the simulation, the model is using data related to vessel and offshore operation performance, waiting queue distribution and number of liftings as well as the cargo-associated area.

Subsequently, the behavior of the queue of vessels waiting for operations in the anchoring area and the queue of cargoes waiting for vessels will be analyzed.

1.2 MOTIVATION

Through the building of a model that correctly represents the offshore logistics of cargo transportation, this study allows a real understanding of the current system of operations between offshore support vessels and Campos Basin offshore units.

The present study focused on general cargo transportation operations carried out by supply vessels departing from the Port of Macae towards the Campos Basin offshore units. The historical data collected covers the period from April 2016 to March 2017. From April 2017 until September 2017, cargo offshore transportation operations to service the Campos Basin have been gradually migrated to the Port of Açu. During this period, the Port of Açu carried out part of the cargo transportation operations to service the Campos Basin so that sufficient historical records (cycle time, anchoring area waiting time, lifting time, among others) have not been consolidated to build an appropriate simulation model comprising operations carried out at this port. On the other hand, due to its longevity as an offshore base for general cargo operations in the Campos Basin, the Port of Macae has a vast mass of historical data sufficing for a coherent and reliable statistical analysis supporting the creation of a robust model. Thus, for the proposed simulation model, the Port of Macae has been chosen as the port of departure for the cargo servicing Campos Basin offshore units.

Moreover, the study aims at (BATISTA, 2005):

1. Modeling, verification and validation of the current system; and

2. Implementing changes in the model by studying the influences in its behavior and extracting statistics that will support the decision-making.

To achieve the results, the following procedures have been adopted:

1. Analysis of the current system;

2. Data collection, system modeling, verification and validation; and

3. Experimentation and analysis.

1.3 METHODOLOGY

There have been few cases where Brazilian oil companies use computer-based tools for the purposes of simulating and optimizing its offshore supply chain. Resizing the logistics system by using such type of tool would represent a huge opportunity to reduce resources deployed without downgrading the service level needed to design an efficient supply chain.

According to KELTON *et al* (2002), "*computer simulation refers to methods for study a wide variety of models of real-word systems by numerical evaluation using software designed to imitate the system's operations or characteristics, often over time*". Thus, the purpose of the simulation is to design and create a computerized model to represent a real or proposed system so that it will give to the user a better understanding of the behavior of system analyzed.

The simulation can be continuous or discrete. In a continuous mode, the state of system can change continuously over time; for instance, level of a reservoir and fuel flow. On the other hand, in a discrete mode, change can occur only at separated points in time such as a manufacturing system and warehouse process, where entities will arrive and leave at specific times and machine breakdowns will take place at specific times (KELTON, 2002).

For this present study, the simulation will be performed by discrete-events using the software Arena© Simulation v.14. The model includes transporters, resources, entities, processes, holding, transporting, assigning and deciding modules.

1.4 PROBLEM DEFINITION

The study will focus on operations performed in Macae, northern state of Rio de Janeiro in Brazil, which is the main base used to service offshore units located in the Campos Basin. Therefore, the simulation performed in this study will set to analyze cargo transportation undertaken by offshore supply vessels. Thus, personal transportation will not be analyzed in this study. The process involving return cargo from offshore units will not be either considered in this present study. The model will be built considering only the transportation of general deck cargoes, leaving aside the transportation of diesel oil, water, dry and wet bulk. Moreover, the study will focus on departures scheduled and hence the transportation destined to fulfill extra or urgent demands will not be modelled.

Since April 2017, the Port of Açu has become the main base from which general deck cargoes, diesel oil and water will be transport to service offshore units of Campos and Espírito Santo Basins. On the other hand, the Port of Macae has been since then focusing its operation on servicing specialized vessels, i.e., anchoring handling supply, diving support, oil recovery supply, line handling and pipe laying supply vessels. Thus, the model considered the vessel-departure schedule and cluster configuration of platforms carried out on March 2017 to represent the departure of vessels that serviced Campos Basin offshore units. In addition, the data related to offshore cargo transportation have been collected for a period covering one year, from April 2016 to March 2017.

The model considers the following data:

- Scheduling of vessel departures;
- Number of vessels used per each category;
- Cargo-lifting distribution per each offshore unit,
- Vessel speed distribution;

- Distance matrix between the Port of Macae and each cluster of offshore units;
- Distribution of traveling time among units;
- Average deck area per lifting;
- Port and offshore single lifting time;
- Probability of waiting and waiting time distribution for operations at each platform;
- Vessel downtime indicator;
- Vessel repairing time distribution under downtime condition;
- Programmable deck area for each type of vessel; and
- Cluster configuration of offshore units.

1.5 THESIS' CONTENT

The study has been divided into 6 chapters:

Chapter 1 begins by presenting purpose, motivation, methodology, and thesis' content. In this context, assumptions, data to be collected and a general description of the problem are also presented.

Chapter 2 presents the literature review, which contains a historical research regarding the publications on the area of offshore logistics as well as studies that analyzed the problem of resource allocation through the support of discrete-event simulation tools.

Chapter 3 presents a description of the current logistics system deployed to service Campos Basin offshore units. This chapter presents also the general description of data related to oil output, location and quantity of offshore units distributed across the Campos Basin. The material and cargo flow performed through the offshore supply chain is also shown as well as the operations carried out in warehouses, consolidation areas, onshore transportation management and ports. Particularly, this chapter describes in detail the current system of offshore support vessel operations in Campos Basin, the characteristics of such vessels and cargo demands from offshore units. Chapter 4 describes in detail the simulation model developed to analyze the problem. In this chapter, the model built is validated through a set of parameters collected from real operations.

Chapter 5 presents the results of the simulation and its practical application regarding the fleet sizing. The study indicates the ideal number of vessels of each type that should be deployed to reach a minimum cost without affecting the service level provided.

Chapter 6 provides the conclusion of the study and presents proposals of improvements regarding the simulation of the offshore supply chain.

2. LITERATURE REVIEW

The offshore logistics system represents a considerable cost for oil and natural gas production so that oil companies has focused more and more on optimizing their upstream logistics (AAS *et al*, 2010). Based on this context, oil companies aim at increasing its logistics offshore system efficiency by reducing the amount of resources used and optimizing processes without compromising the service level for fulfilment of offshore units.

Thus, oil companies measure and monitor its logistics offshore efficiency through a series of indicators, which provides, among other data, the level of fulfilment performed.

In this case, "fulfilment" means to deliver cargoes to offshore units and the deadline to perform the fulfilment is the later date defined by the cargo transport document.

The efficiency of cargo delivering has been affected mainly by weather conditions and the need to wait to operate at an offshore unit. Both influences are measured by the average time in hours, during which each supply vessel has been waiting to operate with an offshore unit due to adverse weather condition or to the fact that such unit is not ready to receive the cargo.

The vessel downtime has also affected the offshore logistics performance, as the supply vessel is a limited and costly resource whose immediate replacement is not possible. The vessel downtime is evaluated through the Supply Vessel Uptime Indicator (SVUI) whose current target is 95%. This indicator is calculated according to Equation 1.

$$SVUI = 100\% \frac{\text{sum of uptime hours of each supply vessel}}{\text{sum of hired hours of each supply vessel}}$$
 Equation 1

Thus, the Supply Vessel Downtime Indicator (SVDI) is evaluated as shown by **Equation 2**.

$$SVDI = 100\% - SVUI$$
 Equation 2

Offshore logistics is commonly referred as upstream logistics, because the oil and natural gas industry operations are divided into two categories – upstream and downstream. According to the book "An Introduction to the Offshore Industry" (2010), upstream operations "consist of exploration, geological evaluation, and the testing and drilling of potential oilfield sites; that is, all of the procedures necessary to get oil out of the ground and also the subsequent installation, operation and maintenance of the oil producing platform." Conversely, "downstream operations include pipelining crude oil to refining sites, refining crude into various products, and pipelining or otherwise transporting products to wholesalers, distributors, or retailers." Thus, upstream logistics has the purpose of providing resources and services to offshore units in order to produce oil or natural gas.

There are few studies on offshore logistics systems reported in the academic literature, as previously observed by LEITE (2012). Furthermore, there are also few studies related to the simulation analysis of the offshore supply chain by using discreteevent simulation. The similarities between the present master's thesis and these related studies are the use of computation-based tools to simulate a certain transport process. Subsequently, the study aims at optimizing results in order to better allocate the resources or building a decision-making tool.

BATISTA (2005) presented a master's thesis that designated and validated a model for simulating the operation analysis of offshore supply vessels in Campos Basin. The study used Arena software for modelling the movement of the vessels in Port of Macae. The study also carried out a thorough description of the operation of supply vessels as well as the needs and the systematics for the fulfillment of Offshore Oil Platforms. The author built a model oriented to make it a tool for decision-making,

however, no consideration has been made regarding the possibility of optimizing the fleet. The author's goal lies in the purpose of building a model that truly represented the reality, but the study has not moved towards the optimization of the vessel fleet.

Another study presented by CONDE (2011) analyzed an oceanic terminal operation with the development of a simulation model using the ARENA software. The study has been able to determine the best moment for the beginning of the operation of mono-buoys, which are an important part of the terminal. The tool created through the model enabled the fleet sizing and the assistance for the ship scheduling as well as for investment analysis. The simulation model developed in the work represented and analyzed an FSO operations and can be used to analyze the operability and storage capacity of any offshore unit as well as for the analysis of operation in ocean terminals that operate other types of product. The study made it possible to determine the production limit of the unit and its storage capacity as well as the best time for interventions and investments. The model has not considered the unavailability nor the downtime of the shuttle tankers arriving into the oceanic terminal due to weather condition or to mechanical breakdowns.

SHYSHOU et al (2010) presented a work where a discrete-event simulation model through Arena Software has been designed and developed for evaluation of size configurations for the fleet of Anchor Handling Tug Supply Vessels (AHTS). This study has been initiated by a Norwegian offshore oil and gas operator and the company had as option to hire AHTS from shipping company on long-term basis or on the spot market to operate offshore mobile units. Anchor handling vessels are among the most expensive ones and they represent a heavy impact on drilling operation costs. Therefore, the simulation model has been built as a tool to decide the cost-optimal fleet of vessels on the long-term hire to cover future operations. Uncertain weather conditions and future spot rates have been allowed for to determine the fleet size. The weather modelling considered the generation of low-sea and high-sea periods whose incidence distributions have been based on historical meteocean data. In the model, operations are only allowed to start if the remaining duration of low-sea period is 1.5 times longer than the operation duration. However, taking only into account consideration meteocean data to assess weather influence on offshore operations represents a considerable weakness, since it involves human decisions and vessel engine power limits. Moreover, the study considered Wait-on-Platform time (WOP) and Waiting-on-Weather time (WOW) as not being correlated, although in real operations those periods are sometimes overlapped.

Another study presented by MAISIUK et al (2014) also analyzed the fleet sizing problem this time for Platform Supply Vessels (PSV). The ARENA-based simulation model served as a tool for strategical fleet sizing and operation planning. The number of weekly supply trips performed by PSV may vary as their operations have been carried out under some uncertainty like weather conditions, demand variation and delays on the supply base. Normally, oil companies resort to time-charter vessels to perform scheduled supply operations. When a hired vessel is not able to complete a voyage before the starting of the next planned voyage, the oil company is forced to hire vessel from the spot market. The authors proposed a model to study the optimal mix of timecharter and spots to be used, considering the future spot rates and weather uncertainty conditions. It has been observed that as the utilization of the vessels decreases, the contribution of every next vessel hired on the long-term contract becomes less visible in terms of spot-hire days. The results also showed that the more vessels visit the offshore units smaller will be the wait-on-weather time. However, the model has not taken into consideration for the evaluation of offshore operation the number of liftings predicted for each offshore installation based on historical distributions. Furthermore, the simulation model considered normative and safe limits of height and wind speed to compute the contribution of the weather on the duration of the offshore operation. This approach may not be correct, since the vessel master takes into consideration to operate not only weather parameters but also engine power limits.

A study presented by CORTÉS *et al* (2007) simulated the freight transport process in the Port of Seville, Spain. The analysis has been performed since the beginning with the movement through the whole estuary of the river until the finishing with the vessels arriving to the port dependencies, where the logistic operators' load and unload processes take place. Furthermore, the simulation has been carried out with Arena Software by considering all the types of cargo existing in that port.

Another study performed by GAMBARDELLA *et al* (1998) presented a decision support system for the management of an intermodal container terminal. The analysis comprehended spatial allocation of containers on the terminal yard, the allocation of resources and the scheduling of operations in order to improve the

economic performance. The research has been divided into two modules: an optimization of the allocation process based on integer linear programming and a discrete-event simulation tool. The latter provided means to validate and check the robustness of the optimization module. The analysis has been performed considering the Contship La Spezia Container Terminal, located in the Mediterranean Sea in Italy.

Furthermore, PARK *et al* (2009) developed a simulation model in order to analyze the container terminal performance in Korean ports by using Arena Software. This analysis included the integration of container berth and yard simulation planning within container terminal. This model also investigated the most important elements in a port system including ship berthing/unberthing, quay cranes per ship, yard trucks allocation to a container and crane allocation in the stacking area.

Another study presented by PETERING (2009) evaluated block widths ranging from two to fifteen rows in a marine container terminal by using a fully-integrated, discrete event simulation model. Experiments consider dozens of yard configurations and four container terminal settings that are designed to reproduce the microscopic, stochastic, real-time environment at a multiple-berth facility. This paper focuses on the design of seaport container terminals. It has been found that the optimal block width ranges from six to twelve rows depending on the amount of equipment deployed and the size, shape and throughput of the terminal.

Recently, a study presented by DIUANA (2017) compared policies related to the supply of diesel oil to offshore units, based on the productive scenario of an oil company operating in Brazil using discrete-event simulation via ProModel software. Through this comparison, the study determined which policy (on-demand or scheduled delivering) presents the best performance as well as the optimal fleet sizing for each one. The study added the cost perspective, considering the cost of shortage of diesel oil for production units and drill rigs. According to the results obtained by this study, scheduled delivering policy tended to be more adequate for the productive scenario of the company studied, considering the consumption characteristics analyzed, since it produces better results of cost and service level.

All the studies listed above deal with the problem of resource allocation, whether they discuss about port equipment or vessels or containers. Similarly, this present master's thesis focuses on how to better allocate offshore supply vessels. This study presented some improvements compared to the above-mentioned studies regarding the analysis of the fleet sizing problem in the offshore supply logistics. Among the improvements, it should be mentioned the modeling of the influence of weather conditions based on historical data of duration and probability of occurrence of WOW. Thus, the model not only considered a duration of time for the WOW condition, but also the probability of occurrence when the vessel arrives at the location. In addition, the WOW and WOP have been analyzed as correlated events in the simulation model. Unlike the studies carried out by MAISIUK *et al* (2014) and SHYSHOU *et al* (2010), the supply vessel uptime rate will be taken into account for the proposed fleet sizing in this present study.

This thesis presents not only a model that truly represents the operational reality, but also a decision-making tool for resource sizing. The modeling of all offshore units allowed for potential intra or extra clusters influences on the final results.

The current supply vessel fleet operated by the company studied is oversized, which can be demonstrated by huge hiring costs and high anchoring waiting time. The state-of-the-art presented by this study lies in the fact that the proposed simulation model enables the fleet downsizing by taking into account operational performance indicators and costs associated with this reduction. Thus, the study presents the perspective of fleet reduction, considering the impact on the cargo transported by supply vessels. In addition, the model uses transporter resources to represent the vessel, unlike other studies, whose representation is carried out as if the vessel has been an entity. The representation of the vessel as a transporter and the cargo as an entity brings some benefits such as the possibility of analyzing the impact of the resource stock out on the cargo transportation as well as a simulation more adherent to the operational reality.

Finally, this present thesis proposes a more reliable estimation methodology of the duration of the operation at offshore units based on the number of liftings derived from historical data.

3. CURRENT LOGISTICS SYSTEM DESCRIPTION

3.1 Introduction

Logistics operations play a fundamental role in Exploration and Production (E&P) activities as offshore units need to be serviced by a wide infrastructure of resources to maintain an elevated productivity of oil wells as well as to ensure related

on-board activities occur in time. The offshore supply chain must be efficient and robust to deal with changes in cargo needs and emergencies as they result from frequent unexpected events (LEITE, 2012).

The city of Macae – northern State of Rio de Janeiro, Campos Basin - hosts the largest offshore infrastructure in Brazil and is one of the most important of the world (LEITE, 2012). This infrastructure is composed by a with a huge fleet of specialized vessel and 70 offshore units, 25 warehouses, 110 trucks, 32 aircrafts, two ports and two airports. Such a wide infrastructure is responsible to carry around 40.000 tons of deck cargo per month. **Figure 1** shows the location of the city of Macae in the State of Rio de Janeiro.



Figure 1 - Macae Location in the State of Rio de Janeiro

Campos Basin is one of Brazil's largest oil production field and accounts for about 50 % for national production. **Figure 2** shows the state-owned PETROBRAS (Petróleo Brasileiro S.A.) national production of oil, gas and condensates over the period from 2006 to 2017.



Figure 2 - PETROBRAS Daily National Production in Brazil (PETROBRAS)

In March 2017, there have been 53 oil offshore units, 10 oil-drilling rigs and 7 Units for Maintenance and Safety (Flotel) in Campos Basin. **Table 1** shows the number of platforms for each type.

Types of Platforms	Number
Floating Production Storage and Offloading	21
	21
Floating Storage and Offloading (FSO)	2
Semi-submersible	39
Drillship	1
Total	63

 Table 1 - Types of Platforms Operated in Campos Basin (Elaborated by the Author)

The average distance between Port of Macae and Campos Basin offshore units is 170 km, while the maximum distance is around 410 km and the minimum is around 120 km. **Figure 3** shows the distribution of Campos Basin's oil field assets.



Figure 3 - Campos Basin's Assets (Adapted from TELES, 2010)

The Campos Basin offshore units are grouped into clusters according to their geographic position and average amount of cargoes received. In March 2017, there have been 16 clusters of oil production platforms, 2 clusters of drilling rigs and 1 of Unit for Maintenance and Safety (data elaborated by the author).

Three main flows occur in the E&P industry: petroleum flow, personal flow and material flow (or cargo flow).

The petroleum flow begins in the exploitation from oil wells and is processed and separated in offshore units. Sometimes, the just-produced oil cargo is stored in platforms called FSO (Floating Storage and Offloading). Alternatively, the oil is extracted, processed, separated and stored in a single platform, the FPSO (Floating Production Storage and Offloading). The oil cargo is carried to onshore refineries by means of shuttle vessels or subsea pipelines. In refineries, a wide variety of petroleumbased products is produced. One of these derived – gasoline – is transported by trucks to gas stations. The logistics deployed to support the exploitation of the petroleum (from wells to offshore units) is called upstream logistics. On the other hand, the logistics deployed to carry oil from the offshore units to refineries and distribute it to customers is called downstream logistics. **Figure 4** shows a typical petroleum flow.



Figure 4 - A Typical petroleum flow

The personal flow involves a huge air infrastructure composed by 32 helicopters and 2 airports, which accounts for an average of 60 flights and 1000 passengers per day in Campos Basin (data elaborated by the author). In some extreme cases, these helicopters are deployed to carry small cargoes.

The material flow is the flagship of this present study. The offshore supply chain developed in Macae to service Campos Basin offshore units is well complex as it involves a supply flux, from national or foreigner supplier, down through warehouses and ports and to fulfilment of offshore units as shown in **Figure 5**.



Figure 5 - Offshore Supply Chain in Campos Basin (FILHO, 2014)

This material flow is developed as each offshore unit requests material via purchase order or request to the suppliers or company warehouses, respectively. After purchased, the material is transported by trucks to and stored in such warehouses. Once inside the warehouse, each purchase order becomes a transport requesting document. Thus, the material enters the cargo consolidation area where the cargoes will be unitized, consolidated and transported to port. The transport requesting document is used to program the cargo transport between warehouses and offshore unit. Transport requesting documents play a major role in the transport programming, because they describe dimensions and weight of the cargo. Such features limit the amount and size of cargo, which will be carried on supply vessel deck or in tanks. Moreover, transport requesting documents provide an earlier and later date to deliver cargo to offshore units, what it calls the "delivery window". In case of cargo delivering takes place before the earlier date, the offshore unit may not be prepared to receive the cargo. Conversely, if the cargo delivering occurs after the later date, the offshore system efficiency will be affected by reducing respective performance indicators (FILHO, 2014).

3.2 Warehouse

In Macae, warehouse area is responsible for receiving, storing, preserving, separating and scrapping materials and equipment, which will be made available to Campos Basin offshore units, storage areas and shores. Warehouse services are outsourced to third-party logistics providers.

One of the core warehouse functions is to transform the requests created by offshore units or other internal clients into transporting requesting documents via the ERP system. In case of no existence of the material required, the offshore unit will order a purchase. After being purchased, the warehouse management will receive the material and then will sent it to be stored or to the clients, such as offshore units, shores, workshops and repair and manufacturing sites. By creating the request, the offshore unit indicates a maximum date ("need-date") until which they will accept the material to be delivered on board. The warehouse will create a transport requesting document for the cargoes by taking into account the shipment schedule registered for each offshore unit in the Warehouse Fulfilment Dashboard and the ideal shipment so that the material will be on board before the need-date.

3.3 Cargo Consolidation

After warehouse turns the request into the transport requesting document, the material will be then identified as an item of such document. The cargo consolidation area has the responsibility to provide services to collect items from storage areas and check, pack and unitize such items, based on a list of transport requesting documents clustered and prioritized by the operation integrated area. After unitization, the cargo consolidation will release the transport requesting document to be programmed. The programming stage means to create a fulfilment where a certain equipment (truck, vessel, helicopter, etc.) is designed to transport a set of transport requesting documents. Before being released by the consolidation, the transport requesting document pass through the following status: creation (the warehouse creates the transport requesting document), collecting and unitization. Thus, the transport requesting document only can be programmed when the consolidation releases it. The cargo consolidation's employees carry out the programming of these documents for the segment between consolidation's unitization areas to Port of Macae and/or to Airport of Macae. Such management has also the responsibility of handling return cargo, inspecting and preserving offshore containers and belonging lifting equipment.

The consolidation performs the logistic operations with a fleet of around 5,000 containers.

The cargo consolidation area has indicators measuring the efficiency of its unitization services and are related to the number of transport requesting document items released for programming within the deadline.

The deadline reference above-mentioned depends on the destination (Port of Macae, Airport of Macae, onshore destinations, etc.), which the cargo is set to be directed to. Such deadline starts from the transport requesting document creation date - set by warehouse - and ends on the transport requesting document releasing date.

It should be emphasized that transport to onshore destinations such as repair and manufacturing sites is assigned to the onshore transportation area whereas the transport to Port of Macae and/or Airport of Macae is performed by the cargo consolidation area.

The return cargo, i.e. the process of handling cargo from the offshore unit to warehouse is called "backload". Instead, the process where the cargo is carried from the warehouse to offshore unit is called "load". Finally, there is the transshipment, which is the process where the cargo is handled between two offshore units. In the backload process, the cargo consolidation receives the container, takes the cargo off it, and then it will be cleaned up and preserved in order to make it available for a next unitization. If the container belongs to an external supplier, then it will be sent to its storage areas. The cargo removed from the container will be sent to the warehouse. **Figure 6** shows the load and backload process flow performed by the cargo consolidation area.



Figure 6 - Cargo Consolidation Area Flow Process

3.4 Onshore Transportation

The onshore transportation area fulfils demands of cargo onshore transportation among various locals, such as oil companies' bases, ports (except Port of Macae, whose transportation is performed by cargo consolidation area), outsourced repair and manufacturing sites, in the North, Northwest and Lowland Coastal of the State of Rio de Janeiro.

The main responsibility of onshore transportation area may be formulated as providing logistics services regarding land transportation of cargo to the E&P units, according to the quality requirements, at the best cost, ensuring the safety and health of its employees and respecting the environment.

The onshore transportation area has indicators measuring the efficiency of its onshore transportation services, such as the percentage of fulfilment of onshore cargoes in time. The goal of these indicators is to maximize the fulfilment of onshore transportation in time.



Figure 7 shows the process flow performed by the onshore transportation area.

Figure 7 – Onshore Transportation Flow Process

3.5 Port Operations

The port operation area is responsible to operate the Port of Macae, which is the main supply base that services the offshore units of Campos Basin. The offshore activities in Campos Basin has increased over past years, which demanded a huge expansion of services and resources provided by the supply chain. Thus, in order to meet such demand, Port of Açu, in City of Campos dos Goytacazes, has been hired and the operations at this port started in 2016.

Figure 8 shows the Port of Macae, which is considered the main port for offshore operations in Brazil, located in Macae, a city 180 km north of Rio de Janeiro.



Figure 8 - Port of Macae

The features of Port of Macae are listed in Table 2.

Number of Offshore Units Serviced	80
Number of Berths	6
Monthly Mooring	322
Size	90 m (length) x 15 (width)
Draught	7.5 m
Access Channel Size	960 m (length) x 190 (width)
Number of Access for Trucks	1
Cargo Yard	Out-going Cargo Areas (4,160 m ²), Return Cargo Areas (3,242 m ²) and Pipe and Waste Areas (1,600 m ²)
Tankage of Diesel	4,620 m ²
Tankage of Water	6,000 m ²

Table 2 - Features of Port of Macae

The Port of Macae has several facilities such as water and diesel tanks. The Port of Macae's diesel tanks meet a small part of the Campos Basin's demand, which is largely supplied by six offshore diesel hubs (tankers). Offshore supply vessels heads for such tankers and picks up diesel for their own consumption as well as for delivering it to offshore units. On the other hand, the diesel supplied from Port of Macae meets needs of smaller vessels' own consumption (line handling vessels and PSV1500), and not more than 20-30% of the moorings involve diesel loading.

A large fleet of specialized vessel is operated such as general cargo, bulk and diesel oil vessel. On the other hand, multipurpose vessels could reduce significantly the number of vessels, because the specialized vessel solution requires an additional fleet of vessel to fulfil demands of offshore units. **Table 3** shows the amount of each type of vessel used to service all oil basins in Brazil.

Туре	Amount	
PSV	159	
UT	12	
OSRV	31	
AHTS	81	
Р	8	
LH	43	
Total	334	

 Table 3 - Type of vessels used to service all Brazilian oil basins (Elaborated by the Author)
 Image: Comparison of the service all Brazilian oil basins (Elaborated by the Author)

Not all vessels are used for the purpose they have been designed. For example, it is possible to find some AHTS' operating as general cargo vessels instead of Anchor Handling Tug Supply vessels. General cargo, diesel oil, drill cuttings, dry bulk and wet bulk are carried typically by Platform Supply Vessels (PSV). In general, small vessels such as LH (Line Handling Vessel) are designed to handle offshore unit lines, however are most used to transport small and emergency cargoes. **Table 4** shows the amount and type of cargo or service performed by such offshore vessels.

Type of Cargo or Service	Number
DIESEL OIL	8
GENERAL CARGO	184
DRY BULK	11
OIL SPILL RECOVERY	36
ANCHOR HANDLING AND	
TUG	59
WET BULK	14
REMOTE OPERATED	
VEHICLE (ROV)	4
LINE HANDLING	13
DRILL CUTTINGS	
TRANSPORT	3
PASSENGERS	2
Total	334

 Table 4 - Type of Cargo or service performed by vessels (Elaborated by the Author)

The port operation area has the following responsibilities:

- Oversee pier operations, such as loading/offloading of vessels, moorings, anchoring, fluid and diesel and water supplying;
- Oversee out-going cargo, return and pipe and waste areas;
- Contact outsourced suppliers in order to ensure that the cargo will arrive before the closing of the departure window;
- Monitor the outsourced port operator in order to ensure that the return cargo (backload) will be well performed;
- Carry out inspection of return cargo in accordance with agreed procedures to ensure that materials are transported in a safe condition;
- Carry out weighing of return and fluids station materials;
- Carry out weighing by sampling of out-going material;
- Coordinate the supply base maintenance and carry out infrastructure modifications (layouts).

The cargoes received by Port of Macae are classified into two types (I and II). The first type relates to stock cargoes and inventoried materials, whereas the second type relates to out-of-cargoes and non-inventoried materials. The type I cargoes are typically oil company-owned materials stored in the warehouse area facilities and transported by the consolidation area to the Port of Macae. Oil company-owned type II cargoes in the possession of third parties are consolidated (collected, checked, packed and unitized) and transported by Cargo Consolidation to the Port. In the other hand, supplier-owned type II cargoes are consolidated and transported by itself to the Port. In this latter case, the only role played by the cargo consolidation area is to release transport requesting documents for programming by such suppliers. Cargoes are also classified into general cargo, dry bulk and wet bulk. The Port of Macae no longer supplies dry bulk and wet bulk through its chemical product plant as this facility has been recently dismantled. Dry bulk and wet bulk accounts for a small part of the quantity of cargo loaded into vessels at this port, most of them being supplied through trucks. Figure 9 shows the quantity of deck cargo in tons distributed according the type of transport requesting document (I or II) over the period between April 2016 and March 2017. Figure 10 shows the amount of normal and emergency cargoes over the same period.
The area of port operations has several indicators that measures the efficiency of its port operations services. The most important of these indicators is the average time that each crane takes to perform a single lifting or lowering operation as it allows the calculation of the port productivity and the time expected for the duration of a cargo loading in the port.



45.000 110,0% 100,0% 97,9% 40.000 95.9 35,000 90,0% 291 30.000 80.0% 25.000 70,0% 20.000 60,0% 15.000 50,0% 10.000 40,0% 5.000 0 30,0% apr/16 may/16 iul/16 aug/16 oct/16 nov/16 dec/16 feb/17 mar/17 iun/16 sep/16 jan/17 Normal Priority Normal Priority Percentage Emergency Priority

Figure 9 – Deck Cargo (in tons) Distributed into Type I and Type II-cargoes

Figure 10 - Deck Cargo (in tons) Distributed into Normal and Emergency Cargoes

Figure 11 shows the berth occupancy rate of loadings dedicated to scheduled operations over the above-mentioned period. Figure 11 - Berth Occupancy Rate in Port of Macae

Table 5 shows the average distribution of the port operation time into activities carried out by offshore supply vessels. On the other hand,

shows the lifting time performed in Port of Macae from April 2016 to March 2017. Through this data, the average lifting time performed during this period can be calculated as being six minutes. This value will be useful for the simulation model to calculate the amount of time each vessel will be loaded in the port.



Figure 11 - Berth Occupancy Rate in Port of Macae

Type of Operations	Time (hour)	Percentage
Scheduled Operations (Load + Backload)	1,716,58	60.65%
Oil Recovery Vessels	123.40	4.36%
Crew Changes/Survey/Others	448.89	15.86%
Emergency Operations	148.87	5.26%
Oil Bunkering and Debunkering	230.10	8.13%
Specialized Vessels	130.19	4.60%
Extra Departure	32.27	1.14%
TOTAL	2,830.31	100.00%

 Table 5 - Distribution of Operational Time in Port of Macae



Figure 12 – Port Lifting Time (min)

3.6 Offshore Transportation

The fleet designed to provide cargo supplying for the Campos Basin's offshore units is composed by ninety-one offshore supply vessels, which carry on average 34,000 items of RTs, 40,000 tons of deck cargo and 56,000 m³ of diesel oil per month. There is also a fleet of seventy Anchor Handling Tug Supply Vessel (AHTS) and thirty-two Oil Spill Recovery Vessel (OSRV) to service all Brazilian oil basins, but both type of vessels are not intended to transport cargo. **Table 6** shows the purposes, the amount and average measures of each type of offshore supply vessel (PSV) used to service Campos Basin.

Offshore support vessels are classified according to the following characteristics:

- Platform Supply Vessel (PSV) classification according to her deadweight. Thus, PSV1500 means that the vessel carries around 1,500 ton of deck cargo;
- Line Handling Vessel (LH) and Anchor Handling Tug Supply Vessel (AHTS) classification according to their boiler horsepower (BHP). For example, LH1800 means that the vessel performs around 1,800 BHP of main power;

Oil Spill Recovery Vessel (OSRV) – classification according to their capacity in volume of recovering oil spills. Thus, OSRV750 means that the vessel can recover until 750 m³ of oil spills.

Purpose of Service	Quantity	Length	Breadth	Deadweight	Deck Area	Service Speed	Brake Horse Power (BHP)
General Cargo Vessels (SL I e SL III)	39	73.3	16,4	3,000	583	10.5	5,800
SOS and Stand-by Vessels	1	41.0	11.0	780	120	10.3	3,300
Transshipment Vessels	20	60.4	14.3	1,601	305	10.0	4,560
Storage Vessels	3	61.6	13.5	1,580	354	10.0	3,800
Oil Diesel Vessels	13	69.5	15.4	2,660	533	12.03	5,260
Dry- and Wet-bulk Vessels	15	69.7	15.8	2,922	544	10	5,230
Total	91	-	-	-	-	-	-

 Table 6 - Maritime Transportation Fleet

The number of vessels along the year of 2016 and 2017 has drastically reduced from 135 vessels at the beginning of 2015 to 91 in March 2017 as shown by **Figure 13**.

Fulfilments performed by general cargo vessels are classified into two categories:

- Service Level I (SL I) type of fulfilment where the vessel carries only normal priority cargoes. This fulfilment has a weekly fixed schedule according to cluster table of offshore units. There is no limit for cargo size transported by means of this fulfilment;
- Service Level III (SL III) type of fulfilment where the vessel carries only emergency priority cargoes, which are typically small-sized and transported by small and fast vessels. Thus, Service Level III take less time to perform the fulfilment than the Service Level I. Certain offshore units have a limited annual number of SL III fulfilments that are allowed to be performed due to

the current cost policy established as this type of service costs twice as much as the Service Level I.

Until recently, there had been the service Level II (SL II), which had the same characteristics of the Service Level III, except that the fulfilment has a daily fixed departure set by demand of each offshore unit. This service has been replaced by SL III, as the current policy cost has demanded a decreasing number of vessels used to perform this type of service, which in turn has prevented the offshore transportation support team from scheduling a daily departure for SL II.



Figure 13 - Offshore Transportation Fleet

When the cargo consolidation area releases a transport requesting document, the segment between Port of Macae and an offshore unit can be programmed by the offshore transportation area. On the other hand, the onshore segment – between cargo consolidation areas and Port of Macae – is programmed by the consolidation sector.

The concept of programming for the offshore transportation logistics relates to the creation by the programmer of a document called "Fulfilment Note" via ERP system into which one or more than two transport requesting documents are inserted. This document has the name of the vessel that will perform the transportation, origins and destinations, according to data contained in each transport requesting document. This procedure aims at optimizing the route to fulfil offshore units that are part of the cluster to be serviced. In general, programming is related to:

- Selection of transport requesting document items and/or package available for transportation;
- Assigning of an equipment for fulfilment (vessel, helicopter, vehicle);
- Setting of routes of the voyage;
- Evaluation of the duration of the voyage and fuel need (air and offshore modal);
- Evaluation of the cargo capacity (mass, volume and area) of the transport equipment according to the route programmed (air and offshore modal);
- Evaluation of the distances from coordinates registered for each installation (offshore units, warehouses, etc.);
- Generating of a fulfilment document.

Each cluster has a fixed schedule as each oil production unit and rig receive cargo two times a week. For each cluster, there is also a fixed departure for the vessel from the Port of Macae. Each fulfilment note contains one or more transport requesting documents and, in turn, each transport requesting document embodies one or more items. As mentioned before, each transport requesting document has an earlier and a later date that defines the window by which the cargo should be delivered to a certain offshore unit. The earlier date is defined as being the twelve hours after the departure of the vessel and the later date 96 hours after.

The fulfilment for load cargo starts from thirty-two hours before the departure of the vessel for service level I and twenty-two hours for service level III. In the other hand, the fulfilment for backload cargo ends up to four hours before the departure of the vessel. **Figure 14** shows the sequence of events before the departure of the vessel.

For programming backload deck cargo, it should take into account the deck area needed of the backload to be performed in the first offshore unit of a certain cluster sequence. However, a safety margin area of 25 % of the total deck cargo area shall not be used.

In Port of Macae, the receiving window for cargoes opens twenty-four hours and closes twelve and six hours before the departure of the vessel for the oil company-owned cargo and supplier-owned cargo, respectively.

Upon the accomplishing of the fulfilment programming, the status of the transport requesting document is changed from "released" to "programmed". On the other hand, when the cargo is delivered to offshore unity the status is finally change over to "delivered".



Figure 14 - Flow of Programming Sequence for Service Level I and Load Cargoes

The offshore transportation area has the following responsibilities:

- Monitor vessels and operations;
- Follow-up fleet sizing;
- Perform operational notes;
- Keep in touch with clients and supplier;
- Program load and backload cargo;
- Perform contract compliance inspection of offshore supply vessels;
- Monitor buoys and tankers;
- Monitor diesel storage of offshore units.

To evaluate the efficiency of its services, the offshore transportation area measures a wide range of indicators such as cargo fulfilment, vessel uptime and cycle time indicator.

Figure 15 shows the performance of the offshore transportation fulfilment indicator. This indicator measures the quantity of SL I cargo liftings that have been

performed onto offshore unit decks within the deadline as percentage of the total amount of cargo liftings performed. The 96 hour-deadline adopted for this indicator is measured from the time the vessel leaves the port. **Figure 15** presents only the indicator performed for load cargo liftings as the purpose of this thesis is to analyze cargoes that are delivered to offshore units.

This indicator is highly influenced by weather conditions and vessel downtime. It represents the main data through which the performance of the offshore transportation can be evaluated as eventual delays may affect the delivering time of the cargo to the final customer – the offshore units.

The data provided by this indicator will be useful for the simulation to evaluate whether the quantity of liftings modelled is well calibrated. The number of liftings in turn allows a suitable calculation of time spent on loading in the port and next to offshore units. Finally, the port and offshore loading time will influence the fulfilment cycle time and hence the time the vessel arrives in the port anchoring area.





Figure 16 shows the vessel uptime indicator over the period from April 2016 until March 2017. This indicator is calculated as percentage of the total hours hired by which the vessel is available for operation. The average uptime over this period, 92.7%, will be used in the simulation model to verify the number of vessels that will proceed to the repairing area whenever they arrive in the anchoring area.



Figure 16 - Supply Vessel Uptime Indicator

The offshore cycle time indicator measures the time that each SL I vessel takes to depart from and return to the port, after delivering cargo to offshore units, i.e. it represents the number of hours of voyages performed by general cargo vessel for fulfilling the schedule to service offshore units. This indicator is calculated as the relation between the amount of voyage hours and number of voyages performed. **Figure 17** shows the performance of the indicator over the period from April 2016 until March 2017. The figure shows also how much of the cycle time is spent in the anchoring area and for port and offshore backloading operations. The remaining time corresponds to the time spent for navigation, waiting on weather and on offshore unit and offshore loading operations. Since the purpose of this thesis is to analyze the load logistics, the remaining time (navigation + waiting time + loading), called from this point on simply "cycle time", will be used as one of the parameters to validate the model.



Figure 17 – Offshore Cycle Time Indicator (h)

Figure 18 shows the monthly number of fulfilments performed by SL I vessels over the period from April 2016 until March 2017. This data will also be useful to validate the simulation model. From this graph, it is possible to verify that the monthly average of fulfilments performed over last year is higher than those that has performed this year, which is justifiable as along this period it has been necessary to reorganize the cluster table in order to adjust it to the shrinking number of the vessel fleet.



Figure 18 - Number of Fulfilments Performed

Figure 19 shows on the same graph both the deck area carried to provide offshore units with Service Level I and the deck occupancy rate.



Figure 19 – Deck Cargo Area Carried (m²) x Deck Occupancy (%)

Figure 20 provides a graph showing the average non-productive time for each condition under which the supply vessel operates. This data applies to all vessels deployed to service Campos Basin offshore units (SL I, SL III, transshipment, diesel oil vessel, deck extension, etc.) and are compared through the same graph to the monthly average SL I vessel productivity.



Figure 20 - Historic Series of Non-Productive Times

WOW (Waiting-on-Weather) code represents the condition where a certain supply vessel is awaiting good weather conditions to operate with an offshore unit (Wait-on-Weather).

WOP (Waiting-on-Platform) code represents the condition where a certain supply vessel is awaiting the authorization by an offshore unit to start the operation.

WOCP (Waiting-on-Cargo-Programming) code represents the condition where a certain anchored supply vessel is awaiting cargo programming.

WOPC (Waiting-on-Port-Calling) code represents the condition where a certain anchored supply vessel is awaiting the port call for mooring.

The four conditions above affect the efficiency of the offshore transportation as they represent the time that the vessel has not performed the task for which it has been hired.

Table 7 shows the cluster table by which offshore support vessels must abide to provide platforms with service level I general cargoes. Clusters with initials "PLAT" service mainly oil production platforms, while clusters with initials "SOND" are set to service only drill rigs. On the other hand, "UMS" clusters provide fulfilments only to Units for Maintenance and Safety. On the geographical grounds, certain UMS and drill rigs are placed into oil production platform clusters. All clusters have two visits per week and are performed mostly by PSV3000 and PSV4500, except clusters ESP1 and ESP2, which are scheduled to special gas-producing platforms once per week and are performed by line handling vessels (LH).

DEPARTURE WEEK DAY	VESSEL DEPARTU RE TIME	CLUSTER	TRIP NUMBER	OFFSHORE UNITS				
	02:00	PLAT14	1	UEP23	UMS5	UEP30	UMS6	
	08:00	PLAT10	1	UEP32	UEP27	UEP50	UEP4	
MONDAY	12:00	PLAT6	1	UEP45	UEP48	UEP53	UEP52	UEP51
	18:00	PLAT2	1	UEP18	UEP14	UEP13	UEP19	
	20:00	UMS	1	UMS2	UMS7	UMS3	UMS1	
	01:00	PLAT11	1	UEP31	UMS4	UEP35	UEP29	
	07:00	PLAT7	1	UEP3	UEP2	UEP34	UEP36	
TUESDAY	13:00	PLAT3	1	UEP47	UEP40	UEP46	UEP39	UMS7
	14:00	SOND1	1	SONDA2	SONDA4	SONDA1	SONDA5	SONDA7
	20:00	PLAT12	1	UEP24	UEP26	UEP22		
WEDNESDAY	02:00	PLAT8	1	UEP10	UEP8	UMS2	UEP7	SONDA9

Table 7 - Cluster Table

DEPARTURE WEEK DAY	VESSEL DEPARTU RE TIME	CLUSTER	TRIP NUMBER	OFFSHORE UNITS				
	02:00	PLAT14	1	UEP23	UMS5	UEP30	UMS6	
	08:00	PLAT10	1	UEP32	UEP27	UEP50	UEP4	
MONDAY	12:00	PLAT6	1	UEP45	UEP48	UEP53	UEP52	UEP51
	18:00	PLAT2	1	UEP18	UEP14	UEP13	UEP19	
	20:00	UMS	1	UMS2	UMS7	UMS3	UMS1	
	08:00	PLAT4	1	UEP6	UEP37	UEP38	UEP49	UEP9
	09:00	PLAT13	1	UEP28	UEP33	UEP1		
	15:00	PLAT9	2	UEP15	UEP17	UMS1	UEP25	
	21:00	PLAT5	2	UEP20	UEP12	UEP41	UEP43	UEP42
	01:00	SOND2	2	SONDA8	SONDA3	SONDA6	SONDA10	UEP11
THURSDAY	03:00	PLAT1	2	UEP16	UMS3	UEP21		
THURSDAY	14:00	PLAT14	2	UEP23	UMS5	UEP30	UMS6	
	20:00	PLAT10	2	UEP32	UEP27	UEP50	UEP4	
	00:01	PLAT6	2	UEP45	UEP48	UEP53	UEP52	UEP51
	06:00	PLAT2	2	UEP14	UEP13	UEP19	UEP18	
FRIDAT	13:00	PLAT11	2	UEP31	UMS4	UEP35	UEP29	
	19:00	PLAT7	2	UEP3	UEP2	UEP34	UEP36	
	01:00	PLAT3	2	UEP40	UEP47	UEP39	UEP46	UMS7
	02:00	SOND1	2	SONDA7	SONDA5	SONDA1	SONDA4	SONDA2
CATUDDAY	08:00	PLAT12	2	UEP24	UEP26	UEP22		
SATURDAT	14:00	PLAT8	2	UEP8	UMS2	UEP7	UEP10	SONDA9
	20:00	PLAT4	2	UEP38	UEP37	UEP6	UEP9	UEP49
	21:00	PLAT13	2	UEP28	UEP33	UEP1		
	03:00	PLAT9	1	UEP25	UEP17	UMS1	UEP15	
	09:00	PLAT5	1	UEP20	UEP12	UEP41	UEP43	UEP42
SUNDAT	13:00	SOND2	1	UEP11	SONDA10	SONDA6	SONDA3	SONDA8
	15:00	PLAT1	1	UEP16	UMS3	UEP21		
SUNDAY	14:00	ESP1	1	UEP5				
MONDAY	15:00	ESP2	1	UEP44				

The timetable shown by **Table 7** has been the last one adopted in Port of Macae in March 2017 before the staggered transferring of the first fulfilments for Campos Basin offshore units to Port of Açu and will be the model through which the simulation will be designed and carried out.

In the Section 3, all load (port to offshore unit flow) and backload (offshore unit to port flow) has been explained. However, this study will focus on building a simulation model regarding the offshore cargo transportation operations with the purpose of sizing the vessel fleet operated. In this context, **Figure 21** shows the entire offshore logistical system since the purchase request from the supplier until the cargo delivering to offshore units as well as the thesis' area of interest.



Figure 21 – Campos Basin's Logistics Chain Flow

4. PROBLEM MODELLING

The modelling of the problem has been carried out in three stages. The first stage, data collection has been performed from the real operations carried out by offshore supply vessels in the port and across the Campos Basin. Data acquisition is one of the most important stage in the simulation and will be useful to create statistical distributions to represent each step of the offshore operations. In this stage, assumptions and limitations have been also considered in order to perform the simulation. The second stage corresponds to the development of the simulation itself. The model has been divided in five areas: time counting, cargo arrival, port, anchoring area and offshore units. The last stage corresponds to the testing and validation of the model, where comparisons between real parameters and model-generated values have been carried out.

4.1 Assumptions and Limitations

The following assumptions and limitations have been defined:

- Since April 2017, SL I operations are being phased out at the Port of Macae and gradually transferred to the Port of Açu. As the transference of

operations to this port is underway, few suitable operation-related data have been found for this location. Thus, the study will focus on offshore operations performed from the Port of Macae to service Campos Basin's units;

- The study will focus on departures scheduled, since the vessel sizing policy focuses only on SL I operations and performance indicators only reflects fulfilments carried out by SL I vessels. Thus, the transportation destined to fulfill extra or urgent demands will not be analyzed;
- The data collecting covers a period of one year from April 2016 until March 2017 until which all SL I operations had been performed from the Port of Macae to fulfil Campos Basin's offshore units;
- Personal transportation will not be considered in this study, since the vast majority of the service is carried out by helicopters and involves a lot of complexities regarding scheduling and management issues;
- Transportation of diesel, water, dry and wet bulk has non-fixed scheduling and is not performed by SL I vessels. As the purpose of this present thesis is to analyze deck general cargo as well as the SL I vessel fleet sizing, the transportation of these products will not be considered;
- The process involving return cargo (backloading) will not be analyzed in this study because the vessel sizing currently carried out in the oil company studied has not considered the backload process, since these cargoes have been determined to have fixed portion on the vessel deck. Since a portion of the deck is reserved to backload in the simulation model, it is understood that the backload is already taken into account for the fleet sizing proposed. Thus, the model proposes modeling of load only, since the modeling of the backload would not provide significant results for fleet sizing. In addition, the representation of the backloading process in the port before the loading process would bring huge complexities to the modeling;
- For the purposing of reducing complexity, the study considered as if all recorded vessel downtime historically are taking place only in the port anchoring area. This assumption is suitable, since, as the sizing of the

optimal vessel fleet takes into account the useful time spent in each operation (both productive and non-productive), the total time due to vessel downtime will be taken into consideration in the model through historical frequency of the occurrence and distribution of the duration time. This method does not take into account delays caused by vessel downtime in delivery of the cargo, since, if a vessel, for instance, is navigating and she breaks down suddenly, there will be a need to return to the port to unload the cargo and load it on another vessel. However, most of the downtime takes place with the boat in the anchoring area or before loading in the port;

- For the simulation model, revisits to offshore units and route sequence modifications will not be modelled, since there is no tangible criteria or parameter to determine the occurrence of the above-mentioned changes and they involve personal decisions from both the programmer and the vessel master. Furthermore, there is no suitable database regarding the frequency, distributions and time duration of those phenomena. However, regardless of whether there will be revisiting or not, the total time of the operation will be taken into account for calculating offshore operation time distributions. Thus, part of the delay caused by revisits or route changes will be taken into account in the model. In this case, the return time to the unit will not be taken into account, but the total navigation time between each platform is small considering the total time of the vessel offshore cycle;
- The waiting-on-weather (WOW) time and waiting-on-platform (WOP) time are highly correlated and thereby will be analyzed as if they have been a single waiting time. Thus, upon the arrival at the 500-m zone of the unit, the simulation model will decide whether the vessel will await based on WOW and WOP occurrence frequency. If so, the vessel will wait a time corresponding to the combination of WOW and WOP times, which are in turn provided by historical distribution data;
- The model takes into consideration a distance matrix between the port anchoring area and Campos Basin platforms and between the Port of Macae and the anchoring area to calculate time navigation across the basin;

- For the purpose of reducing computational time and simulating complexity, distances between platforms in the same cluster will be modelled as a time distribution (process module). This is a reasonable approach, since offshore units within the same cluster are geographically close to one another and the navigating time between their 500-m zone may vary from one to two hours depending on the cluster;
- Considering that the navigating time between the anchoring area and the Port of Macae (around 20 minutes) is quite small compared to full cycle time, it will be considered as close as possible to zero;
- The port cargo arrival window opens twenty-four hours before and closes six hours before the vessel departure time according to the table cluster. As no suitable data has been found for the arrival times into the port gate, the model considered that the cargo arrives fifteen hours before the departure time;
- The route time within the port facilities has not been simulated as the offshore cycle time is counted from the beginning of the loading.
 Furthermore, the port route time adds nothing to the vessel fleet sizing, which is the focus of this study;
- For all scenarios simulated, the model will consider a minimum fleet of one vessel of each type (PSV4500, PSV3000, PSV1500 and LH2500);
- The diesel consumed from the port loading until the return to the anchoring area will be based on an average value found from navigation, port loading and offshore loading stages separately. This assumption is reasonable, since consumption codes for each one of the above-mentioned stages are not very different among them and the model aims at computing an average cost value for the diesel consumption;
- The simulation model considered as if the diesel supplying for consumption of the vessel has been carried out during the period of cargo loading at the port. In other words, the model did not consider the total time (around 36 hours) in which supplier vessels take to navigate towards a tanker across the Basin for diesel supplying, the time of diesel loading operation, the waiting

times for weather condition (WOW) around the tanker and the return time to the port of Macae for continuity of the cluster. The amount of diesel consumed by such vessels is small and sufficient so that the vessel has approximately a 40-day autonomy on average. Thus, considering the number of fulfilments performed by each vessel during this 40-day period and the total time spent for diesel supplying (36 hours) once within this period, the contribution of this time in the vessel's cycle time may be considered negligible.

4.2 Modelling and Data Collecting

For the simulation, it is important to elaborate the conceptual model of the problem studied. **Figure 22** shows a diagram representing the simulation model segregated by sections.



Figure 22 – Simulation Model Sections

4.2.1 Time Counting Section

Figure 23 shows a flowchart representing the computational simulation intended for counting the days of the week and the hours. This part of the model is important, since it represents a time counter, which will hold the cargo in the port until the date and time determined by the table cluster according to vessel departure time schedule (Table 7).



Figure 23 - Time Counting Flowchart

To represent the time counting, an entity coming into the model each hour under the name "*date_count*" has been created. Thus, every time the entity enters the model, the time is updated by one hour. In this part of the model, two variables will be used -"hour" and "day" - to measure the time. According to the flowchart shown above, a checking is carried out to verify whether the counting reached the value of 23 hours. If not, the entity runs out of the model to be disposed and another entity arrives into the model to continue the counting. Otherwise, if so, a new checking is necessary, this time with respecting to the counting reaching the day 7 (Saturday). If so, it is necessary to zero out the hour counting and restart the day counting to day 1 (Sunday). If not, the hour counting is zeroed out and the day is changed to the following the by incrementing the day counting by one. After that, the entity will be disposed.

4.2.2 Cargo Arrival Section

Figure 24 shows a flowchart describing the model carried out to represent the cargo arrival into the port. Cargoes have been represented in the model as a set of cargoes (one single entity) which cycles through the entire model until to be disposed in

the anchoring area. For instance, the entity "cargo_PLAT1" represents all cargoes of the cluster "PLAT1" and enters the model twice a week (each 168 hours), since production platforms, unit of maintenance and safety and drill rigs require two visits per week. With respect to special units (clusters ESP1 and ESP2), the entity will arrive into the model once a week. For each entity, the area and the number of liftings will be calculated in this simulation model according to historical distribution data.



Figure 24 – Cargo Arrival Flowchart

As explained above, for the clusters "PLAT", "SOND" and "UMS", the entity "cargo" comes into the model twice a week. Thus, two entities arrive in the model at the same time every 168 hours. As for clusters "ESP", only one entity arrives in the model every 168 hours. After arriving into the model, the entity will wait until being freed according to the vessel departure time set up by the above-mentioned table cluster as well as by the port cargo receiving window. For example, for the cluster "PLAT01", whose departure times are Sunday 15 pm and Thursday 3 am, the first entity will wait until Sunday 0 am and the second one will wait until Wednesday 12 pm.

Then, an assignment will be associated to the entity. The purpose of this assignment is to calculate the number of liftings based on a set of historical data collected over the period of one year from April 2016 until March 2017. The number of liftings will be useful to calculate the time spent on loading in the port berth and next to

the offshore unit. The Arena Input Analyzer tool has been used to find out the best distribution for each offshore unit regarding the number of liftings performed during the above-mentioned period and **Table 8** presents the results found for each clusters and respective platforms. Chi-square and Kolmogorov-Smirnov goodness-of-fit tests have been carried out to find out the best-fit distribution for each cluster's number of liftings. The great variety of distribution found is due to a diversified cargo profile performed by each offshore unit. For instance, offshore units located in mature fields demand a huge amount of chemical products carried in metal tanks. On the other hand, newer offshore units demand few chemical products as well as few repairing and maintenance equipment. As for drill rigs, there is a great demand for risers, chemical products and drilling well-oriented specialized equipment such as Wellheads and Christmas Tree Equipment.

Cluster	Offshore Unit	Lifting Distribution		
	UEP16	TRIA(2.5, 12, 28.5)		
PLAT1	UMS3	POIS(6.99)		
	UEP21	4.5 + 38 * BETA(1.48, 1.41)		
	UEP18	1.5 + ERLA(3.05, 3)		
PLAT2	UEP14	1.5 + 33 * BETA(3.44, 5.8)		
	UEP13	NORM(17.7, 5.81)		
	UEP19	3.5 + GAMM(3.69, 3.03)		
	UEP40	4.5 + ERLA(3.39, 3)		
	UEP47	TRIA(1.5, 9, 21.5)		
PLAT3	UEP39	3.5 + LOGN(16.9, 12.5)		
	UEP46	NORM(11.2, 3.7)		
	UMS7	1.5 + 26 * BETA(1.04, 2.49)		
	UEP38	TRIA(3.5, 10.7, 30.5)		
	UEP37	2.5 + GAMM(1.39, 4.41)		
PLAT4	UEP6	1.5 + WEIB(5.97, 2.15)		
	UEP9	1.5 + 10 * BETA(1.23, 1.73)		
	UEP49	5.5 + WEIB(15.5, 1.5)		
PLAT5	UEP20	NORM(24, 8.99)		
	UEP12	4.5 + GAMM(3.76, 3.46)		

Table 8 - Lifting Distribution

Cluster	Offshore Unit	e Lifting Distribution		
	UEP41	1.5 + ERLA(2.09, 3)		
	UEP43	1.5 + WEIB(3.71, 0.821)		
	UEP42	POIS(7.29)		
	UEP45	3.5 + 25 * BETA(1.98, 2.09)		
	UEP48	3.5 + ERLA(4.85, 2)		
PLAT6	UEP53	1.5 + LOGN(4.51, 2.49)		
	UEP52	1.5 + GAMM(1.39, 3.32)		
	UEP51	1.5 + ERLA(1.76, 3)		
	UEP3	1.5 + 14 * BETA(1.35, 2.19)		
PLAT7	UEP2	NORM(10.7, 5.27)		
12.117	UEP34	1.5 + GAMM(1.78, 2.54)		
	UEP36	TRIA(2.5, 8, 31.5)		
	UEP10	POIS(10.6)		
	UEP8	3.5 + WEIB(10, 1.93)		
PLAT8	UMS2	1.5 + 32 * BETA(1.24, 3.26)		
	UEP7	4.5 + WEIB(10.4, 1.96)		
	SONDA9	1.5 + ERLA(1.87, 3)		
	UEP15	6.5 + WEIB(11, 1.86)		
PLAT9	UEP17	TRIA(5.5, 14.4, 43.5)		
12.119	UMS1	1.5 + GAMM(4.64, 1.45)		
	UEP25	NORM(11.6, 3.99)		
	UEP32	2.5 + WEIB(14.5, 2.47)		
PLAT10	UEP27	3.5 + WEIB(17.5, 1.86)		
12.1110	UEP50	2.5 + ERLA(1.12, 4)		
	UEP4	1.5 + WEIB(6.63, 1.54)		
	UEP31	1.5 + WEIB(21.3, 1.51)		
PLAT11	UMS4	1.5 + ERLA(2.66, 3)		
12/11/1	UEP35	2.5 + GAMM(3.18, 5.06)		
	UEP29	3.5 + WEIB(16.9, 2.02)		
	UEP24	1.5 + WEIB(20, 1.94)		
PLAT12	UEP26	2.5 + WEIB(17.8, 1.64)		
	UEP22	POIS(7.7)		
PLAT13	UEP28	NORM(20.6, 7.34)		

Cluster	Offshore Unit	Lifting Distribution
	UEP33	5.5 + WEIB(16.3, 2.31)
	UEP1	1.5 + WEIB(13.6, 2.05)
	UEP23	NORM(19.7, 7.94)
PLAT14	UMS5	1.5 + GAMM(3.29, 2.23)
	UEP30	NORM(20.1, 8.58)
	UMS6	1.5 + WEIB(7.87, 1.91)
	SONDA2	1.5 + WEIB(10.3, 1.38)
	SONDA4	1.5 + WEIB(9.98, 1.45)
SOND1	SONDA1	1.5 + GAMM(3.41, 2.35)
	SONDA5	1.5 + LOGN(16.1, 18.9)
	SONDA7	1.5 + GAMM(9.27, 1.43)
	SONDA8	1.5 + 30 * BETA(2.05, 3.6)
	SONDA3	1.5 + WEIB(15.8, 1.34)
SOND2	SONDA6	1.5 + ERLA(5.1, 2)
	SONDA1	1.5 + GAMM(13.6, 1.21)
	UEP11	1.5 + LOGN(4.56, 3.86)
ESP1	UEP5	1.5 + LOGN(1.77, 1.56)
ESP2	UEP44	1.5 + 9 * BETA(0.925, 1.22)

Through the distributions found according to **Table 8**, the number of liftings will be calculated for each platform belonging to a specific cluster and then will be summed up to find the total number of liftings of that cluster. The number of liftings of each platform will be used to calculate the time the vessel will operate with the unit, while the total number of liftings of the cluster will be used to calculate the time the vessel will be operating in the quay.

Then, the entity will remain in the queue until the number of quays busy is smaller than six as Port of Macae has six quays. Thus, to represent this condition, a variable "NR" is used. According to the *Arena Variable Guide Book*, "NR" represents the *Number of busy resource units*. In this case, a quay has been configured as a resource, which has a capacity of six units.

Finally, the entity moves to the Port Station, which corresponds to a physical or logical location where processing occurs in the model. This station marks both the end of the arrival cargo process defined in this model and the entry into the Port area.

4.2.3 Port Section

Figure 25 shows a flowchart describing the model built to represent the port loading.





Figure 25 – Port-Loading Flowchart

The calculation of cargo area for the entity involved the multiplication of a factor by the number of lifting associated to that entity. Through data collected over the period from April 2016 to March 2017, it has been observed that the area per lifting is approximately equal to 6 m^2 , which makes sense since the typical area of most cargo offshore containers fluctuates around that value (e.g., 2 m x 3 m, 6 m x 1 m and 2.4 m x 2.4 m). **Table 9** shows the average area per lifting found for each cluster.

Cluster	Average Area per Lifting
PLAT1	5.95
PLAT2	6.51
PLAT3	6.21
PLAT4	5.05
PLAT5	4.92
PLAT6	5.47
PLAT7	5.85
PLAT8	6.28
PLAT9	5.47
PLAT10	8.42
PLAT11	5.70
PLAT12	5.88
PLAT13	5.47
PLAT14	6.48
SOND1	6.49
SOND2	6.54
ESP1	5.43
ESP2	5.72
AVERAGE	5.99

 Table 9 - Average Area per Lifting

An attribute has been assigned to the entity to calculate the cargo area. The attribute "amount_cargo" provides the number of lifting associated with the entity that flows through the model.

An assignment has been also used to calculate the initial time for the offshore cycle, which in turn considers the time taken from the scheduled beginning of port loading up to the return to the port anchoring area.

Then, a checking will be carried out to verify whether the entity goes to special offshore units (UEP5 and UEP44) or not. This step is necessary, since, due to their

design and operational features, these offshore units require type LH2500 vessels. Thus, PSV1500, PSV3000 and PSV4500 cannot be used for operations with such platforms. There is no need to carry out a check on deck capacity for ESP1 and ESP2 clusters, since the number of liftings onto these units is small and they are only serviced once a week. On the other hand, for cargoes going onboard type PSV1500 or PSV3000 or PSV4500 vessels, a check on deck capacity is needed and a certain logic has been put in place in this model to reproduce cargo programmer-made decisions. If the entity type belongs to the ESP1 or ESP2 clusters, a LH2500 will be allocated to transport the cargo represented by that entity. If not, the entity will be moved to a second checking, which will verify the deck capacity.

Table 10 shows the vessel deck capacity as well as the number of vessels used as SL I service for each class. The programmable area is a fraction of the total deck area and is based on statutory and job safety requirements as well as negotiations between oil companies and ship-owners. 75 % of the programmable area is used for load cargo programming whereas 25 % is reserved for the first backload cargo along the route sequence.

Vessel type	Programmable Area	Load (75%)	Quantity
PSV 4500	840	630	20
PSV 3000	613	460	5
PSV 1500	360	270	2
LH 2500	84	63	3
	30		

Table 10 – Vessel Deck Capacity (m³)

The first check to be done is to verify whether the quantity of cargo expressed as the number of liftings associated with the entity is smaller than 270 m². If so, a PSV1500 or PSV3000 or PSV4500 type vessel is chosen. If not, if the quantity of cargo is smaller than 460 m², a PSV3000 or PSV4500 type vessel is chosen. If the amount of cargo is greater than 460 m², a PSV4500 type vessel shall be chosen.

If the cargo area is equal or smaller than 270 m² it means that the three classes of vessel can perform the transportation. The logic built for this model is that in this case the preference will be given to the PSV1500 so that the vessel capacity is better used

and hence optimized. However, a checking on the number of entities waiting to be serviced by each class of vessels. Thus, if the number of entities waiting to be serviced by PSV1500 vessels is smaller than entities waiting for either PSV3000 or PSV4500, a PSV1500 type vessel shall be allocated to transport the cargo which area is smaller than 270 m².

On the other hand, if the number of entities in queue waiting to be serviced by PSV1500 is greater than those waiting for PSV3000 and smaller than those waiting for PSV4500, a PSV3000 shall be chosen. If the number of entities waiting to be serviced by PSV4500 is smaller than those waiting for either PSV1500 or PSV3000, a PSV4500 must be allocated to perform the transportation. In fact, in the current configuration of the offshore logistic system, the number of entities waiting for any type of vessel is zero as there is no cargo waiting for a vessel to be released, i.e., when the cargo moves to the port there is already a vessel allocated to transport it.

However, this logic will be useful to size the vessel fleet insofar as the number of vessels is reducing upon the optimization and, at some point, this low quantity of vessels will have in turn an influence on the number of cargo entities in queue.

If none of the previous conditions is satisfied and if the cargo area is equal or smaller than 460 m², only PSV3000 and PSV4500 can be allocated to perform the transportation. The vessel chosen will depend on the number of entities in queue waiting to be transported. If the number of entities in queue waiting for a PSV3000 is smaller than the number of them waiting for a PSV4500, the PSV3000 type vessel will be allocated to transport a cargo whose area is smaller than 460 m². On the other hand, if the number of entities in queue waiting for a PSV4500 is greater, than this type of vessel will be selected to perform the transportation.

In case of the cargo area is greater than 460 m², the vessel allocated will be a PSV4500. On the other hand, if the area exceeds the limit of 630 m², then the entity heads for a buffer, which will count the number of entities that have been left over. The current logistic system has been configured to avoid cargo leftover, since the programmer will be programming the cargo to fit in the vessel deck capacity. Even if a vessel set to perform the transportation breaks down, another similar vessel will be allocated. Due to programming errors, there may be situations where cargo leftovers take place. However, the occurrence of this type of error can be considered negligible

regarding the total number of fulfilments performed. In addition, there are several programmers checking the same fulfilment created and a robust software to support the decision-making process during fulfilment programming. Thus, the assumption that the model will never generate leftover cargoes may be considered reasonable. The buffer has been built in the model as a means of ensuring that the generated distributions did not create excessive cargo leftovers and therefore could be considered adequate for the proposed simulation.

It is important to state that fleet sizing proposed by this thesis will ensure that all scenarios simulated takes into consideration the presence of at least one PSV4500. This assumption grounds on the fact that about 22 % within a total of 1,708 fulfilments carried out over the period from April 2016 to March 2017 had cargo area higher than the maximum capacity of a PSV3000 vessel and hence needed to be transported by a PSV4500. **Figure 26** shows the area distribution per each fulfilment carried out over this period.



Figure 26 – Area Distribution per each Fulfilment

After the vessel class is chosen, the entity will wait for the vessel (transporter). Thus, there will be four vessel-allocating queues depending on the class: LH2500, PSV1500, PSV3000 and PSV4500. The logic built for this model is that vessel heads to the port anchoring area when finishing a supply operation and then will wait until a cargo entity requests her. A 1000-km/h speed has been assigned to the requesting, which means the vessel will move at a speed of 1000 km/h from the anchoring area to the port to load the cargo. This underpins the assumption explained above, under which the allocation of a vessel will be instantaneous from the moment the vessel is released

and assigned to that particular entity. In this model, the four transporters LH_2500, PSV_1500, PSV_3000 and PSV_4500 have respectively 3, 2, 5 and 20 units, which represent the number of vessels of each class. **Figure 27** presents a list of the features attributed to each transporter. The distance between stations is specified by a matrix of distance (Distance Set) through which the vessel will navigate.

	Name	Number of Units	Туре	Distance Set	Velocity	Units	Initial Position Status	Report Statistics
1 🕨	PSV_4500 💌	20	Free Path	PSV_4500.Distance	1.0	Per Hour	0 rows	I
2	PSV_3000	5	Free Path	PSV_3000.Distance	1.0	Per Hour	0 rows	
3	PSV_1500	2	Free Path	PSV_1500.Distance	1.0	Per Hour	0 rows	
4	LH_2500	3	Free Path	LH_2500.Distance	1.0	Per Hour	0 rows	

Figure 27 – Transporter Features

The transporter initial speed defined has been the ARENA-set default value (1 km/hour). This condition will not influence the speed of the vessel, since the value set upon the vessel allocation will prevail. The distance set defined in this module is shown by the distance matrix shown by **Table 11**.

ID	Beginning Station	Ending Station	Distance (km)
1	Port	anchoring_area	1
2	Port	UEP16	179
3	Port	UEP18	157
4	Port	UEP47	140
5	Port	UEP38	116
6	Port	UEP20	175
7	Port	UEP45	139
8	Port	UEP3	126
9	Port	UEP10	124
10	Port	UEP15	193
11	Port	UEP32	213
12	Port	UEP31	205
13	Port	UEP24	156

Table 11 - Distance Matrix (km)

ID	Beginning Station	Ending Station	Distance (km)
14	Port	UEP28	174
15	Port	UEP23	176
16	Port	SONDA2	129
17	Port	SONDA8	131
18	Port	UMS2	173
19	Port	UEP5	209
20	Port	UEP44	408
21	UEP16	anchoring_area	179
22	UEP18	anchoring_area	157
23	UEP47	anchoring_area	140
24	UEP38	anchoring_area	116
25	UEP20	anchoring_area	175
26	UEP45	anchoring_area	139
27	UEP3	anchoring_area	126
28	UEP10	anchoring_area	124
29	UEP15	anchoring_area	193
30	UEP32	anchoring_area	213
31	UEP31	anchoring_area	205
32	UEP24	anchoring_area	156
33	UEP28	anchoring_area	174
34	UEP23	anchoring_area	176
35	SONDA2	anchoring_area	179
36	SONDA8	anchoring_area	131
37	UMS2	anchoring_area	173
38	UEP5	anchoring_area	209
39	UEP44	anchoring_area	408

An attribute associated to the type of vessel will be assigned to the cargo entity. This parameter is extremely important, since it may be recovered later in the model to find out the type of vessel is being used at a determined stage of the offshore cycle.

An assignment for the port loading time counting has been placed in the model. The port loading time will be used as one of the validation parameters. The time taken to carry out the loading ("port_loading_time" attribute) will be calculated as an attribute associated to the cargo entity. In addition, a variable ("total_port_loading_time") is used to count via iteration method the total port loading time performed in the model during the simulation.

Upon the beginning of the port loading process, the cargo entity picks up a resource called "quay", to which a capacity of six has been associated, meaning that the port has six berths to moor offshore supply vessels. The resource seizing logic chosen has been the "Seize Delay Release", which indicates that a resource will be allocated, followed by process delay and then the allocated resource will be freed.

The loading time specified in this module is expressed as the multiplication of the port average lifting time by the number of liftings ("amount_cargo" attribute) associated to the cargo entity. As shown previously, the average lifting time performed in Port of Macae is 6 min (0.1 hour) and the number of liftings had been assigned upon the cargo arrival section of the model.

Then, checking will be carried out to verify to which cluster the entity belongs and then the cargo will be moved to its respective cluster. After that, it heads for a set of transporting modules and then it will be transferred to its destination (cluster's first unit).

The vessel speed distribution has been collected from an oil company-owned specific software that extracts AIS (Automatic Identification System) signal data and enables the analysis of speeds performed by a set of vessels of interest within a desired period. Data collected over the period from April 2016 until March 2017 for each vessel trip performed in a total of 1,708 shows via Arena Input Analyzer that the speed set is a normal distribution with mean of 8.24 knots (15.3 km/h) and standard deviation of 1.39 knot (2.6 km/h) as presented by **Figure 28**.



Figure 28 – Vessel Speed Distribution Best Fit Obtained through Arena Input Analyzer

4.2.4 Offshore Units Section

This section of the model aims at presenting the logic built in ARENA to simulate the loading of the offshore units. **Figure 29** shows a flowchart describing the structure of this logic.





Figure 29 – Offshore Loading Flowchart

The offshore units have been defined in this model as stations. The cargo entity goes to the station corresponding to the first unit's 500-m zone, where a checking will verify whether the cargo will be waiting for the improvement of the weather condition (WOW) and/or the green light from the unit to proceed (WOP) to operation based on the historical data of the fulfilments that involved WOW or/and WOP code (waiting probability).

Then, the entity will wait a time expressed as a distribution derived also from historical data. **Table 12** shows historical percentage of WOW or/and WOP and waiting time distributions.

Cluster	Unit	Waiting Probability	Waiting Time Distribution (h)
PLAT1	UEP16	32%	LOGN(14, 45.6)
	UMS3	46%	92 * BETA(0.286, 1.78)
	UEP21	26%	GAMM(18.1, 0.776)
PLAT2	UEP18	22%	WEIB(10.9, 0.696)
	UEP14	34%	LOGN(13.3, 39.1)
	UEP13	22%	LOGN(17, 53.4)
	UEP19	22%	91 * BETA(0.368, 1.53)
PLAT3	UEP40	15%	LOGN(13.7, 51)
	UEP47	11%	WEIB(12.3, 0.689)
	UEP39	17%	109 * BETA(0.339, 1.72)
	UEP46	14%	LOGN(10.6, 23.9)
	UMS7	41%	95 * BETA(0.347, 2.17)
PLAT4	UEP38	16%	WEIB(16.5, 0.774)
	UEP37	20%	LOGN(6.21, 16.8)
	UEP6	9%	EXPO(24.2)
	UEP9	18%	WEIB(9.5, 0.557)
	UEP49	20%	WEIB(9.18, 0.67)
PLAT5	UEP20	23%	WEIB(9.68, 0.825)
	UEP12	26%	104 * BETA(0.29, 2.47)
	UEP41	32%	LOGN(9.17, 18.2)
	UEP43	13%	35 * BETA(0.382, 0.97)
	UEP42	30%	LOGN(5.93, 13.5)

Table 12 - Waiting Probability and Waiting Time Distribution
Cluster	Unit	Waiting Probability	Waiting Time Distribution (h)
	UEP45	15%	LOGN(6.62, 17.7)
	UEP48	12%	WEIB(10.1, 0.719)
PLAT6	UEP53	19%	LOGN(11.5, 29.8)
	UEP52	8%	EXPO(7.2)
	UEP51	11%	LOGN(8.16, 23.7)
	UEP3	35%	LOGN(10.7, 24.8)
ρι Δτ7	UEP2	57%	44 * BETA(0.208, 0.861)
1 12/11 /	UEP34	24%	LOGN(25.3, 76.5)
	UEP36	36%	129 * BETA(0.258, 1.45)
	UEP10	17%	LOGN(12.2, 39.5)
	UEP8	22%	66 * BETA(0.456, 2.17)
PLAT8	UMS2	42%	66 * BETA(0.347, 1.6)
	UEP7	33%	146 * BETA(0.198, 2.22)
	SONDA9	36%	86 * BETA(0.226, 1.08)
	UEP15	28%	LOGN(23.6, 80.5)
PLAT9	UEP17	48%	LOGN(16.6, 47.8)
	UMS1	38%	LOGN(17.6, 61.1)
	UEP25	15%	LOGN(16.5, 51.5)
	UEP32	16%	123 * BETA(0.387, 1.83)
PLAT10	UEP27	18%	LOGN(18.9, 61.8)
	UEP50	8%	WEIB(8.04, 0.734)
	UEP4	35%	LOGN(13.6, 32.9)
	UEP31	26%	LOGN(29.8, 123)
PLAT11	UMS4	35%	WEIB(8.7, 0.707)
1 24 11 11	UEP35	18%	76 * BETA(0.494, 1.52)
	UEP29	12%	LOGN(17.1, 63.4)
	UEP24	24%	LOGN(12.2, 38.8)
PLAT12	UEP26	36%	WEIB(12.9, 0.723)
	UEP22	21%	118 * BETA(0.237, 4.83)
<u> </u>	UEP28	10%	TRIA(0, 56, 118)
PLAT13	UEP33	14%	LOGN(6.95, 18.5)
	UEP1	43%	LOGN(9.97, 32)
PLAT14	UEP23	27%	LOGN(23, 86.6)
	UMS5	24%	NORM(22.6, 15.1)

Cluster	Unit	Waiting Probability	Waiting Time Distribution (h)
	UEP30	26%	WEIB(8.85, 0.726)
	UMS6	20%	LOGN(4.4, 8.46)
	SONDA2	35%	LOGN(4.42, 7.74)
	SONDA4	37%	118 * BETA(0.393, 2.76)
SOND1	SONDA1	44%	118 * BETA(0.174, 0.846)
	SONDA5	58%	118 * BETA(0.368, 2.59)
	SONDA7	52%	118 * BETA(0.437, 2.65)
	SONDA8	23%	LOGN(6.9, 15.1)
	SONDA3	35%	118 * BETA(0.46, 3.92)
SOND2	SONDA6	53%	118 * BETA(0.393, 3.89)
	SONDA1	38%	118 * BETA(0.367, 1.48)
	UEP11	9%	NORM(7.09, 2.15)
ESP1	UEP5	0%	7 + 60 * BETA(0.24, 0.247)
ESP2	UEP44	8%	6 + WEIB(4.52, 0.282)

The cargo entity then goes to a stage where the vessel is approaching the offshore unit inside the 500-meter exclusive zone. Data collected from vessel trip records show that most of approaching is carried out in around 45 min (0.75 hour).

The entity starts the loading process, where the cargo onboard the vessel will be offloaded onto the platform deck. The loading time specified is expressed as the product of the offshore average lifting time by the number of liftings associated to the cargo entity for that offshore unit. As shown by **Figure 30**, the average lifting time during the period from April 2016 until March 2017 is 12 min (0.2 hour).



Figure 30 – Offshore Lifting Time

After going through the loading process, an assignment will be associated to the entity. This assignment calculates the time between the beginning of the loading in the port and the finishing of the loading onto the platform. Then, the time calculated will be compared to the deadline expected (96 hours). As explained before, this deadline is considered for the evaluation of the offshore transportation fulfilment indicator.

If the cargo is the delivering time is shorter than the 96-hour limit, the number of liftings associated to the entity will be counted as if being delivered within the deadline. If not, the number of liftings will be counted as if being after the deadline expected. Both numbers of entities delivered late or in time are expressed in the model as variables ("amount_delayed" and "amount_intime", respectively) that will be updated through an iteration process every time the cargo is delivered to the unit.

From this point on, the cargo will be considered as delivered, although the controlling entity will continue to flow through the model carrying cargo information such as number of liftings and deck area.

The set entity and vessel moves away from the offshore unit out of the 500meter exclusive zone. As in the case of the approaching, data collected from vessel trip records show that vessels take on average 45 min (0,75 hour) to leave the 500-meter zone. As explained previously, the time a vessel takes to navigate from an offshore to another within a same cluster is a value that ranges from 1 hour to 2 hours with a few exceptions of values out of this range. Thus, data from Vessel Trip Report for navigation among units have been collected and distributions have been found through Arena Input Analyzer to represent the navigating time between two platforms' 500-m zone in the model (**Figure 31**).



Figure 31 – Navigation Time Distribution between Units in a Same Cluster

This approach has been taken in order to reduce the complexity of the model regarding the handling of the distance matrix. As the navigating time between the anchoring area and the port has been assumed to be zero and distances to the offshore units have been taken from the anchoring area, the distance matrix holds only one column. If the present study had considered the distance among units within the same cluster instead of the navigating time, the distance matrix would possess several columns increasing considerably the complexity of the model.

The process logic of cycling through the next offshore repeats as described in this section. After moving away from the last offshore unit of the cluster, there will be a checking on the type of vessel that performed the supply operation in order to obtain the numbers of fulfilments that each class of vessel carried out in the model monthly and compare them to real values. Thus, the variable "vesseltype" defined upon the allocation of vessel in the port section will be checked out. If the variable is equal to 1, an assignment counts the number of fulfilments performed by a PSV4500. On the other hand, if the variable is equal to 2, an assignment counts the number of fulfilments performed by a PSV3000. If the variable is equal to 3, an assignment counts the number of fulfilments performed by a PSV1500. If the variable is equal to none of those values (1 to 3), the assignment will count the number of fulfilments performed by a LH2500.

After this checking, the set entity and vessel moves to the port anchoring area. The speed distribution set for the transporter is the same found for the navigation from the port to the first offshore unit of the cluster.

4.2.5 Anchoring Area Section

This section describes interactions taking place in the port anchoring area. All vessel downtime occurrences have been analyzed as if has been taken place in this location. Therefore, vessels stay in downtime according to the probability of breaking down based on historical indicators and distributions. Furthermore, the controlling entity that guided the "cargo" throughout the model will be disposed after the vessel is called by the port to carry out another loading. **Figure 32** shows the simulation logic built to represent all operations being performed in the anchoring area.







Figure 32 – Anchoring Area Flowchart

After arriving into the anchoring area station, an assignment related to the end of cycle time counter will be carried out. The time spent from the beginning of the port loading ("initialtime" attribute) until the returning to the anchoring area ("finalcycletime" attribute) will be compared to real values in the validation stage of this thesis.

After closing out the offshore cycle for the purpose of timing, a checking on the type of vessel based on the attribute "vesseltype" defined in the port loading section will be made. Based on her type, the vessel goes to her respective class of diesel consumption. The diesel oil consumption will be based on the cycle time calculated and the average of consumption for each stage of the offshore operation (port loading, navigation, waiting and offshore loading) as well as the diesel unit cost for the oil company studied. **Table 13** presents average values for diesel oil consumption according to the class of the vessel.

Vessel Type	Diesel Consumption (L/h)	Arena Variable
PSV4500	510	Dieselconsumption_PSV4500
PSV3000	320	Dieselconsumption_PSV3000
PSV1500	260	Dieselconsumption_PSV1500
LH2500	120	Dieselconsumption_LH2500

Table 13 - Oil Diesel Consumption

The assignment for the diesel consumed is carried out according to the class of the vessel. The value (R\$1.00 / liter) for the diesel cost unit ("Dieselprice" variable) has been set based on the internal cost of diesel for the oil company not on the market price, which is usual in accounting procedures to calculate diesel exceeding consumption and stocking handling. **Equation 3** shows the calculation of the diesel consumption cost for a vessel PSV4500.

The variable "dieselcostvessel" represents the sum iterator of consumptions of all types of vessels as shown by **Equation 4**.

Dieselcostvessel = dieselcostvessel + dieselcostvesselPSV4500 Equation 4

The entity then moves to a checking to verify whether the vessel will undergo a downtime or not based on a historical average of the uptime indicator. As shown previously, the average uptime performed by SL I vessels over the period ranging from April 2016 to March 2017 is 93%. Thus, in 7% of cases, the vessel will go to the

downtime process, where she will be repaired or pending issues will be tackled during a certain time provided by historical distribution (**Figure 33**).



Figure 33 – Repairing Time Distribution

For real-valued data, the number of intervals in the histogram is determined as the square root of the number of data points, with the restriction that the number of intervals be at least 5 and not more than 40. As the downtime records held 634 data points, the Arena Input Analyzer calculated 25 intervals for the histogram shown in the Figure 33. For the Chi-Square Test to find the distribution fitting, the Arena Input Analyzer used only two intervals considered to have significative relative frequency for the exponential distribution obtained. The **Figure 33** shows only the three first intervals - 0.04 h to 50.47 h, 50.47 h to 100.91 h and 100.91 h to 151.34 h - which have relative frequency of 91.96%, 6.31% and 0.95%, respectively, while the remaining intervals have frequency close to zero (<0.5%).

Then, the time spent in the anchoring area is calculated through an assignment for the purpose of evaluating the diesel consumed in this place. This calculation is carried out after the downtime, since during the time the vessel undergoes a downtime, the ship company pays for the diesel consumed. After being repaired, the diesel oil consumed is then paid by the oil company.

Again, another checking on the type of vessel is done. For instance, if she is a LH2500 vessel, the transporter goes also to another checking that will verify whether

there is no vessel already waiting for the cargo programming, i.e., whether the number in queue (NQ) of LH2500 vessels is smaller than one.

If there is any vessel waiting (NQ ≥ 1), the set entity and transporter will wait until there is no vessel waiting for cargo programming.

If there is no vessel waiting (NQ = 0) or the queue becomes empty, the set entity and transporter (vessel) moves to the queue immediately after passing again through the check to verify if NQ = 0. In the queue, the transporter will stay on hold until there is at least one entity in the port requesting a vessel for allocation, i.e., until the number of entities in the queue for requesting a LH2500 is higher than zero ("request_LH_2500>0).

Thus, as explained before, it is important that transporter spends a time as close as possible to zero to navigate from the anchoring area to the port to carry the controlling entity, otherwise if there have been two transporters waiting for one transporter requesting, both transporters would be authorized to proceed to launch forth into seeking the entity in the port, since the condition "request_LH_2500>0" would not be satisfied as long as the first vessel released has not met the entity in wait. Then only of them would be allocated to the entity in wait and the other would stay around in the model without being counted the time she is waiting in the anchoring area, i.e., without generating statistical data on waiting cargo programming for this transporter as the vessel left the anchoring area station. The same logic built for LH2500 works for the other offshore supply vessels.

The set entity and transporter, after leaving the cargo programming waiting queue, will be split and the transporter will be freed from the controlling entity to seek the other entity requesting transporter in the port and the controlling entity will in turn be disposed.

By means of an assignment, the time the vessel waited in the anchoring area will be calculated. The diesel consumption in the anchoring area cost will be calculated based on the vessel class and the time the vessel is awaiting in that location as shown by **Equation 5** for PSV4500 vessel.

diesel_cost_for_PSV4500_anchoring = anchoring_time x dieselconsumption_PSV4500 x dieselprice Equation 5

Table 14 shows the diesel consumption cost in the anchoring area for each type of vessel. As can be seen, the diesel consumed in the anchoring is much smaller than the average consumed along the path going from the port loading until the return to the anchoring area, which is reasonable, since the dynamic positioning system is deactivated when the vessel is anchored.

Vessel Type	Diesel Consumption (L/h)	Arena Variable
PSV4500	104	Dieselconsumption_PSV4500_anchoring
PSV3000	55	Dieselconsumption_PSV3000_anchoring
PSV1500	28	Dieselconsumption_PSV1500_anchoring
LH2500	12	Dieselconsumption_LH500_anchoring

 Table 14 - Diesel Consumption in the Anchoring Area (L/h)

The total cost of diesel consumed for all vessels will be calculated through the iterative variable "*Dieselcostvessel_anchoring*" as shown by **Equation 6**.

dieselcostvessel_anchoring = dieselcostvessel_anchoring + diesel_cost_for_PSV4500_anchoring = **Equation 6**

Some additional statistics collected during the simulation will be defined. For the model, two types of statistics have been used to collect data: output and timepersistent. **Figure 34** shows the data collected upon the finishing of the simulation.

	Name	Туре	Expression	Collection Period	Report Label	Output File
1	delay_number	Output	amount_delayed	Entire Replication	delay_number	
2	intime_number	Output	amount_intime	Entire Replication	intime_number	
3	PSV4500_counting	Output	count_psv_4500	Entire Replication	PSV4500_counting	
4	PSV3000_counting	Output	count_psv_3000	Entire Replication	PSV3000_counting	
5	PSV1500_counting	Output	count_psv_1500	Entire Replication	PSV1500_counting	
6	LH2500_counting	Output	count_lh_2500	Entire Replication	LH2500_counting	
7	port_loading_time_result	Output	total_port_loading_tim	Entire Replication	port_loading_time_result	
8	cycletime_avg	Time-Persistent	cycletime	Entire Replication	cycletime_avg	

Figure 34 – Statistics Data Collected – Statistics Module

The data "delay_number" and "intime_number" will collect the number of cargoes that have been delivered to the offshore units after and within the deadline, respectively.

The outputs PSV4500_counting, PSV3000_counting, PSV1500_counting and LH2500_counting count the number of fulfilments that have been performed with PSV4500, PSV3000, PSV1500 and PSV4500, respectively. The counting is carried out in the Offshore Unit Section after the operation with all platforms of the cluster.

On the other hand, the output "port_loading_time_result" collects the average port loading time, which is in turn computed through the difference between the end and start times of the port loading operation.

Finally, "cycle_avg" calculates the average cycle time (from scheduled starting of the loading operation until arrival in the anchoring area) over the entire period of the simulation.

4.3 Validation

The simulation model built in this study will be tested by comparing modelgenerated data with real values, i.e., the validation will evaluate if the model truly represents the reality. Since the fleet size varied sharply over the year of 2016 and the current fleet remained flat during the three first months of 2017, the comparison will consider the average operation parameters performed over period ranging from January 2017 until March 2017. **Table 15** shows the proposed comparison as well as the deviation between the model and the reality. The model has been run with 20 replications and a 2-month warm-up over the period of one year.

Comparative Table								
Data	Simulation	Real Operation	Deviation					
Cycle Time (h)	61.86	63.67	3%					
Number of Liftings Delivered	6,906	6,979	1.0%					
Percentage of Liftings Delivered within the Deadline (%)	96.50%	95.37%	1.2%					
Deck Area Carried (m ²)	41,436	42,021	1.4%					
Vessel Deck Occupancy (%)	63.9%	62.7%	1.9%					
Number of Fulfilments Performed	137	135	1.2%					
Load Berth Occupancy Time (h)	673.0	700.3	4.1%					

Table 15 - Comparative Table for the Validation

Comparative Table							
Data	Simulation	Real Operation	Deviation				
Waiting Time in the Anchoring Area (PSV4500+PSV3000+PSV1500) (day)	1.05	1.10	4.8%				
Waiting Time in the Anchoring Area (LH2500) (day)	3.67	3.87	5.4%				

The values found in the table above have been obtained by dividing those generated in the simulation by twelve to represent a monthly period. The deck area carried in the simulation has been calculated by multiplying the number of liftings delivered by six, which is a number that lives up to the one found in the operation as explained previously. The number of fulfilments performed has been found by counting the number of fulfilments carried out by each type of vessel (54 by PSV4500, 52 by PSV3000, 24 by PSV1500 and 7 by LH2500). The average vessel deck occupancy has been obtained through the formula shown by **Equation 7**:

Average Vessel Occupancy (%) =
Total of Deck Area Carried (m^2)
$\sum_{i=1}^{4} (Number \ of \ Fulfiments_i \times Vessel \ Deck \ Capacity(m^2)_i)$

Equation 7

i: number of vessel types

Replacing the values in the **Equation 7**:

Average Vessel Occupancy (%) = $\frac{41.436}{(630 \times 54 + 460 \times 52 + 270 \times 24 + 63 \times 7)}$

Average Vessel Occupancy = 63.9%

The values found in the table have been considered satisfying and the deviation within an acceptable range. The fact that the cycle time obtained through the simulation has been smaller than the real value is reasonable, since the model has not considered returns to the platforms in the same fulfilment. The high deviation for the waiting time in the anchoring area has been considered acceptable as well, since the cycle time obtained in the simulation is smaller than the real cycle time, implying that the vessel will arrive in that place earlier. Thus, the error found in the waiting time accumulated its own error as well as the error obtained for the cycle time.

Furthermore, a consistency analysis has been done to verify whether the model is behaving as expected based on real operational data. The number of entities exiting the buffer reached the maximum value 1 in three replications out of a total of 20 and 0 in the remaining replications. Regarding the number of fulfilments performed by each replication as well as the number of liftings carried out, the number of leftover occurrence has been deemed negligible. Thus, that the model built to simulate the real operations worked as expected. Also, the simulation results match with the fact that the number of entities waiting in the queue for loading each offshore unit shall be zero, showing that no vessel is waiting another vessel to operate with platforms.

As explained before, the number of entities in queue for vessel allocation shall be zero. As presented in **Figure 35**, the report issued by Arena shows that the simulation provided results that lived up to what is expected from the operational experience.

Model Filename:	C:\Use	\Users\Rafael Basilio\Desktop\ARENA MODELOS\Final Page						17	of	31	
15:57:45		Category Overview							junho 21, 2017		
Unnamed Pr	Jnnamed Project										
Replications:	20	Time Units:	Hours								
Queue											
Other											
Number Waiting			Average	Half Width	Minimum Value	Maximum Value					
request_LH_2500.Q	lueue		0,00	(Insufficient)	0,00	0,00					
request_PSV_1500	.Queue		0,00	(Insufficient)	0,00	0,00					
request_PSV_3000	Queue		0,00	(Insufficient)	0,00	0,00					
request_PSV_4500	.Queue		0,00	(Insufficient)	0,00	0,00					

Figure 35 – Average Port Loading Time Calculation

Finally, it is possible to conclude that the modelling of all platforms and all clusters – although it brought huge complexities to the simulation – has been crucial, since the model has been validated through parameters reasonably close to the reality.

5. RESULTS AND DISCUSSION

The study has been carried out through three scenarios regarding the impact on the service level and the cost perspective has been added to the analysis. In the first scenario, the influence of the gradual downsizing of the number of PSV4500 vessels and the maintenance of the number of other vessels have been analyzed over the anchoring area waiting time, vessel allocating time, cycle time and offshore transportation fulfilment indicator. The same has been done for PSV3000 vessels in the second scenario. Since the number of LH2500 and PSV1500 are small and the oil company needs at least three LH2500 vessels to service the two special offshore units (one vessel for each special unit and an addition third one to fill in for the two vessels in case of downtime), further scenarios to analyze the contribution of the number of these vessels alone over the above-mentioned parameters have not been framed. The last scenario took into account the proportional reduction of the entire fleet by the following percentages: 75%, 50% and 25%. **Table 16** shows the simulation scenarios proposed by this study.

Scenario	Vessel Analyzed	Description	Sub-scenarios analyzed	Goal
Ι	PSV4500	Gradual reduction of the PSV4500 fleet	I to VIII	Analyze the impact of the reduction of the PSV4500 fleet on the indicators
п	PSV3000	Gradual reduction of the PSV3000 fleet	I to IV	Analyze the impact of the reduction of the PSV3000 fleet on the indicators
III	PSV4500, PSV3000 and PSV1500	Proportional Reduction of the entire fleet (75%, 50% and 25%)	I to III	Find the optimal fleet regarding efficiency and cost

Table 16 - Simulation Scenarios Proposed

In order to carry out the analysis, an Intel[®] Core i7 2.0 GHz and 4.0 GB RAM memory CPU machine has been used. The computation time for one replication has been 34.0 seconds. Since a number of 20 replications has been set up in the model, the time to run the entire simulation for each fleet level in each scenario reached about 680 seconds (11.3 minutes).

5.1 Warm-up Time Determination

The simulation has been run over a 9000-hour period (one year) and the cycle time found has been analyzed. The variable "cycle time" has been chosen since is the main indicator used in the offshore transportation area, which is in turn used for the purpose of evaluation of the offshore logistics performance. Due to the fact that the cycle time is a time indicator, this parameter gathers the inefficiency both of the logistics itself and the offshore unit, the weather contribution as well as other unproductivity issues and hence is a good thermometer to size the vessel fleet. For instance, if there is a short cycle time, the vessels will arrive earlier in the anchoring area and hence if the fleet is not well sized, a huge number of vessels will be waiting for cargo programming, which generates in turn a burdensome time of unproductivity codes. Thus, in general, a short cycle time and a great anchoring area waiting time indicate the need to cut down on the fleet. To determine the warm-up period, a simulation with a fleet of 20 PSV4500, 5 PSV3000, 2 PSV1500 and 3 LH2500 has been run. **Figure 36** shows the variation of the cycle time along the entire replication over the period of about one year.



Figure 36 - Cycle Time Variation for the Determination of the Warm-up Period

As shown in the figure above, the cycle time becomes stable from the hour 1,100 (1.5 month). Thus, a time of 1,440 hours (2 months) has been considered for the warm-up period.

5.2 **Replication Number Determination**

The method used in this study to determine the minimum number of replications has been adopted by DIUNA (2017) and is based on work developed by CHWIF (2013). According to this method, the number of replications will be provided by confidence interval, which is in turn based on a pilot sample proposed. The variable "cycle time" has been chosen again to be monitored along the proposed 20-replication sample. **Table 17** shows the outcome of the pilot round of 20 replications for the cycle time.

Replication	Average Cycle Time
1	61.8514
2	61.8613
3	61.8607
4	61.8631
5	61.8505
6	61.8545
7	61.8735
8	61.8749
9	61.8620
10	61.8874
11	61.8683
12	61.8842
13	61.8717
14	61.8506
15	61.8887
16	61.8727
17	61.8562
18	61.8673
19	61.8652
20	61.8899
Mean	61.8677
Standard	
Deviation	0.0102

Table 17 - Average Cycle Time for the Determination of the Minimum Number of ReplicationsRequired

According to CHWIF (2013), the optimal number of replications can be defined by finding the confidence interval for the variable chosen to be monitored. The **Equation 8** defines the confidence interval of an *n*-sized sample with statistic confidence of $100\%(1 - \alpha)$ (DIUANA, 2017).

$$h = t_{n-1,\alpha} * \frac{s}{\sqrt{n}}$$
 Equation 8

h: Half of the confidence interval

 $t_{n-1,\alpha}$: Student's t-distribution percentile with n-1 degrees of freedom

s: sample standard-deviation

n: sample size

From *h*, the confidence interval is built as $[\bar{x} - h, \bar{x} + h]$, where \bar{x} represents the sample mean.

Thus, by replacing the value found for the pilot sample in the **Equation 8**, the confidence interval can be built regarding the result of the cycle time variable with a statistic confidence of 95%, i.e., $\alpha = 0.05$.

In the Student's t-distribution table, $t_{19,0.025} = 2.093$. Thus, the value of h is given by:

$$h = 2.093 * \frac{0.0102}{\sqrt{20}} = 0.0048$$

Therefore, as the replication mean is $\bar{x} = 61.8677$, the confidence interval is [61.8629, 61.8725].

Also, according to CHWIF (2013), the optimal number of replications n^* , with a precision desired not less than h^* , is given by **Equation 9**.

$$n^* = \left[n\left(\frac{h}{h^*}\right)^2\right]$$
 Equation 9

 h^* : confidence interval precision aimed

So, from the 20-replication pilot sample with a confidence interval precision not smaller than 0.005, the optimal number of replications is determined.

$$n^* = \left[20\left(\frac{0.0048}{0.005}\right)^2\right] = 18.1908$$

The number of replications needed to obtain a confidence interval of 95% and precision of 0.005. Thus, to make sure that the results will have a higher reliability, a simulation with 20 replications has been run.

5.3 **Results Obtained**

The first scenario comprehended the simulation of the downsizing only of the PSV4500 vessel fleet with the purpose of studying the influence of the fleet size for this

type of vessel on parameters such as anchoring area waiting time, vessel allocating waiting time, cycle time and offshore transportation fulfilment indicator. **Table 18** shows the fleet size used in each sub-scenario simulated for the first scenario proposed by this study.

Sub-scenario	0	Ι	II	III	IV	V	VI	VII	VIII
PSV4500	20	18	16	14	12	10	8	6	4
PSV3000	5	5	5	5	5	5	5	5	5
PSV1500	2	2	2	2	2	2	2	2	2
TOTAL	27	25	23	21	19	17	15	13	11

Table 18 - First Scenario – Reduction of the Number of PSV4500

The sub-scenario "0" relates to the current fleet size adopted in Campos Basin offshore logistics system. **Figure 37** presents the results of the simulation regarding the vessel allocation waiting time, i.e., the time the entity waits in queue to be allocated to a transporter (vessel).



Figure 37 - First Scenario – Vessel Allocation Waiting Time

Although, the number of PSV4500 is greater than that of PSV3000, the demand for vessel allocation is lower than that for the latter, which is reasonable, as the average cargo area (around 360 m²) fits in a PSV3000 vessel and hence the demand for this vessel increases as the number of PSV4500 decreases.

Figure 38 shows the anchoring area waiting time according the fleet size for PSV4500 vessels simulated.



Figure 38 - First Scenario – Anchoring Area Waiting Time

The anchoring area waiting time is more sensitive to the downsizing of the fleet than the vessel allocation waiting time, since, if there is an exceeding number of vessels, the time the cargo spends to be allocated to a transporter will be almost or equal to zero. On the other hand, the effect of a decreasing fleet will dawn on the anchoring area waiting time as there is a lower number of vessels that will be waiting for cargo programming in that place. The reduction of PSV4500 vessels will increase the optimization of the fleet, since this vessel is more expensive and provides an exceeding deck area as the average cargo area per each fulfilment is 360 m². The reduction of the number of PSV4500 makes the PSV3000 anchoring area waiting time drop even faster, as this latter type of vessel has sufficient deck area to accommodate the average cargo area and then responds to a stronger demand for allocation.

Figure 39 shows the influence of the downsizing of the PSV4500 fleet on the cycle time.



Figure 39 - First Scenario – Cycle Time

The impact upon the cycle time resulting from the reduction of the PSV4500 is higher from the moment the time spent in queue for vessel allocation is greater than zero, which is suitable, since the cycle time is counted from the moment the port loading starts. **Figure 40** shows the influence of the downsizing of the PSV4500 fleet on the offshore transportation fulfilment indicator. As it occurred to the cycle time, the influence on the indicator will be seen only from the moment the anchoring area waiting time is greater than zero.



Figure 40 - First Scenario – Offshore Transportation Fulfilment Indicator

From the current configuration to the sub-scenario VI, the number of PSV4500 vessels dropped from 20 to 8 (-60%), although the vessel allocation waiting time has not increased significantly (+ 1.07 h). This situation indicates an opportunity of fleet downsizing and it is possible to conclude that the fleet of PSV4500 vessels is completely oversized.

The second scenario comprehended the simulation of the downsizing only of the PSV3000 vessel fleet with the purpose of studying the influence of the fleet size for this type of vessel on parameters such as anchoring area waiting time, vessel allocating waiting time, cycle time and offshore transportation fulfilment indicators. **Table 19** shows the fleet size used in each sub-scenario simulated for the second scenario proposed by this study.

Sub-scenario	0	Ι	II	III	IV
PSV4500	20	20	20	20	20
PSV3000	5	4	3	2	1
PSV1500	2	2	2	2	2
TOTAL	30	29	28	27	26

Table 19 – Second Scenario – Reduction of the Number of PSV3000

Figure 41 presents the results of the simulation regarding the vessel allocation waiting time.



Figure 41 - Second Scenario – Vessel Allocation Waiting Time

Reducing the number of PSV3000 vessels proven to have no influence on the vessel allocation waiting time, since there is still an exceeding number of PSV4500 vessels capable of absorbing all demand for cargoes whose area fits in a PSV3000 vessel. Thus, the cycle time and offshore transportation fulfilment indicator will not vary according to the decreasing PSV3000 vessel fleet proposed.

Figure 42 shows the anchoring area waiting time according the fleet size for PSV3000 vessels simulated.



Figure 42 - Second Scenario – Anchoring Area Waiting Time

The impact of a PSV3000 fleet decreasing on the anchoring area waiting time is almost flat, which is explained by the fact that the number of this type of vessel compared to the total fleet is little representative.

Considering that the number of PSV1500 vessels is small, the deck of these vessels is capable of carrying few cargoes and the model does not accept a zero number of transporters, a scenario with the reduction only of the PSV1500 fleet will not be simulated. Furthermore, as shown above for PSV3000, the reduction of the number of PSV1500 vessels would not have any influence on the cycle time and the offshore transportation fulfilment indicator.

The third scenario proposed comprehends the proportional reduction by 75%, 50% and 25% of the current fleet. To this scenario, the cost perspective associated with stock out, charter and Diesel consumption has been added.

 Table 20 presents the sub-scenarios for this third scenario proposed according to

 proportional reduction.

Sub-scenario	0	Ι	II	III
PSV4500	20	15	10	5
PSV3000	5	4	3	2
PSV1500	2	2	1	1
TOTAL	27	21	14	8

Table 20 – Third Scenario - Fleet Reduction (75%, 50% and 25%)

Figure 43 shows results found for the third scenario regarding the vessel allocation waiting time.



Figure 43 – Third Scenario – Vessel Allocation Waiting Time

As can be seen above, under the aggressive reduction of the fleet under the subscenario III, the vessel allocation waiting time skyrocketed. The sub-scenario II presents a good opportunity to reduce significantly the fleet by affecting smoothly the time required to allocate a transporter to an entity.

Figure 44 shows results found for the third scenario regarding the anchoring area waiting time.



Figure 44 – Third Scenario – Anchoring Area Waiting Time

Although the third scenario presented a proportional reduction of the fleet, the impact of this downsizing dawns more on the anchoring area waiting time for PSV4500 vessels, since this type of vessel has the greatest fleet surplus compared to other vessel classes.

It should be emphasized that the fleet sizing cannot be based only on the individual reduction of the fleet of PSV4500 or PSV3000, since the impact of the downsizing of the two fleets on the indicators shows that they are highly correlated. Thus, analyzing the reduction of the fleet as a whole (Scenario III) may bring more cost-effective results.

Figure 45 and **Figure 46** show the cycle time and the offshore transportation fulfilment indicator, respectively.



Figure 45 – Third Scenario – Cycle Time



Figure 46 – Third Scenario – Offshore Transportation Fulfilment Indicator

According to internal resource sizing policy, the target for the offshore cycle time indicator shall be remain between 60 and 70 hours. For the offshore transportation fulfilment indicator, the target shall be at least 90%. Thus, the sub-scenario III is the only that does not meet the requirement for a good service level.

To settle on the ideal fleet that both will present a lower system operation cost and meet the requirements for a suitable service level, it is necessary to calculate costs of diesel oil consumption, monthly charter rates and stock out associated to loss of oil output or drill rig downtime.

The monthly charter cost is calculated according to the **Equation 10**.

Monthly Charter Cost =
$$30 \times DT_A \times \sum_{i=1}^{3} (N_i \times R_i)$$
 Equation 10

 DT_A : average downtime

i: types of vessel

 N_i : number of vessel for the type i

 R_i : charter daily rate

 Table 21 shows the parameters adopted to calculate the monthly charter cost according to Equation 10.

Vessel	Parameter	Daily Rate
PSV4500	R (i = 1)	R\$ 95.000,00
PSV3000	R (i = 2)	R\$ 72.000,00
PSV1500	R (i = 3)	R\$ 50.000,00
Average Downtime	DTA	0.93

Table 21 – Third Scenario – Charter Rates

The calculation of the stock out cost for drill rigs and Units for Maintenance and Safety is carried out based on the impact of a cargo delivering delay on the operation of such units. **Equation 11** presents the formula for the stock out costs associated with drill rigs and UMS.

Stockout Cost =
$$\sum_{j=1}^{2} \left(\frac{LDRD_j \times R_j \times NC_j}{NT} \right) \times \frac{\sum_{i=1}^{3} (NFP_i \times VAWT_i)}{24}$$
 Equation 11

j: type of unit - Drill rig (i = 1) and UMS (i = 2)

LDRD_j: Logistic-related Drill Rig Downtime Indicator

 R_i : Daily Rate associated to type *j* of unit

NC_j: Number of Clusters associated to type *j* of unit

NT: Total Number of Clusters simulated (NT = 17)

 NFP_i : Number of fulfilments performed by vessel of the type j

VAWT_i: Vessel Allocation Waiting Time (per fulfilment) of the type *j* (*hours*)

The *LDRD* indicator is monthly evaluated by the oil company with the purpose of measuring the impact of the cargo delivering delay on the total downtime of a drill rig. This indicator has been seized by the present study as an approximate probability that the cargo delivering delay will affect costs associated with the drill rig daily rate. As there is no such indicator for UMS, the same value for drill rigs will be used for stock cost calculation for such UMS. The purpose of **Equation 11** is to calculate the impact of cargo delivering delay caused by a shortage of vessel (vessel allocation waiting time greater than zero) on the operation of drill rigs and units for maintenance and safety. As the simulation model has been built to verify the number of delayed fulfilments experienced by each offshore unit, the impact of a delay will be calculated considering the number of clusters associated to a certain type of unit within the total of clusters simulated. Thus, the total cost related to cargo stock out will be rated among the offshore units according to the number of clusters associated to them (exclusive and shared clusters). **Table 22** shows the share of each type of offshore unit within the total number of clusters.

Type of Units	Exclusive	Shared Clusters					
	Clusters	PLAT1	PLAT3	PLAT8	PLAT11	PLAT14	TOTAL
Production	9	0,67	0,80	0,60	0,75	0,50	12,32
UMS	1	0,33	0,20	0,20	0,25	0,50	2,48
Drill Rig	2	0,00	0,00	0,20	0,00	0,00	2,20
TOTAL						17	

Table 22 – Third Scenario – Offshore Unit's share in Each Cluster

 Table 23 presents the number of fulfilments performed by each class of vessels

 according to results provided by ARENA.

Table 23 – Third Scenario – Fulfilment Performed According to Type of Vessel

Sub-scenario	0	I	II	III
PSV4500	24	24	25	26
PSV3000	52	52	52	51
PSV1500	54	54	53	53
Total	130	130	130	130

 Table 24 provides the parameters used to calculate the stock out cost associated to drill rigs and UMS, according to Equation 11.

Table 24 – Third Scenario – Drill Rig and UMS Charter Rates

Definition	Daily Rate (R)	NC	LDRD
Drill Rig (i = 1)	R\$ 1.000.000,00	2,20	1%
UMS (i = 2)	R\$ 700.000,00	2,48	1%

The calculation of the stock out cost for oil production units is carried out considering that the risk of a cargo delivering delay may impact on the oil output of such units. **Equation 12** provides the calculation of stock out costs for oil production platforms.

Stockout Cost
=
$$OBP \times ET \times \frac{LDRD \times CBO \times NC}{NT}$$

 $\times \frac{\sum_{i=1}^{3} (NFP_i \times VAWT_i)}{24}$ Equation 12

CBO: Campos Basin oil output (*CBO* = 1.000.000 barrels/day)

OBP: Oil barrel price American dollars;

ET: Exchange Rate.

The same value used for *LDRD* associated to drill rigs has been used for the oil production units. In addition, the value of US\$ 50.00 has been adopted for the oil barrel price with an exchange rate of 1 US\$ = 3.10 R\$.

Diesel consumption-related costs for navigation + loading (port + offshore) have been calculated by ARENA and the result is presented in **Table 25**. The consumption of diesel for navigation + loading has not varied, since regardless of the number of vessels, the time spent for navigation and loading will not change. On the other hand, the cycle time changed, since its counting starts from the beginning of the loading predicted by the table cluster. Thus, even if there is no vessel to be allocated, i.e., vessel allocation waiting time is greater than zero, the cycle time counting begins.

Sub-scenario	0	I	II	III
Diesel - Navigation + Operation (Port + Unit)	R\$ 7.188.481,11	R\$ 7.188.481,11	R\$ 7.188.481,11	R\$ 7.188.481,11
Diesel - Waiting in the Anchorage Area	R\$ 20.086,39	R\$ 17.856,42	R\$ 13.254,71	R\$ 10.181,23
Monthly Charter Cost	R\$ 65.844.000,00	R\$ 50.582.700,00	R\$ 33.926.400,00	R\$ 18.665.100,00
Stock out Cost	R\$ 0,00	R\$ 0,00	R\$ 8.351.919,45	R\$ 328.881.393,35
Total Costs	R\$ 73.052.567,50	R\$ 57.789.037,53	R\$ 49.480.055,27	R\$ 354.745.155,69

Table 25 – Third Scenario – Cost Table

Figure 47 shows a graphic display for the values presented in Table 25.



Figure 47 - Third Scenario – Cost Curves

As can be seen in the figure above, the sub-scenario II represents the situation whose cost is the lowest among the sub-scenarios analyzed. Furthermore, the performance of cycle time and offshore transportation fulfilment indicators meet the target aimed by the oil company.

6. CONCLUSION

The present study aimed at developing a simulation model focused on the optimization of the offshore supply vessel fleet with the purpose of reducing costs without affecting the service level provided by such resources.

The methodology employed in this study has been based on the theoretical conceptualization of the system analyzed and its characterization, followed by a structuration of a logical-mathematical model, which has been implemented and validated computationally.

The scenario II with 10 PSV4500, 3 PSV3000 and 1 PSV1500 has proved to be the scenario in which the fleet size has been reduced to a minimum without compromising the service level required to service offshore units. Although the simulation model built took into account the cargo area and the number of entities in queue requesting a transporter to settle on the vessel to be used, under the current operation policy, the cargo programmer tends to allocate a dedicated vessel for each cluster. However, as the model concluded that a number of 14 vessels and therefore smaller than the current number of clusters, a smaller fleet in turn compels the programmer to work within the system of pool fleet, i.e., the vessel to be programmed for a certain cluster will be that which arrived early in the anchoring area. The scenario III represented the scenario with the most aggressive downsizing, but the service level resulted from it provided indicators out of the target aimed by the oil company. Furthermore, this scenario presented prohibitive cost for the service level proposed, which would affect oil output as well as rise drill rig and UMS downtime.

Although the model simulation has been built to represent offshore operations with origin in Port of Macae, it can be adapted to other ports and Exploitation and Production basins.

The simulation model developed in this study aimed at representing all operations performed by a SL I vessel, except the backloading process. But, with due considerations, the model has been capable of simulating port and offshore loading as well as the representation of productivity-undermining issues such as waiting-onweather time and vessel downtime.

Finally, the study proved to be useful for evaluating the offshore transportation logistics by determining the ideal fleet of offshore supply vessels. Therefore, the model can be used to support strategic logistical decisions applied to other offshore supply chain.

7. FUTURE WORKS

In order to improve the study, within the scope of work proposed and considering the continuation of the simulation method, some considerations can be made about future work expectations. One of them is to allow for a decision logic for revisits to offshore units, route sequence changes and backloading process. This will narrow down the possibilities of imprecision and will strengthen the representability of the model before real operations.

A future study shall be carried out on the proposed cost equations based on software-supported sensitivity analysis with an objective of testing its the robustness regarding uncertainties brought up by cargo stock out costs.

It is proposed to improve the lifting distribution generated in this study with the purpose of reducing the variability found through the Arena Input Analyzer, since distinct distributions shall not be used for similar phenomena. It is recommended to perform a thoroughly investigation regarding magnitude, frequency and place of downtime occurrences in order to improve the modelling and formulation of this process in the simulation.

It would also be appropriate to analyze a model in which the Campos Basin offshore logistics system has been serviced by a system of three or more ports arranged in such a way as to provide the least distance to offshore units according to the region of the basin fulfilled. The analysis could consider the reduction of navigation and fleet costs due to lower diesel consumption and a smaller cycle time.

An optimization analysis is recommended upon more diversified scenarios for fleet sizing, considering, for instance, scenarios of non-proportional fleet reduction in which there would be an increase in the number of PSV3000 and a decrease in the amount of PSV4500, which could in turn lead to lower fleet costs without affecting the available deck area. A study is also recommended to take into consideration the utilization rate of each class of vessel allocated to streamline the optimization analysis.

Furthermore, it is also recommended to modify the model to simulate operations in Port of Açu to check whether there is room to reduce even further the vessel fleet, considering operation features of this Port (overhead cranes and covered docks) and a smaller average distance to the offshore units.

Finally, it is also recommended to widen the scope of this work to simulate potential operations performed by multi-purposed vessels in order to improve the use of their entire capacity and reduce the time spent on loading.

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