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.

Orientador: Jean-David Job Emmanuel Marie Caprace

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"*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**

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

Rafael Basílio da Silva

Setembro/2017

Orientador: Jean-David Job Emmanuel Marie Caprace

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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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 costs perspective will be incorporated for analysis purposes.

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# 1. INTRODUCTION

## 1.1 PURPOSE

This study aims to present 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 area associated to the cargo.

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. Furthermore, the study aims at (BATISTA, 2005):

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

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

To achieve the results, the following procedures were 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 to simulate and optimize 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.

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, north of the 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 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. Furthermore, the study will focus on departures scheduled and hence the transportation destined to fulfill extra or urgent demands will not be analyzed.

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 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 were 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 with 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 was 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 employed 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 employed to reach a minimum cost without affecting the level of serviced 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 (WALLACE, 2010). Based on this context, oil companies aim to increase its logistics offshore system efficiency by reducing the amount of resources used and optimizing processes without compromising the service level of the 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 with 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 bad 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 which immediate replacement is not possible. The vessel downtime is evaluated through the Supply Vessel Uptime Indicator (SVUI), which 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 (SDUI) 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 discrete-event 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 support vessels as well as the needs and the systematics of supplying to 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 sizing of the fleet 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 (ARENA) 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 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 perform 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 time-charter 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 (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 (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 was 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 BATISTA (2016) 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 software ProModel. Through this comparison, the study determined which policy (on-demand or scheduled delivering) presents the best performance as well as the optimal sizing of the fleet for each one. The study added the perspective of cost, 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, 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 consideration of potential intra or extra clusters influences on the final results. Finally, this present thesis proposes a more reliable estimation methodology of the duration of the operation with the offshore units based on the number of liftings derived from historical data.

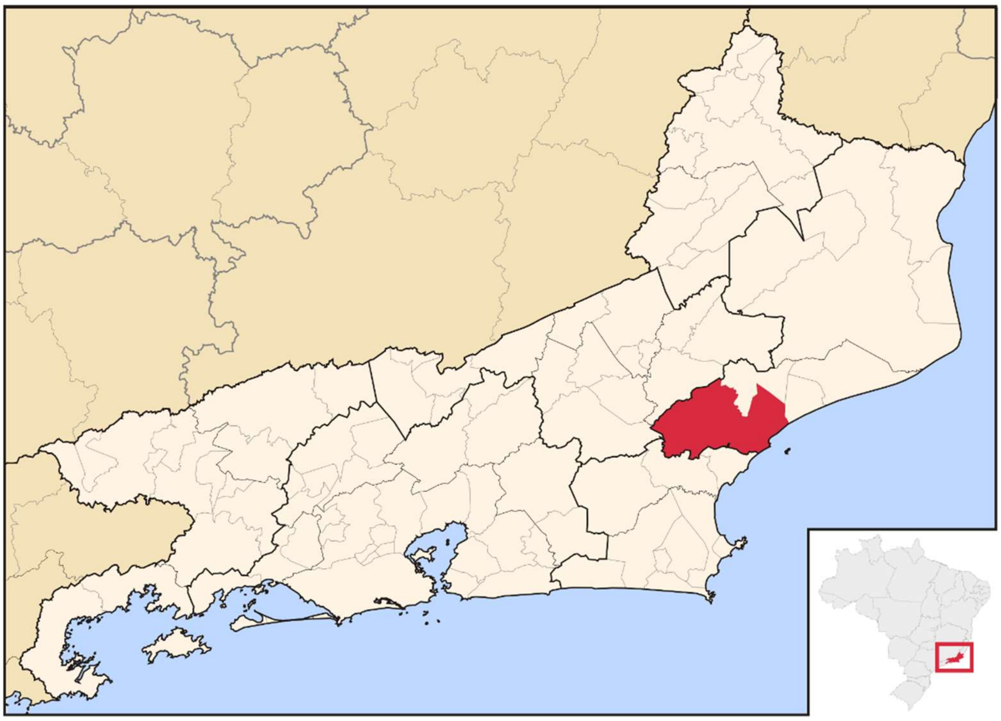
# 3. CURRENT LOGISTICS SYSTEM DESCRIPTION

## 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).

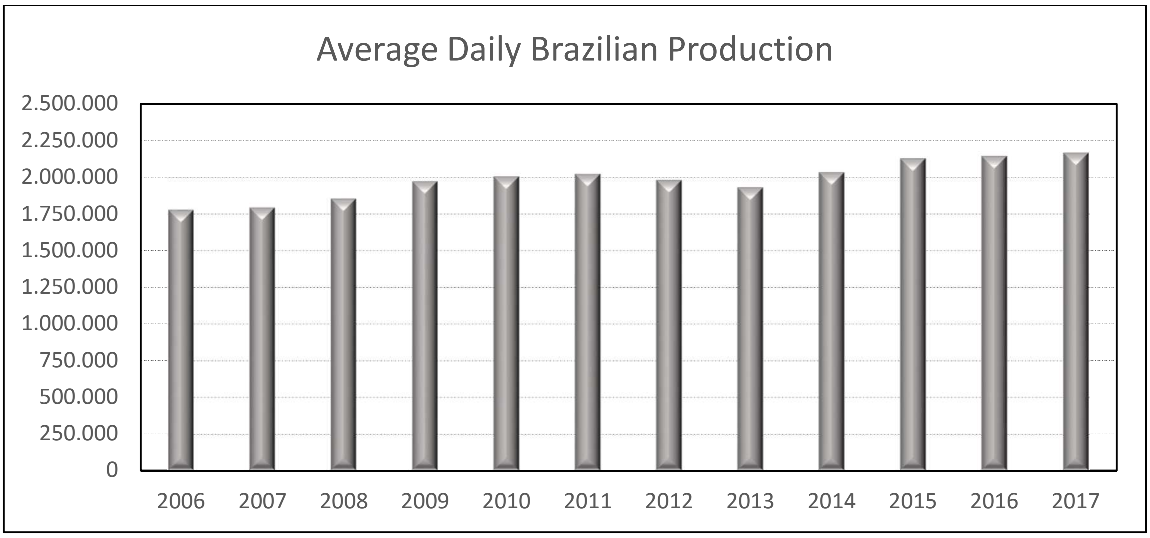
The city of Macae – northern State of Rio de Janeiro, Campos Basin - hosts the largest offshore infrastructure in Brazil and is one of the most important of the world (LEITE, 2012). This infrastructure is composed by a with a huge fleet of specialized vessel and 70 offshore units, 25 warehouses, 110 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)*



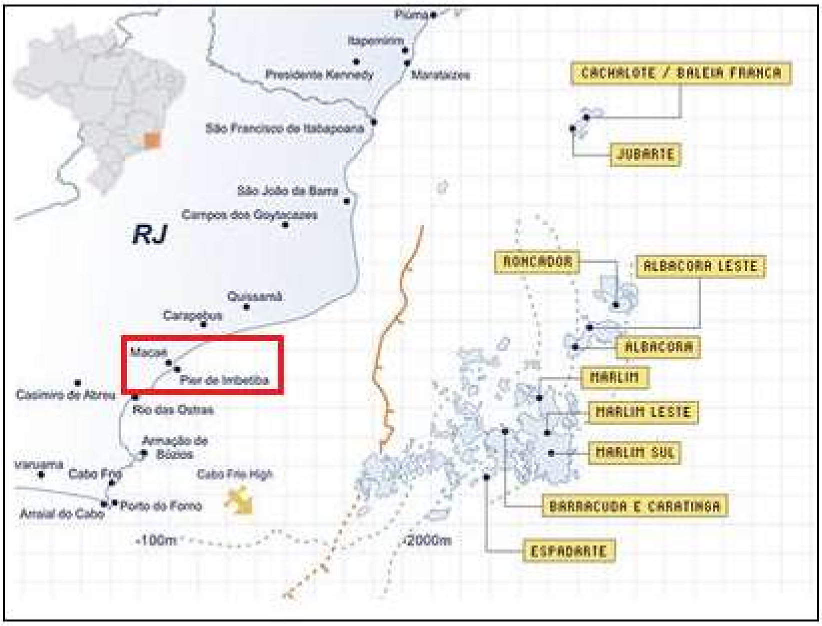

In March 2017, there have been 53 oil offshore units, 10 oil-drilling rigs and 7 Units for Maintenance and Safety (Flotel) in Campos Basin. **Table 1** shows the number of platforms for each type.

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

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

The average distance between Port of Macae and Campos Basin offshore units is 160 km, while the maximum distance is 220 km and the minimum is 100 km. **Figure 3** shows the distribution of Campos Basin's oil field assets.

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

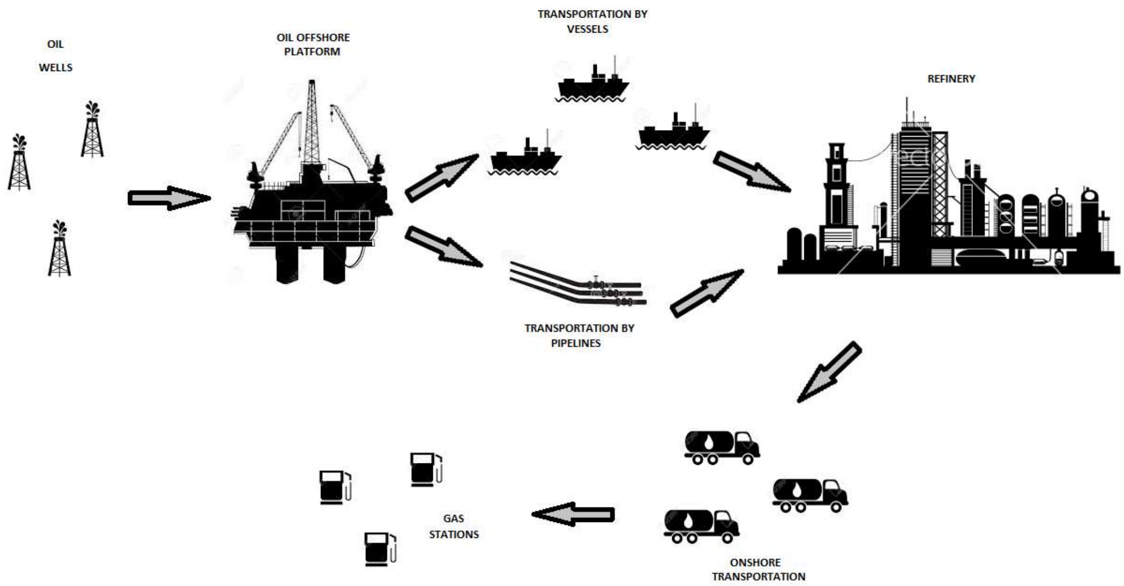



The Campos Basin offshore units are grouped into clusters according to their geographic position and average amount of cargoes received. In March 2017, there have been 16 clusters of oil production platforms, 2 clusters of drilling rigs and 1 of Unit for Maintenance and Safety (data elaborated by the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

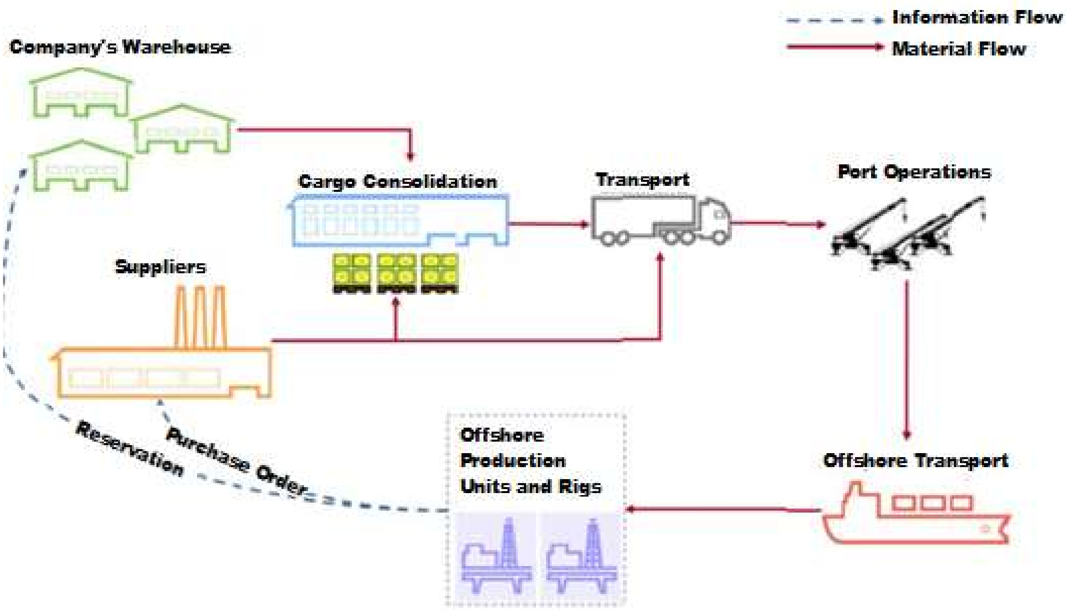
***Figure 4 - A Typical petroleum flow***




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 object of the 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** (FILHO, 2014).

***Figure 5 - Offshore Supply Chain in Campos Basin***




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 e 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 area of integration of operations. 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 also has 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.

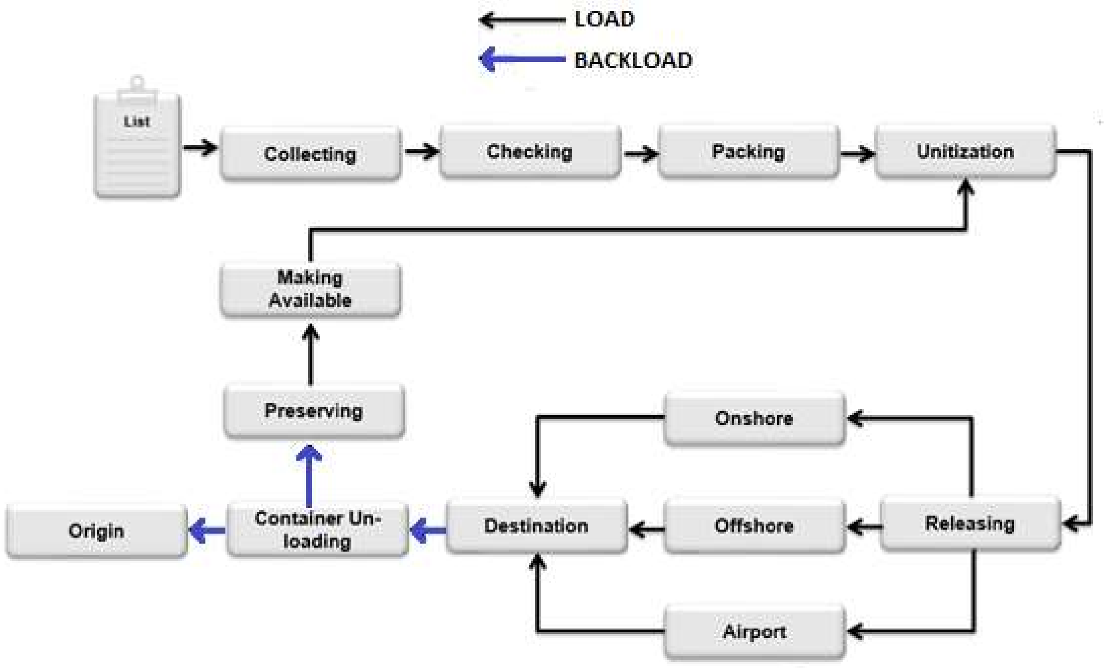
The cargo consolidation area has indicators measuring the efficiency of its unitization services and are related to the number of transport requesting document items released for programming within the deadline.

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 from 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

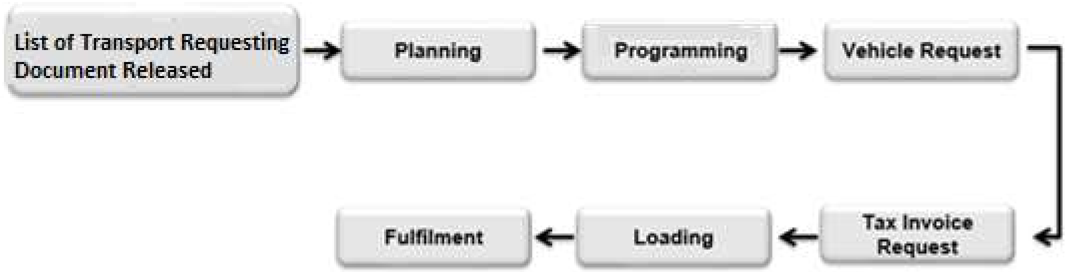
The onshore transportation area fulfils demands of cargo onshore transportation among various locals, such as oil companies' bases, ports (except Port of Macae, which transportation is performed by cargo consolidation area), outsourced repair and manufacturing sites, in the North, Northwest and Lowland 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 on time. The goal of these indicators is to maximize the fulfilment of onshore transportation on 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 operating 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**.

***Table 2 - Features of Port of Macae***

| | |
|---|---|
| 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 m²), Return Cargo Areas (3,242 m²) and Pipe and Waste Areas (1,600 m²) |
| Tankage of Diesel | 4,620 m² |
| Tankage of Water | 6,000 m² |

The Port of Macae has several facilities such as water and Diesel tanks, wet-bulk and dry-bulk tank plants. The Port of Macae's Diesel tanks meet a small part of the Campos Basin's demand, which is largely supplied by six offshore hub of Diesel tanker. Offshore supply vessels heads for such tankers and picks up Diesel oil from there in order to deliver it to offshore units later. On the other hand, the Diesel supplied from Port of Macae meets needs of smaller vessels' own consumption (line handling vessels and emergency vessels), 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.

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

| Type | Amount |
|---|---|
| PSV | 159 |
| UT | 12 |

| | |
|---|---|
| OSRV | 31 |
| AHTS | 81 |
| P | 8 |
| LH | 43 |
| **Total** | **334** |

Not all vessels are used for the purpose they were designed for. 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 the vessels.

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

| 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** |

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.

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

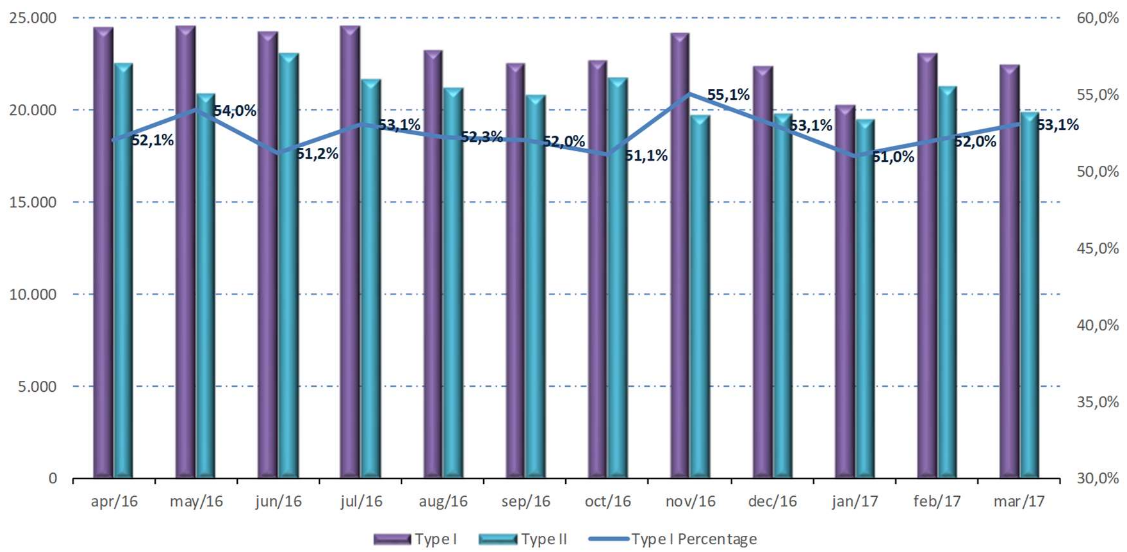



*Figure 10 - Deck Cargo (in tons) Distributed into Normal and Emergency Cargoes*

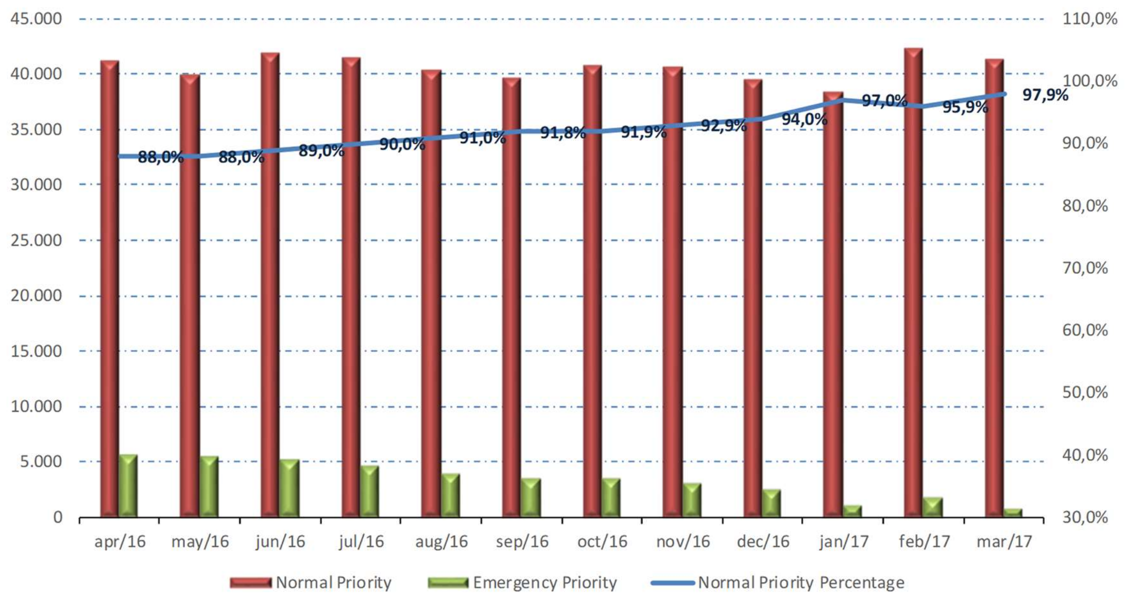



**Figure 11** shows the berth occupancy rate of loadings dedicated to scheduled operations over the above-mentioned period. **Table 5** shows the average distribution of the port operation time into activities carried out by offshore supply vessels. On the other

hand, **Figure 12** shows the lifting time performed in Port of Macae from April 2010 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***

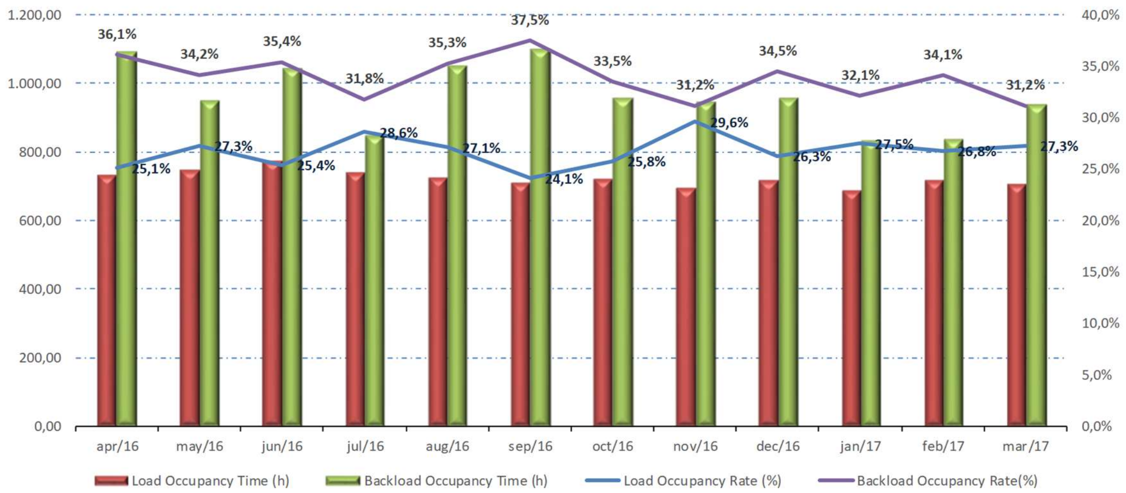
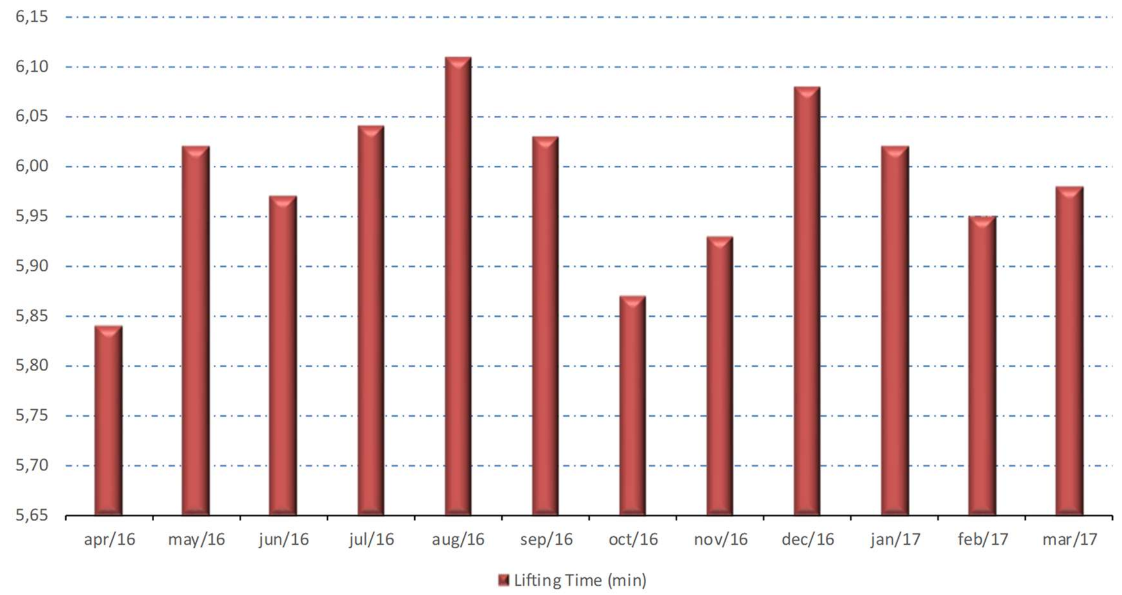



***Table 5 - Distribution of Operational Time in Port of Macae***

| | | |
|---|---|---|
| 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% |

***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.

***Table 6 - Maritime Transportation Fleet***

| 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** | - | - | - | - | - | - |

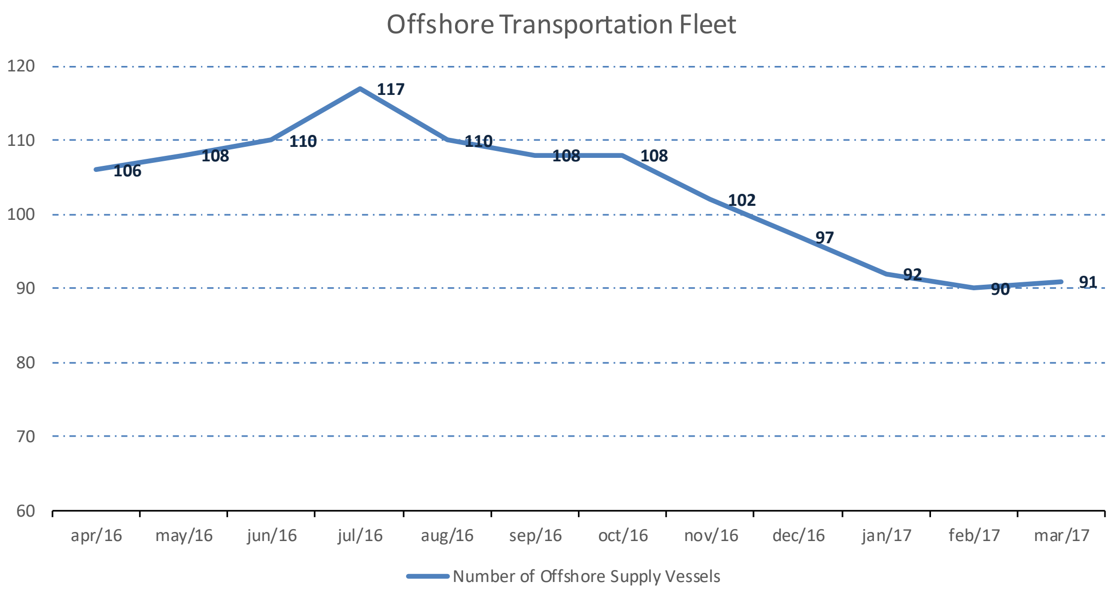
The number of vessels along the year of 2016 and 2017 has drastically reduced from 135 vessels at the beginning of 2015 to 91 in March 2017 as shown by **Figure 13**.

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. The onshore segment – between cargo consolidation areas and Port of Macae – is programmed by the consolidation sector and the offshore segment – between Port of Macae and offshore units – is programmed by the offshore transportation 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 RTs 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.

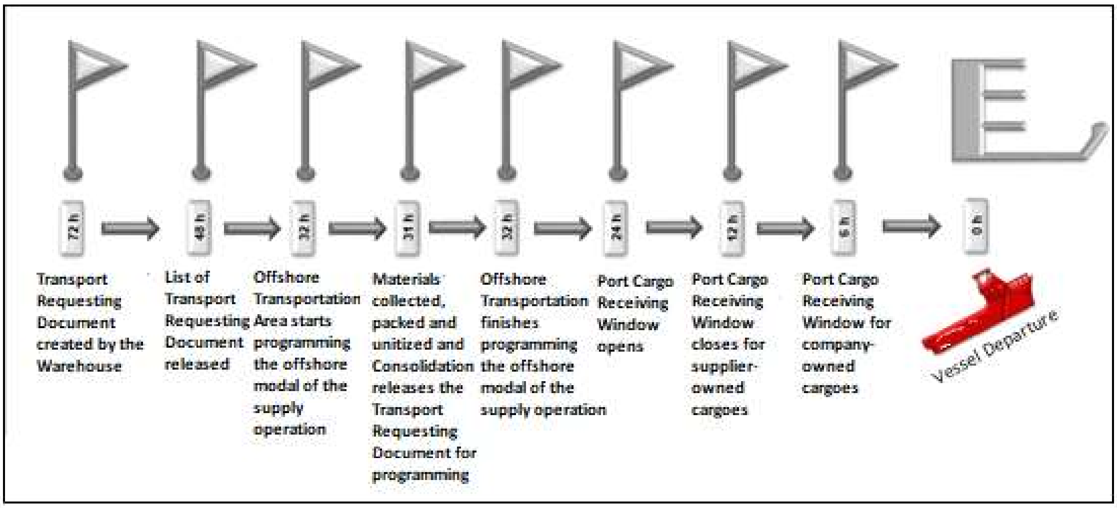
The fulfilment for load cargo starts from thirty-two hours before the departure of the vessel for service level I and twenty-two hours for service level III. In the other hand, the fulfilment for backload cargo ends up to six hours before the departure of the vessel. **Figure 14** shows the sequence 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 should 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 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 15 – Offshore Transportation Fulfilment Indicator***

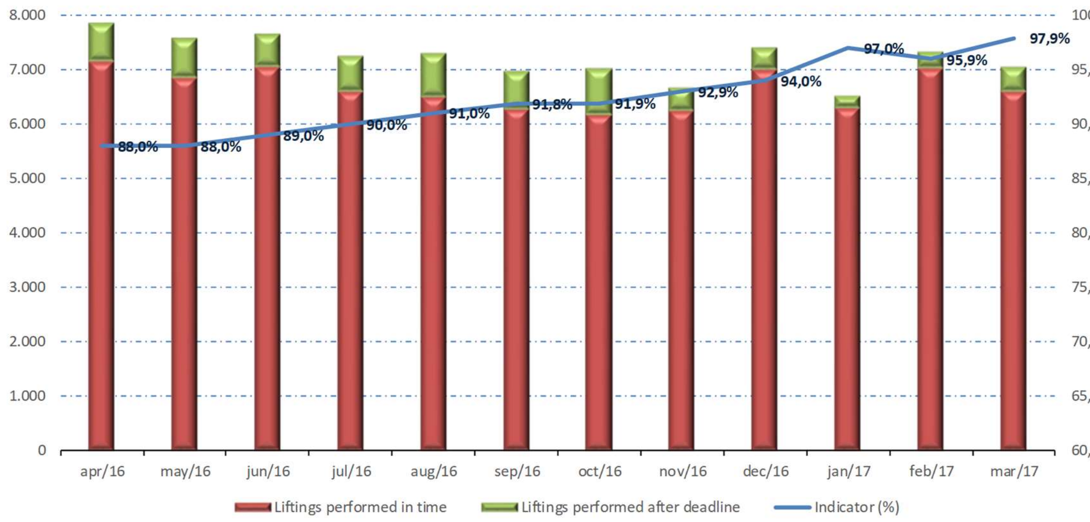
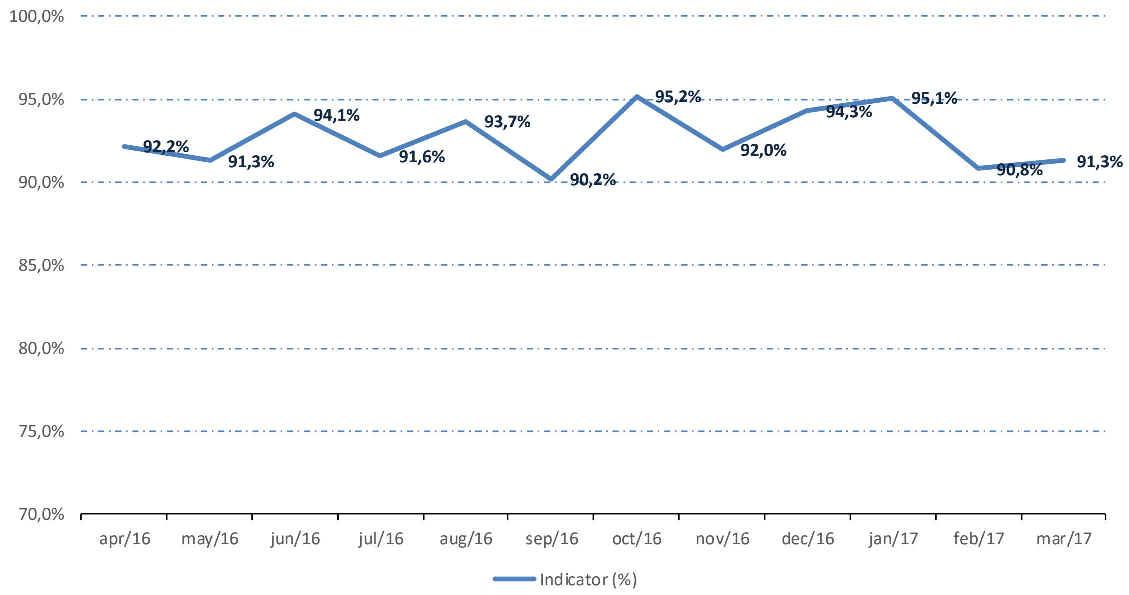



**Figure 16** shows the vessel uptime indicator over the period from April 2016 until March 2017. This indicator is calculated as percentage of the total hours hired by which the vessel is available for operation. The average uptime over this period, 92.7%, will be used in the simulation model to verify 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 offshore unit availability 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)***

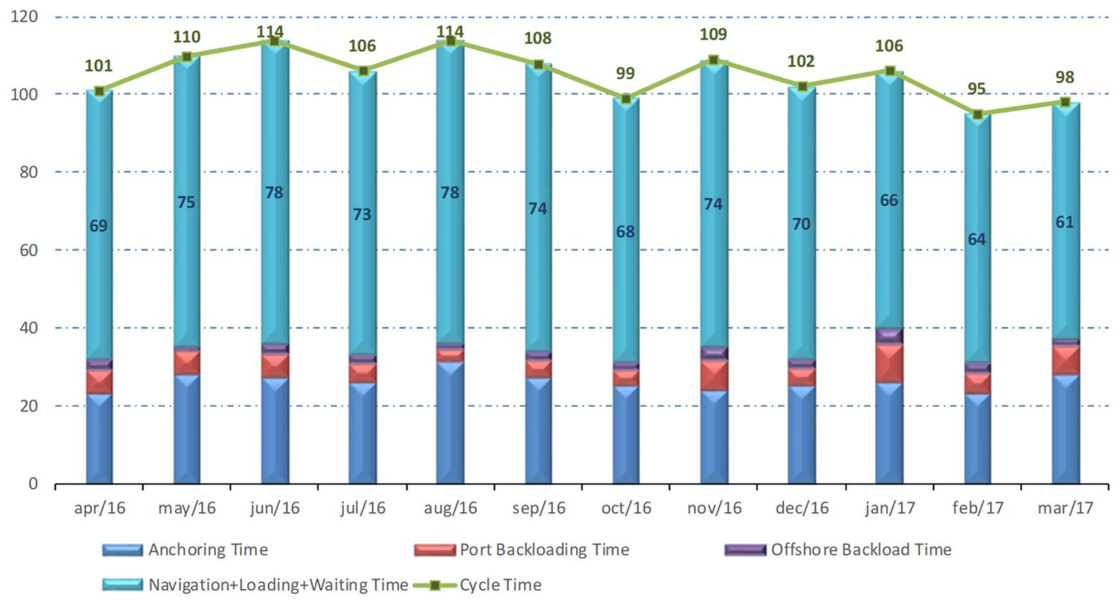



**Figure 18** shows the monthly number of fulfilments performed by SL I vessels over the period from April 2016 until March 2017. This data will also be useful to validate the simulation model. From this graph, it is possible to verify that the monthly average of fulfilments performed over last year 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***

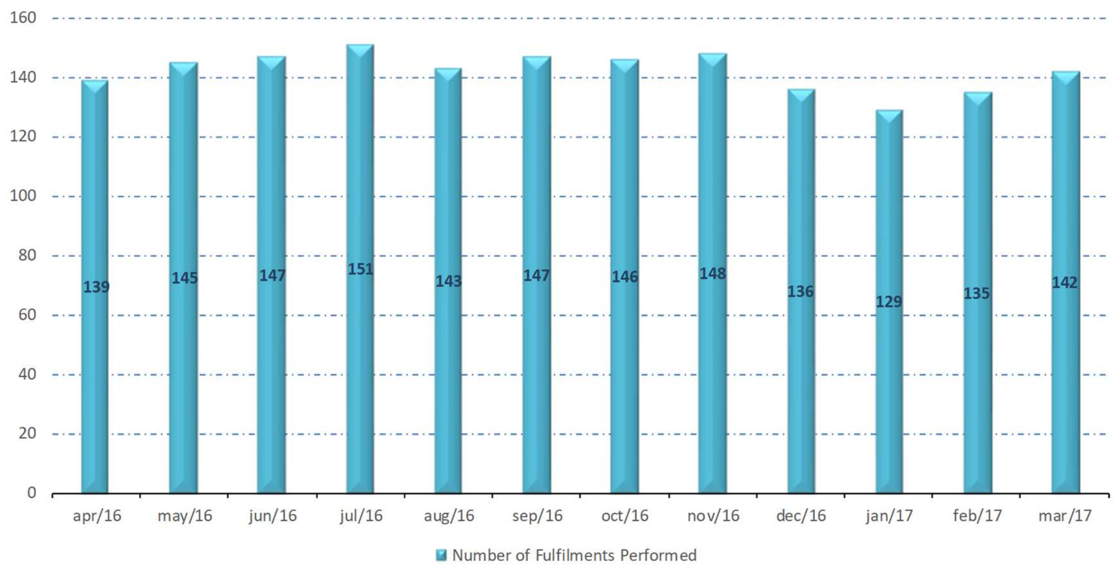



**Figure 19** shows on the same graph both the deck area carried to provide offshore units with Service Level I and the deck occupancy rate.

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

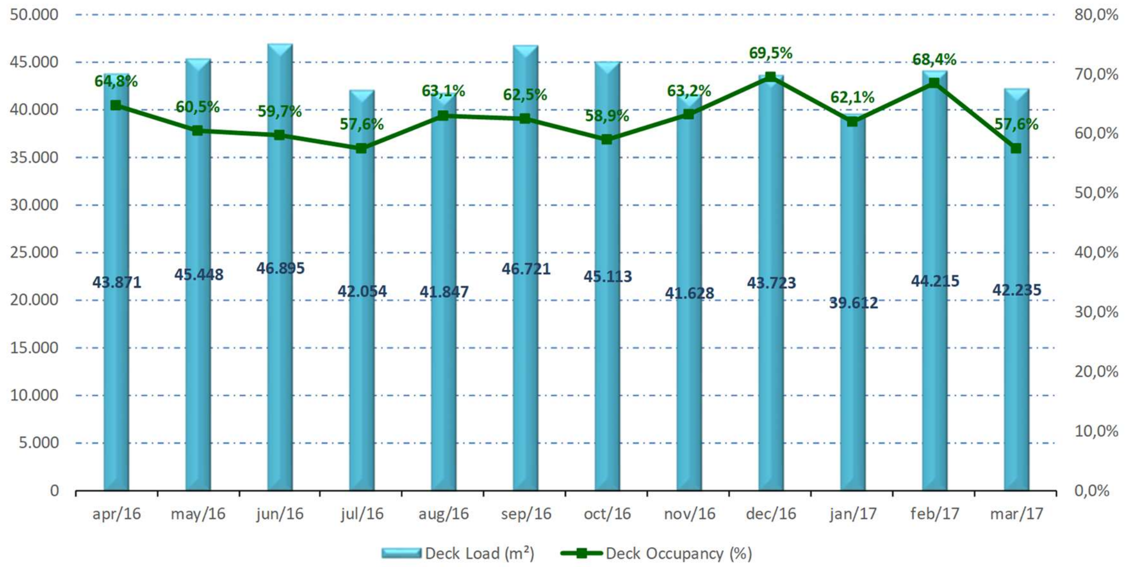
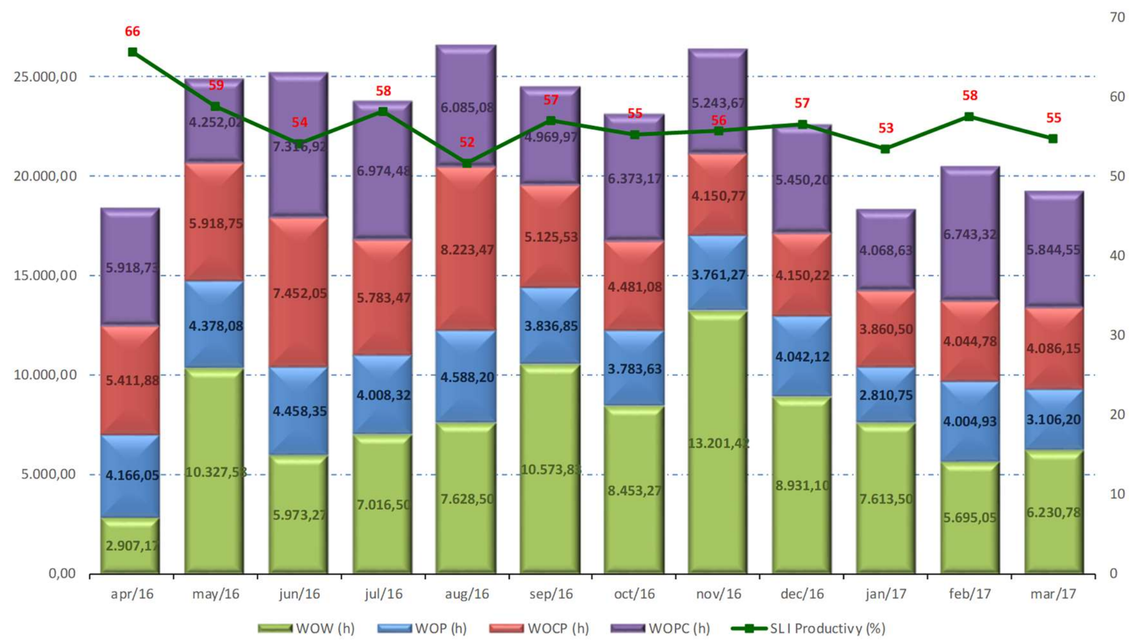



**Figure 20** provides a graph showing the average non-productive time for each condition under which the supply vessel operates. This data applies to all vessels employed to service Campos Basin offshore units (SL I, SL III, transshipment, Diesel oil vessel, deck extension, etc.) and are compared through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

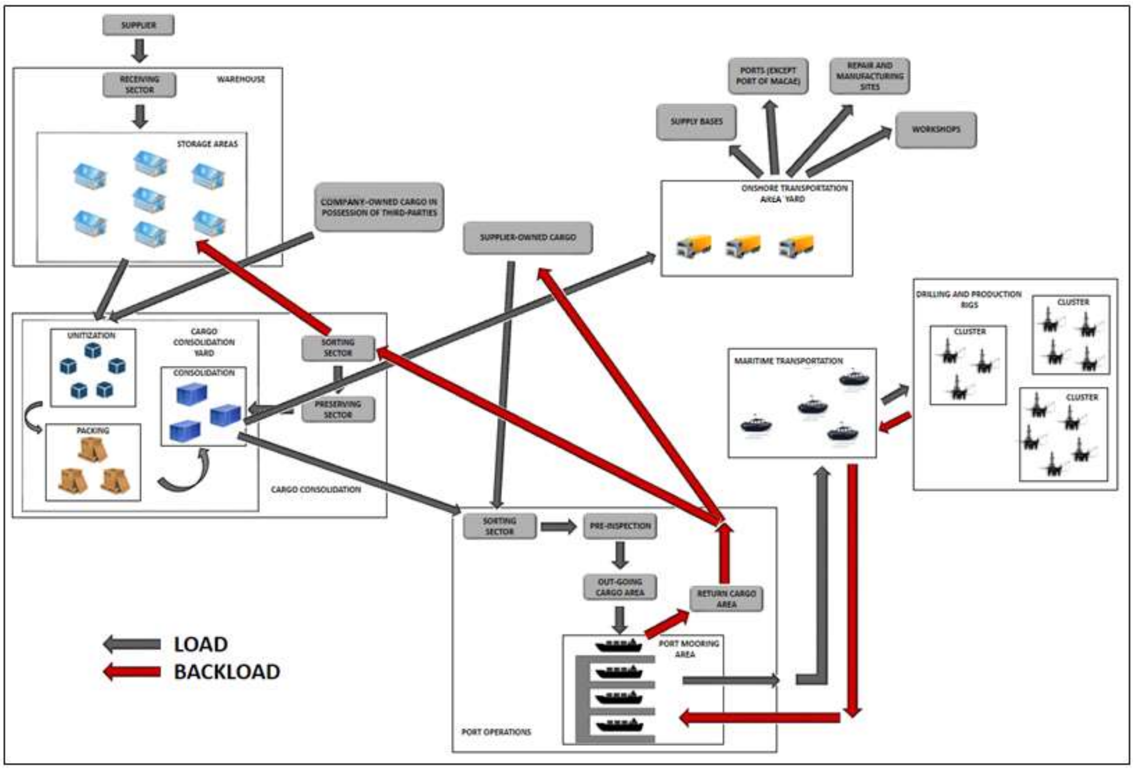
***Table 7 - Cluster Table***

| DEPARTURE WEEK DAY | VESSEL DEPARTURE TIME | CLUSTER | TRIP NUMBER | OFFSHORE UNITS | | | | |
|---|---|---|---|---|---|---|---|---|
| MONDAY | 02:00 | PLAT14 | 1 | UEP23 | UMS5 | UEP30 | UMS6 | |
| | 08:00 | PLAT10 | 1 | UEP32 | UEP27 | UEP50 | UEP4 | |
| | 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 | |
| TUESDAY | 01:00 | PLAT11 | 1 | UEP31 | UMS4 | UEP35 | UEP29 | |
| | 07:00 | PLAT7 | 1 | UEP3 | UEP2 | UEP34 | UEP36 | |
| | 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 |
| | 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 |
| THURSDAY | 01:00 | SOND2 | 2 | SONDA8 | SONDA3 | SONDA6 | SONDA10 | UEP11 |
| | 03:00 | PLAT1 | 2 | UEP16 | UMS3 | UEP21 | | |
| | 14:00 | PLAT14 | 2 | UEP23 | UMS5 | UEP30 | UMS6 | |
| | 20:00 | PLAT10 | 2 | UEP32 | UEP27 | UEP50 | UEP4 | |
| FRIDAY | 00:01 | PLAT6 | 2 | UEP45 | UEP48 | UEP53 | UEP52 | UEP51 |
| | 06:00 | PLAT2 | 2 | UEP14 | UEP13 | UEP19 | UEP18 | |
| | 13:00 | PLAT11 | 2 | UEP31 | UMS4 | UEP35 | UEP29 | |
| | 19:00 | PLAT7 | 2 | UEP3 | UEP2 | UEP34 | UEP36 | |
| SATURDAY | 01:00 | PLAT3 | 2 | UEP40 | UEP47 | UEP39 | UEP46 | UMS7 |
| | 02:00 | SOND1 | 2 | SONDA7 | SONDA5 | SONDA1 | SONDA4 | SONDA2 |
| | 08:00 | PLAT12 | 2 | UEP24 | UEP26 | UEP22 | | |
| | 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 | | |
| SUNDAY | 03:00 | PLAT9 | 1 | UEP25 | UEP17 | UMS1 | UEP15 | |
| | 09:00 | PLAT5 | 1 | UEP20 | UEP12 | UEP41 | UEP43 | UEP42 |
| | 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. 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.

*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 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:

- Evaluation of the distances from coordinates registered for each installation (offshore units, warehouses, etc.);

- Since April 2017, SL I operations are gradually being 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 vessel downtime historically recorded 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 of 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 were 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

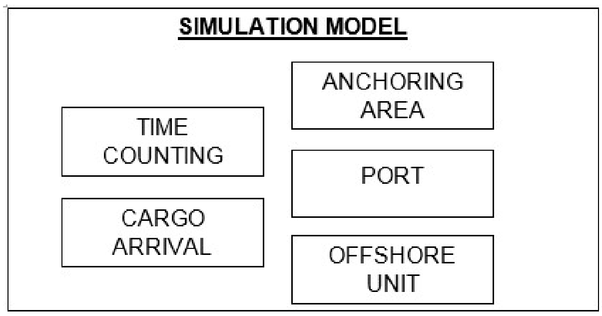
corresponding to the sum of WOW and WOP times, which is in turn provided by historical distribution data;

- 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), since the navigating time between them within a cluster is around one hour;
- 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 cargo arrival window into the port 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 to compute an average cost value for the Diesel consumption.

## 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.

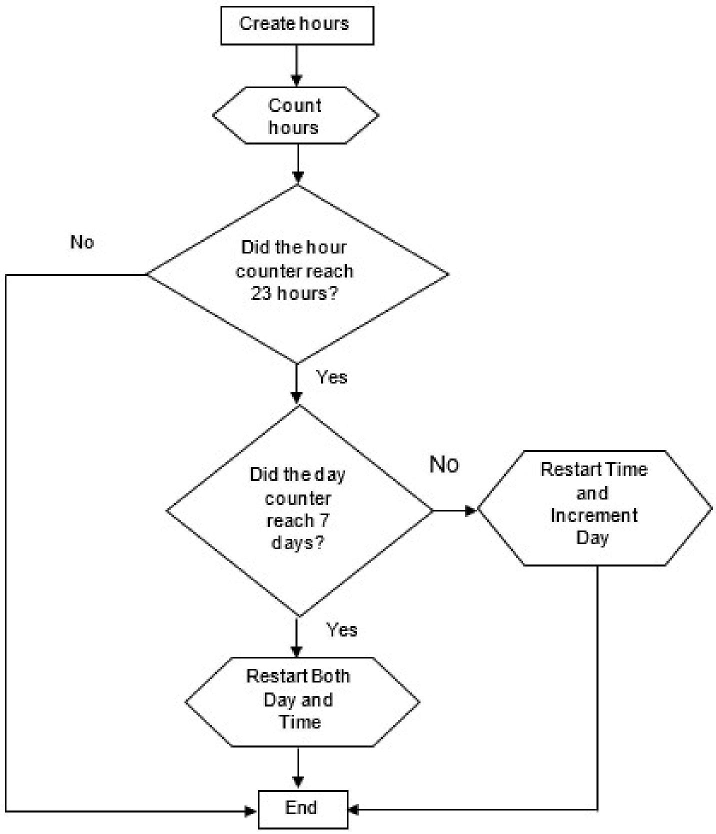
***Figure 22 – Simulation Model Sections***




### 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***

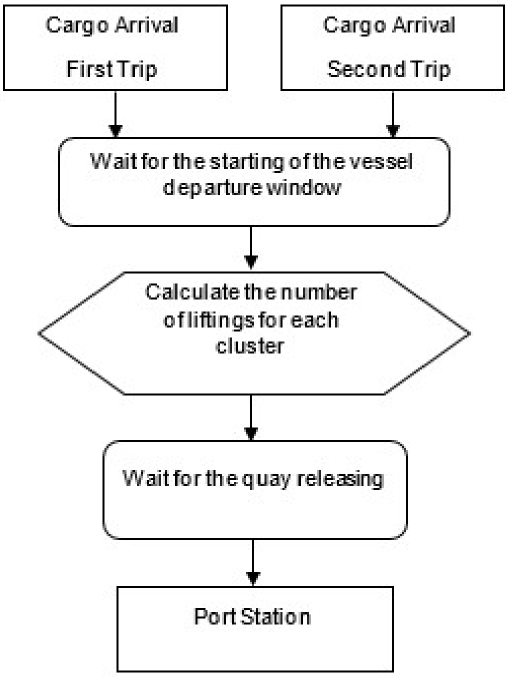


To represent the time counting, an entity coming into the model each hour under the name "*date_count*" has been created. Thus, every time the entity enters the model, the time is updated by one hour. In this part of the model, two variables will be used - "hour" and "day" - to measure the time. According 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 2017 until March 2016. 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.

***Table 8 - Lifting Distribution***

| Cluster | Offshore Unit | Lifting Distribution |
|---|---|---|
| PLAT1 | UEP16 | TRIA(2.5, 12, 28.5) |
| | UMS3 | POIS(6.99) |
| | UEP21 | 4.5 + 38 * BETA(1.48, 1.41) |
| PLAT2 | UEP18 | 1.5 + ERLA(3.05, 3) |
| | UEP14 | 1.5 + 33 * BETA(3.44, 5.8) |
| | UEP13 | NORM(17.7, 5.81) |
| | UEP19 | 3.5 + GAMM(3.69, 3.03) |
| PLAT3 | UEP40 | 4.5 + ERLA(3.39, 3) |
| | UEP47 | TRIA(1.5, 9, 21.5) |
| | UEP39 | 3.5 + LOGN(16.9, 12.5) |
| | UEP46 | NORM(11.2, 3.7) |
| | UMS7 | 1.5 + 26 * BETA(1.04, 2.49) |
| PLAT4 | UEP38 | TRIA(3.5, 10.7, 30.5) |
| | UEP37 | 2.5 + GAMM(1.39, 4.41) |
| | 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) |
| | UEP41 | 1.5 + ERLA(2.09, 3) |
| | UEP43 | 1.5 + WEIB(3.71, 0.821) |
| | UEP42 | POIS(7.29) |
| PLAT6 | UEP45 | 3.5 + 25 * BETA(1.98, 2.09) |
| | UEP48 | 3.5 + ERLA(4.85, 2) |
| | UEP53 | 1.5 + LOGN(4.51, 2.49) |
| | UEP52 | 1.5 + GAMM(1.39, 3.32) |

| | | |
|---|---|---|
| | UEP51 | 1.5 + ERLA(1.76, 3) |
| PLAT7 | UEP3 | 1.5 + 14 * BETA(1.35, 2.19) |
| | UEP2 | NORM(10.7, 5.27) |
| | UEP34 | 1.5 + GAMM(1.78, 2.54) |
| | UEP36 | TRIA(2.5, 8, 31.5) |
| PLAT8 | UEP10 | POIS(10.6) |
| | UEP8 | 3.5 + WEIB(10, 1.93) |
| | UMS2 | 1.5 + 32 * BETA(1.24, 3.26) |
| | UEP7 | 4.5 + WEIB(10.4, 1.96) |
| | SONDA9 | 1.5 + ERLA(1.87, 3) |
| PLAT9 | UEP15 | 6.5 + WEIB(11, 1.86) |
| | UEP17 | TRIA(5.5, 14.4, 43.5) |
| | UMS1 | 1.5 + GAMM(4.64, 1.45) |
| | UEP25 | NORM(11.6, 3.99) |
| PLAT10 | UEP32 | 2.5 + WEIB(14.5, 2.47) |
| | UEP27 | 3.5 + WEIB(17.5, 1.86) |
| | UEP50 | 2.5 + ERLA(1.12, 4) |
| | UEP4 | 1.5 + WEIB(6.63, 1.54) |
| PLAT11 | UEP31 | 1.5 + WEIB(21.3, 1.51) |
| | UMS4 | 1.5 + ERLA(2.66, 3) |
| | UEP35 | 2.5 + GAMM(3.18, 5.06) |
| | UEP29 | 3.5 + WEIB(16.9, 2.02) |
| PLAT12 | UEP24 | 1.5 + WEIB(20, 1.94) |
| | UEP26 | 2.5 + WEIB(17.8, 1.64) |
| | UEP22 | POIS(7.7) |
| PLAT13 | UEP28 | NORM(20.6, 7.34) |
| | UEP33 | 5.5 + WEIB(16.3, 2.31) |
| | UEP1 | 1.5 + WEIB(13.6, 2.05) |
| PLAT14 | UEP23 | NORM(19.7, 7.94) |
| | UMS5 | 1.5 + GAMM(3.29, 2.23) |
| | UEP30 | NORM(20.1, 8.58) |
| | UMS6 | 1.5 + WEIB(7.87, 1.91) |
| SOND1 | SONDA2 | 1.5 + WEIB(10.3, 1.38) |
| | SONDA4 | 1.5 + WEIB(9.98, 1.45) |
| | 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.

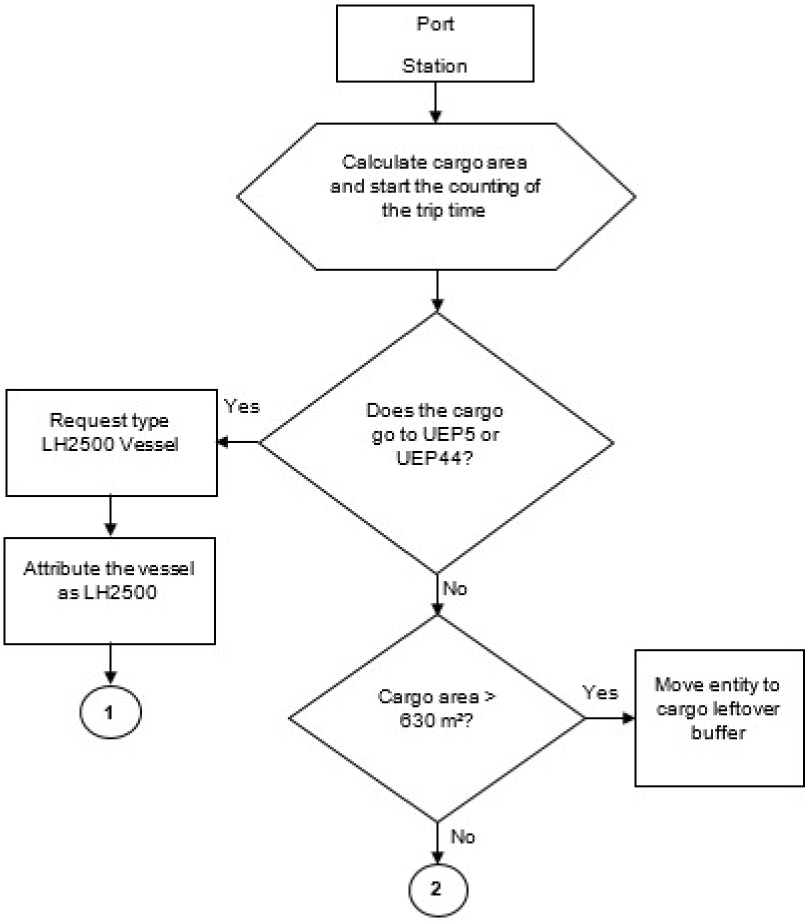
Then, the entity will remain in the queue until the number of quays busy is smaller than six as Port of Macae has six quays. Thus, to represent this condition, a variable "NR" (*Number of busy resource units)* is used. In this case, a quay has been configured as a resource, which has a capacity of six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

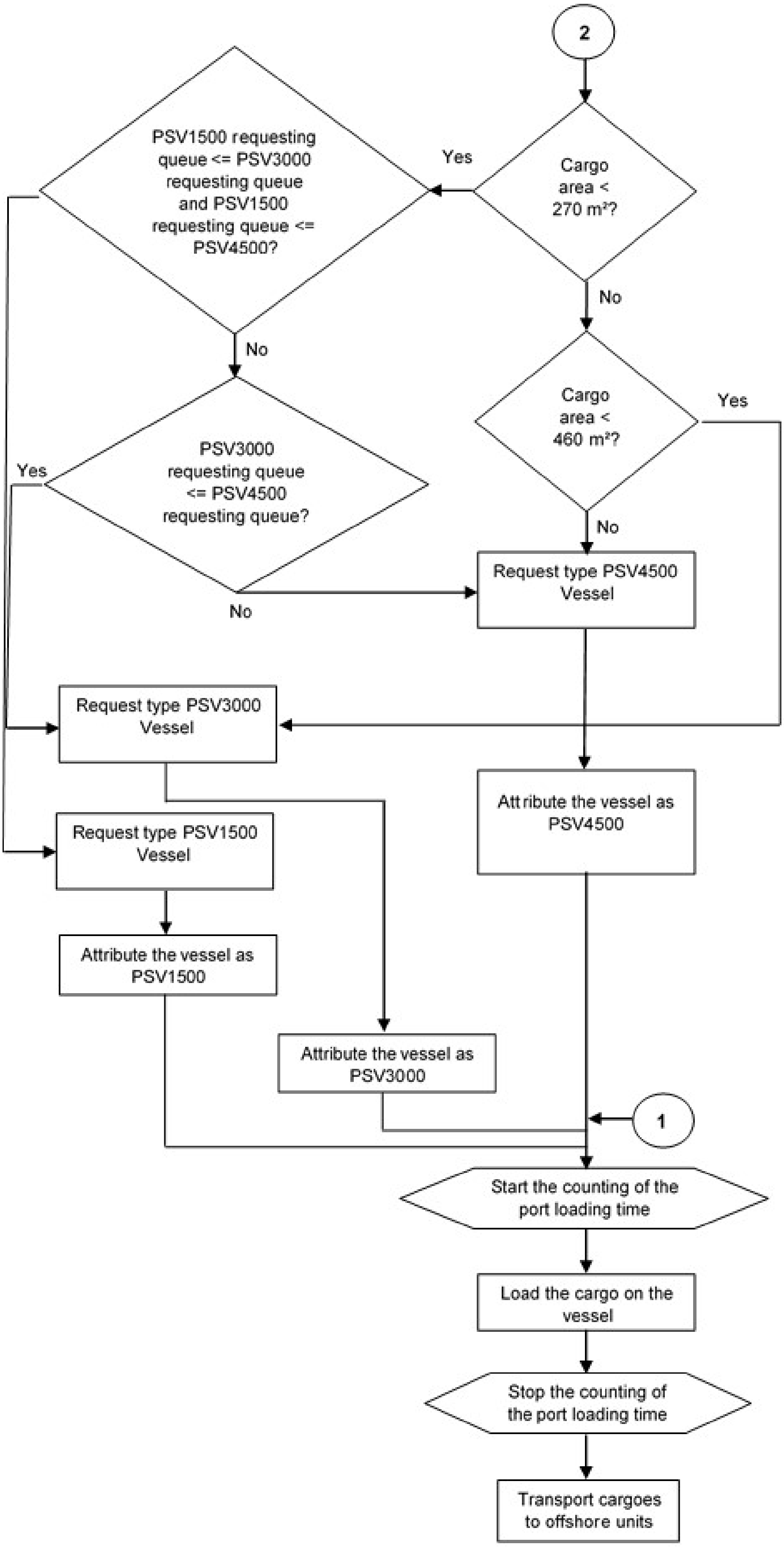
### 4.2.3 Port Section

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

***Figure 25 – Port-Loading Flowchart***



Port
Station
Calculate cargo area and start the counting of the trip time
Does the cargo go to UEP5 or UEP44?
Yes
Request type LH2500 Vessel
Attribute the vessel as LH2500
1
No
Cargo area > 630 m²?
Yes
Move entity to cargo leftover buffer
No
2


2
Cargo area < 270 m²?
Yes
PSV1500 requesting queue <= PSV3000 requesting queue and PSV1500 requesting queue <= PSV4500?
No
PSV3000 requesting queue <= PSV4500 requesting queue?
Yes
No
Cargo area < 460 m²?
Yes
No
Request type PSV4500 Vessel
Request type PSV3000 Vessel
Request type PSV1500 Vessel
Attribute the vessel as PSV4500
Attribute the vessel as PSV1500
Attribute the vessel as PSV3000
1
Start the counting of the port loading time
Load the cargo on the vessel
Stop the counting of the port loading time
Transport cargoes to offshore units

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 m², 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.

***Table 9 - Average Area per Lifting***

| 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** |

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 decisions made by the cargo programmer. 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.

***Table 10 – Vessel Deck Capacity***

| 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 |
| **TOTAL** | | | **30** |

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.

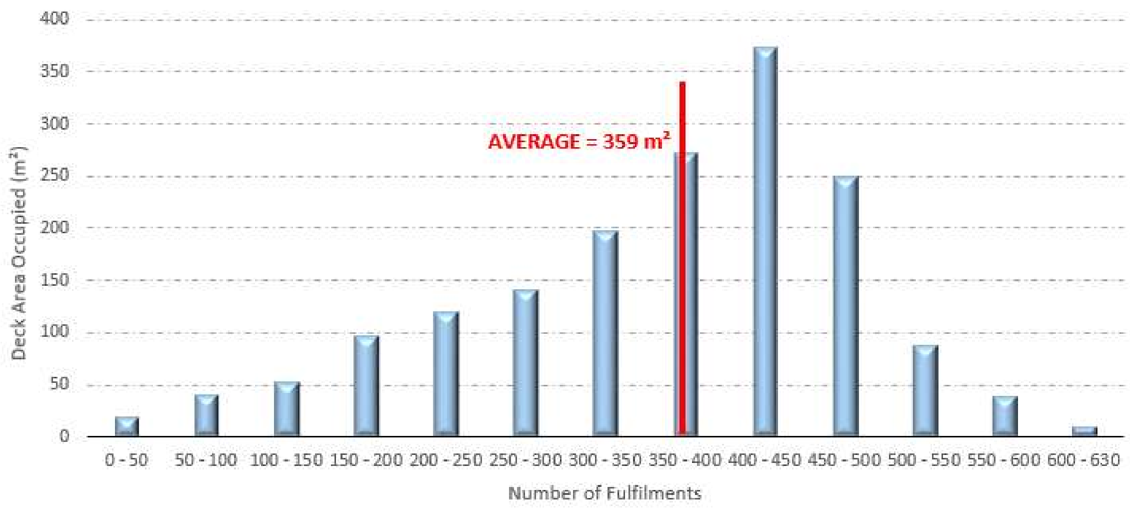
On the other hand, if the number of entities in queue waiting to be serviced by PSV1500 is greater than those waiting for PSV3000 and smaller than those waiting for PSV4500, a PSV3000 shall be chosen. If the number of entities waiting to be serviced by PSV4500 is smaller than those waiting for either 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 the 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 leftover. The current logistic system has been configured to avoid cargo leftover, since the programmer will be program 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. Thus, the assumption is that the model will never generate leftover cargoes if there is still PSV4500 composing the fleet. 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 2017 to March 2016 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 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.

*Figure 27 – Transporter Features*

| | Name | Number of Units | Type | Distance Set | Velocity | Units | Initial Position Status | Report Statistics |
|---|---|---|---|---|---|---|---|---|
| 1 | PSV_4500 | 20 | Free Path | PSV_4500.Distance | 1.0 | Per Hour | 0 rows | ☑ |
| 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 | ☑ |

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**.

*Table 11 - Distance Matrix (km)*

| 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 |
| 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 pivotal, 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.

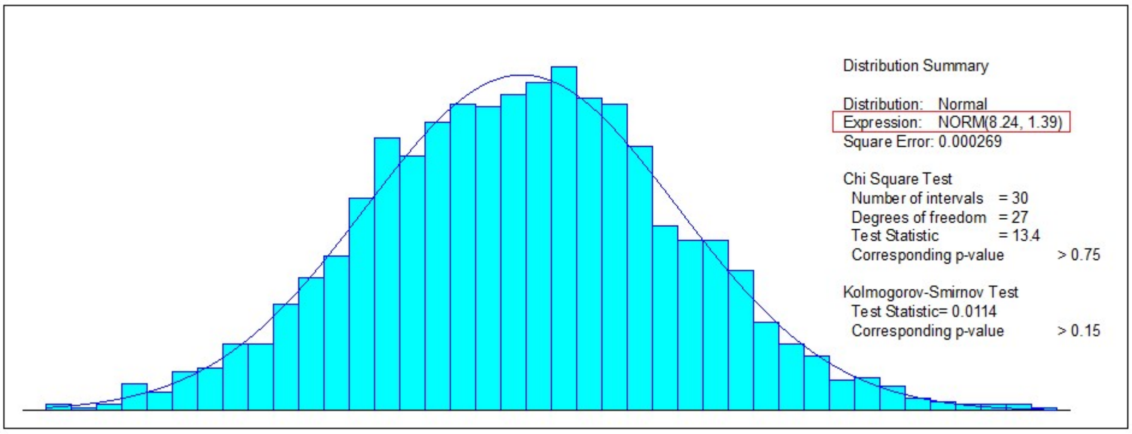
Upon the beginning of the port loading process, the cargo entity picks up a resource called "quay", to which a capacity of six has been associated, meaning that the port has six berths to moor offshore supply vessels. The resource seizing logic chosen has been the "Seize Delay Release", which indicates 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 made to verify which cluster the entity belongs and then the cargo will be moved to its respective cluster. After checking to which cluster the entity belongs, it heads for a set of transporting modules. The entity will be then transferring to its destination (cluster's first unit).

The speed data collected from vessel AIS data (Automatic Identification System) over the period from April 2017 until March 2017 for each fulfilment 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**.

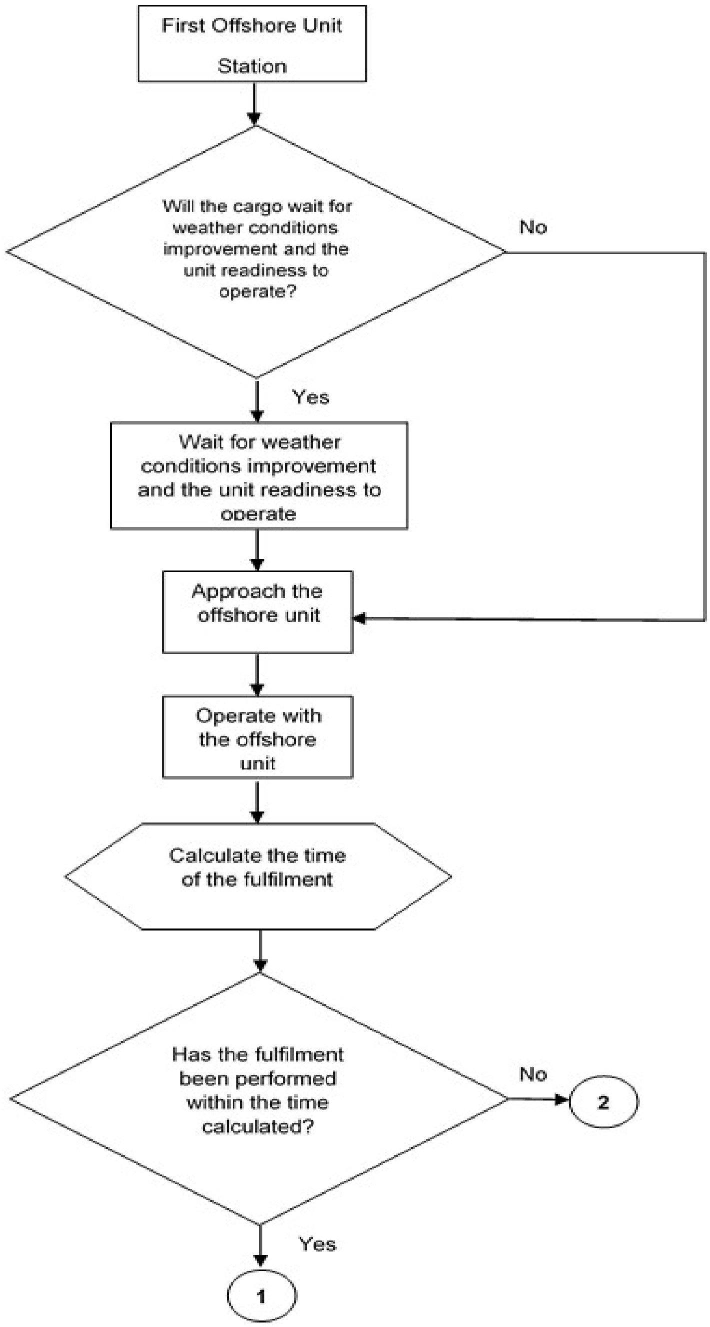
***Figure 28 – Vessel Speed Distribution Best Fit Obtained through Arena Input Analyzer***

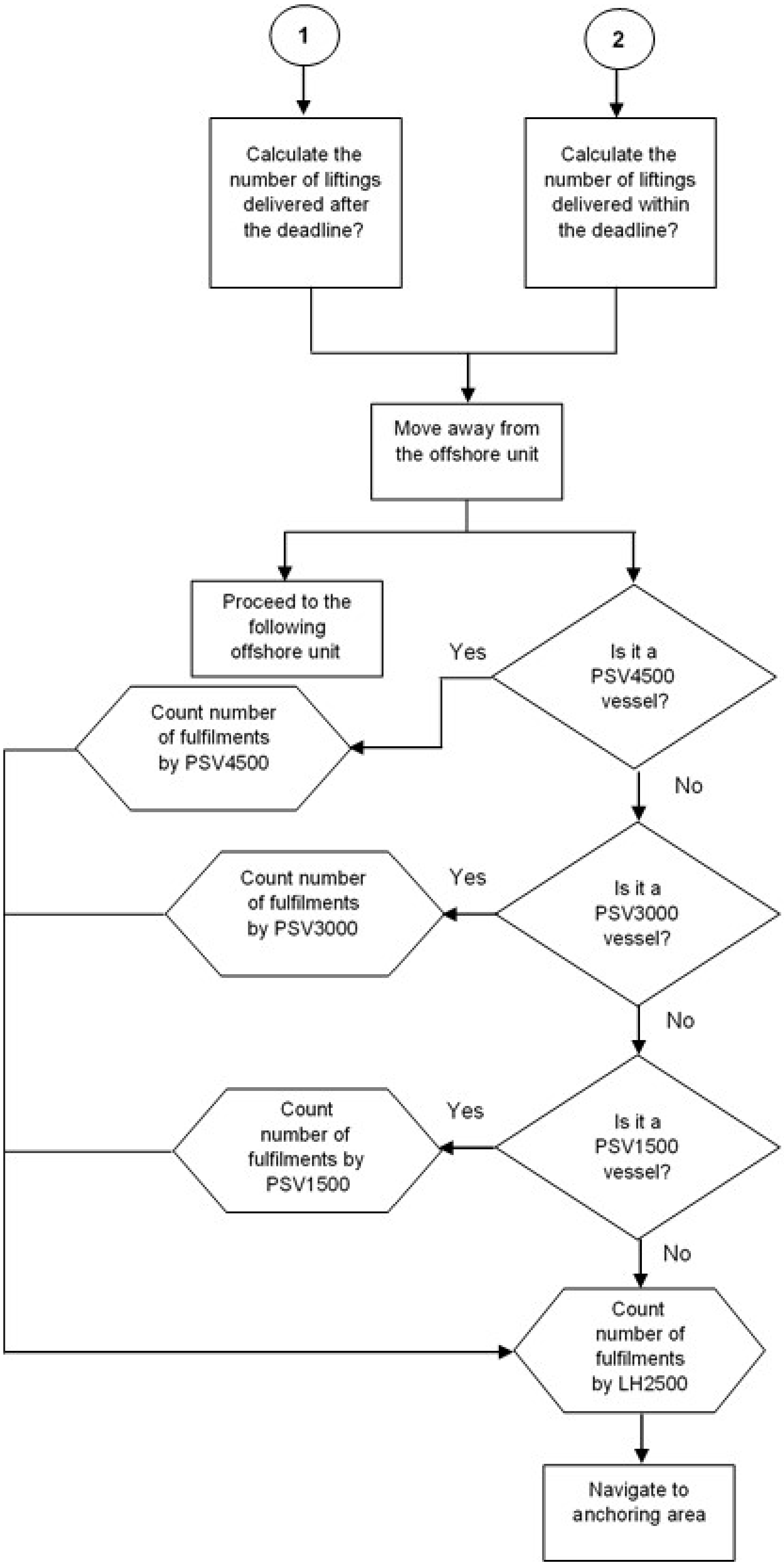



### 4.2.4 Offshore Units Section

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*




1
2
Calculate the number of liftings delivered after the deadline?
Calculate the number of liftings delivered within the deadline?
Move away from the offshore unit
Proceed to the following offshore unit
Is it a PSV4500 vessel?
Yes
No
Count number of fulfilments by PSV4500
Is it a PSV3000 vessel?
Yes
No
Count number of fulfilments by PSV3000
Is it a PSV1500 vessel?
Yes
No
Count number of fulfilments by PSV1500
Count number of fulfilments by LH2500
Navigate to anchoring area

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 AM05 or/and AM11 and waiting time distributions.

***Table 12 - Waiting Probability and Waiting Time Distribution***

| 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) |

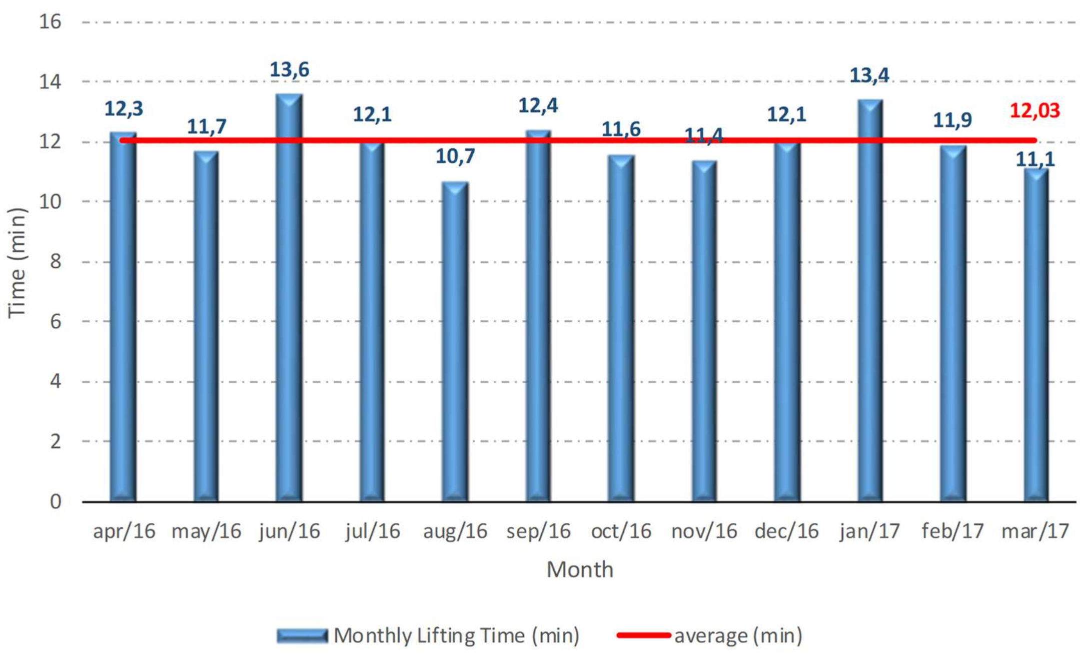
| | | | |
|---|---|---|---|
| PLAT6 | UEP45 | 15% | LOGN(6.62, 17.7) |
| | UEP48 | 12% | WEIB(10.1, 0.719) |
| | UEP53 | 19% | LOGN(11.5, 29.8) |
| | UEP52 | 8% | EXPO(7.2) |
| | UEP51 | 11% | LOGN(8.16, 23.7) |
| PLAT7 | UEP3 | 35% | LOGN(10.7, 24.8) |
| | UEP2 | 57% | 44 * BETA(0.208, 0.861) |
| | UEP34 | 24% | LOGN(25.3, 76.5) |
| | UEP36 | 36% | 129 * BETA(0.258, 1.45) |
| PLAT8 | UEP10 | 17% | LOGN(12.2, 39.5) |
| | UEP8 | 22% | 66 * BETA(0.456, 2.17) |
| | UMS2 | 42% | 66 * BETA(0.347, 1.6) |
| | UEP7 | 33% | 146 * BETA(0.198, 2.22) |
| | SONDA9 | 36% | 86 * BETA(0.226, 1.08) |
| PLAT9 | UEP15 | 28% | LOGN(23.6, 80.5) |
| | UEP17 | 48% | LOGN(16.6, 47.8) |
| | UMS1 | 38% | LOGN(17.6, 61.1) |
| | UEP25 | 15% | LOGN(16.5, 51.5) |
| PLAT10 | UEP32 | 16% | 123 * BETA(0.387, 1.83) |
| | UEP27 | 18% | LOGN(18.9, 61.8) |
| | UEP50 | 8% | WEIB(8.04, 0.734) |
| | UEP4 | 35% | LOGN(13.6, 32.9) |
| PLAT11 | UEP31 | 26% | LOGN(29.8, 123) |
| | UMS4 | 35% | WEIB(8.7, 0.707) |
| | UEP35 | 18% | 76 * BETA(0.494, 1.52) |
| | UEP29 | 12% | LOGN(17.1, 63.4) |
| PLAT12 | UEP24 | 24% | LOGN(12.2, 38.8) |
| | UEP26 | 36% | WEIB(12.9, 0.723) |
| | UEP22 | 21% | 118 * BETA(0.237, 4.83) |
| PLAT13 | UEP28 | 10% | TRIA(0, 56, 118) |
| | 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) |
| | UEP30 | 26% | WEIB(8.85, 0.726) |

| | | | |
|---|---|---|---|
| | UMS6 | 20% | LOGN(4.4, 8.46) |
| SOND1 | SONDA2 | 35% | LOGN(4.42, 7.74) |
| | SONDA4 | 37% | 118 * BETA(0.393, 2.76) |
| | SONDA1 | 44% | 118 * BETA(0.174, 0.846) |
| | SONDA5 | 58% | 118 * BETA(0.368, 2.59) |
| | SONDA7 | 52% | 118 * BETA(0.437, 2.65) |
| SOND2 | SONDA8 | 23% | LOGN(6.9, 15.1) |
| | SONDA3 | 35% | 118 * BETA(0.46, 3.92) |
| | 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 unloaded onto the platform. The loading time specified is expressed as the multiplication 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 2017 until March 2016 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.

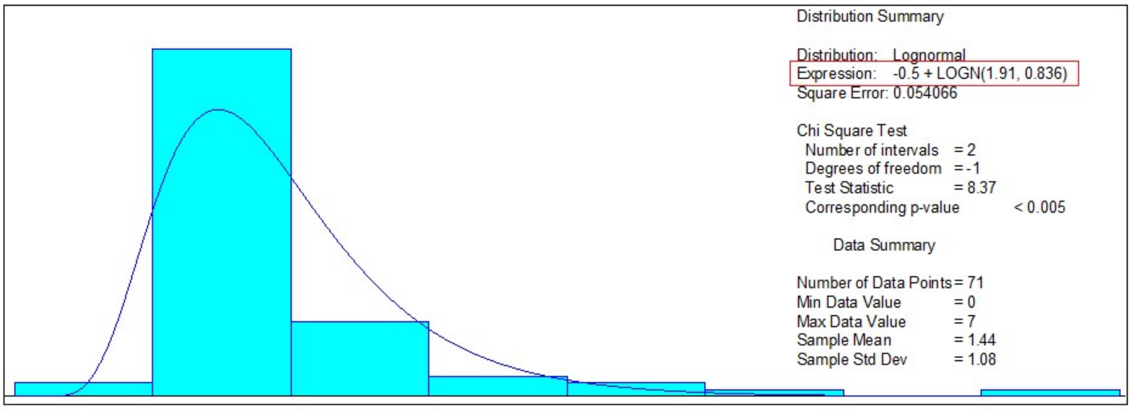
If the cargo is the delivering time is shorter than the 96-hour limit, the number of liftings associated to the entity will be counted as if being delivered within the deadline. If not, the number of liftings will be counted as if being after the deadline expected. Both numbers of entities delivered 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 are 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 area.

The set entity and vessel moves away from the offshore unit out of the 500-meter 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 distribution have been found through Arena Input Analyzer to represent any distance between two platforms in the model (**Figure 31**). This has been done to reduce the complexity of the model regarding the handling of the distance matrix.

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



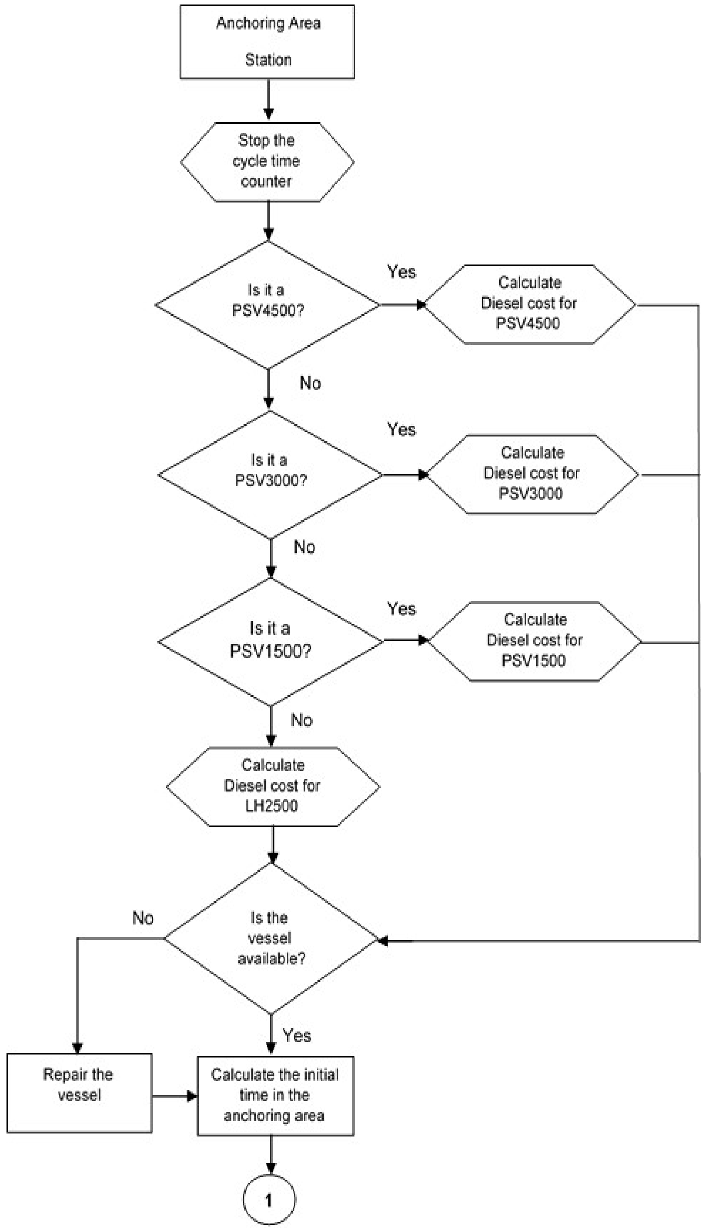

The process logic of cycling through the next offshore repeats as described in this section. After moving away from the last offshore unit of the cluster, there will be a checking on the type of vessel that performed the supply operation in order to obtain the numbers of fulfilments that each class of 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.

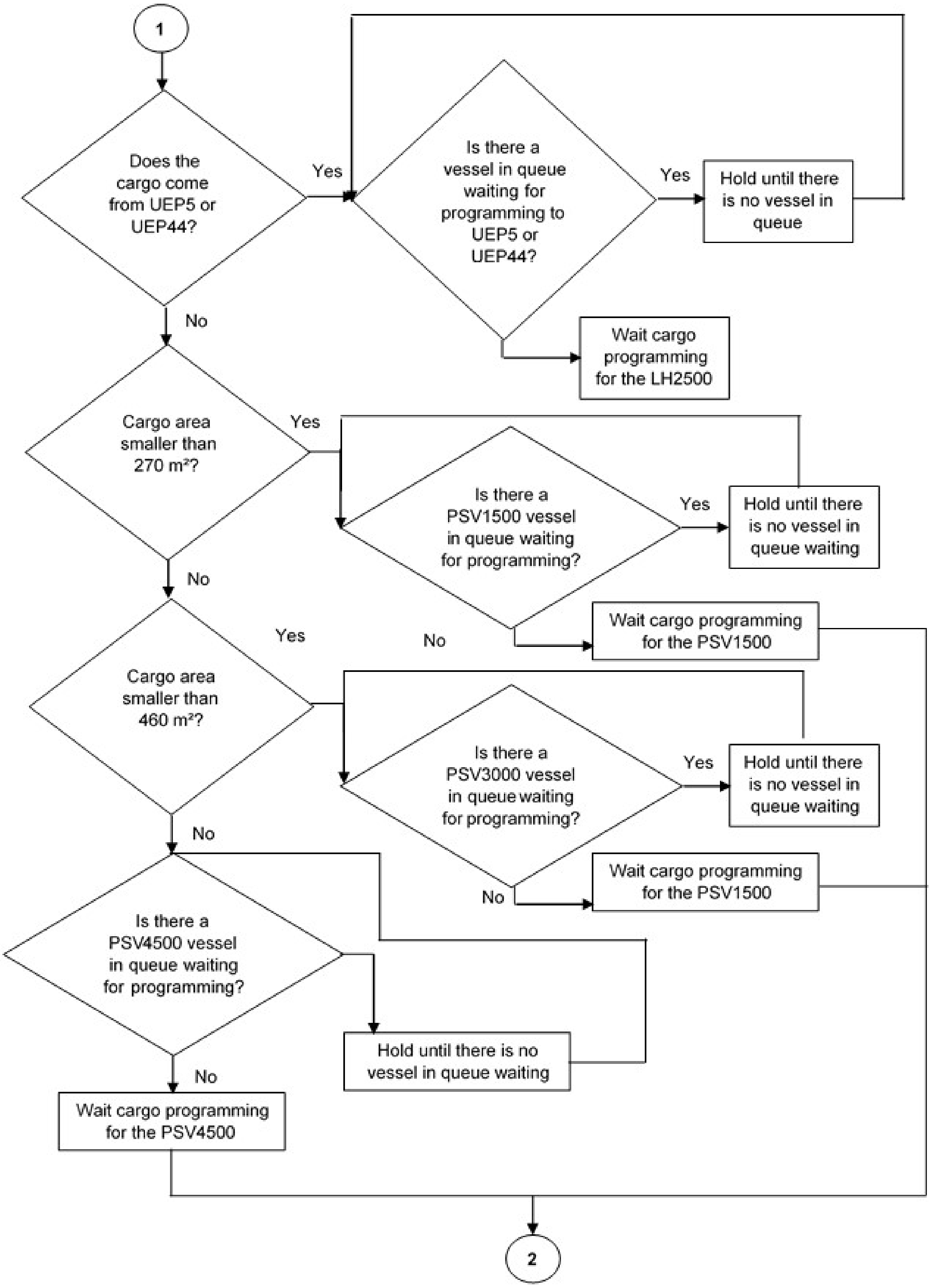
After this checking, the set entity and vessel moves to the port anchoring area. The speed distribution set for the transporter is the same found for the navigation from the port to the first offshore unit of the cluster.

### 4.2.5 Anchoring Area Section

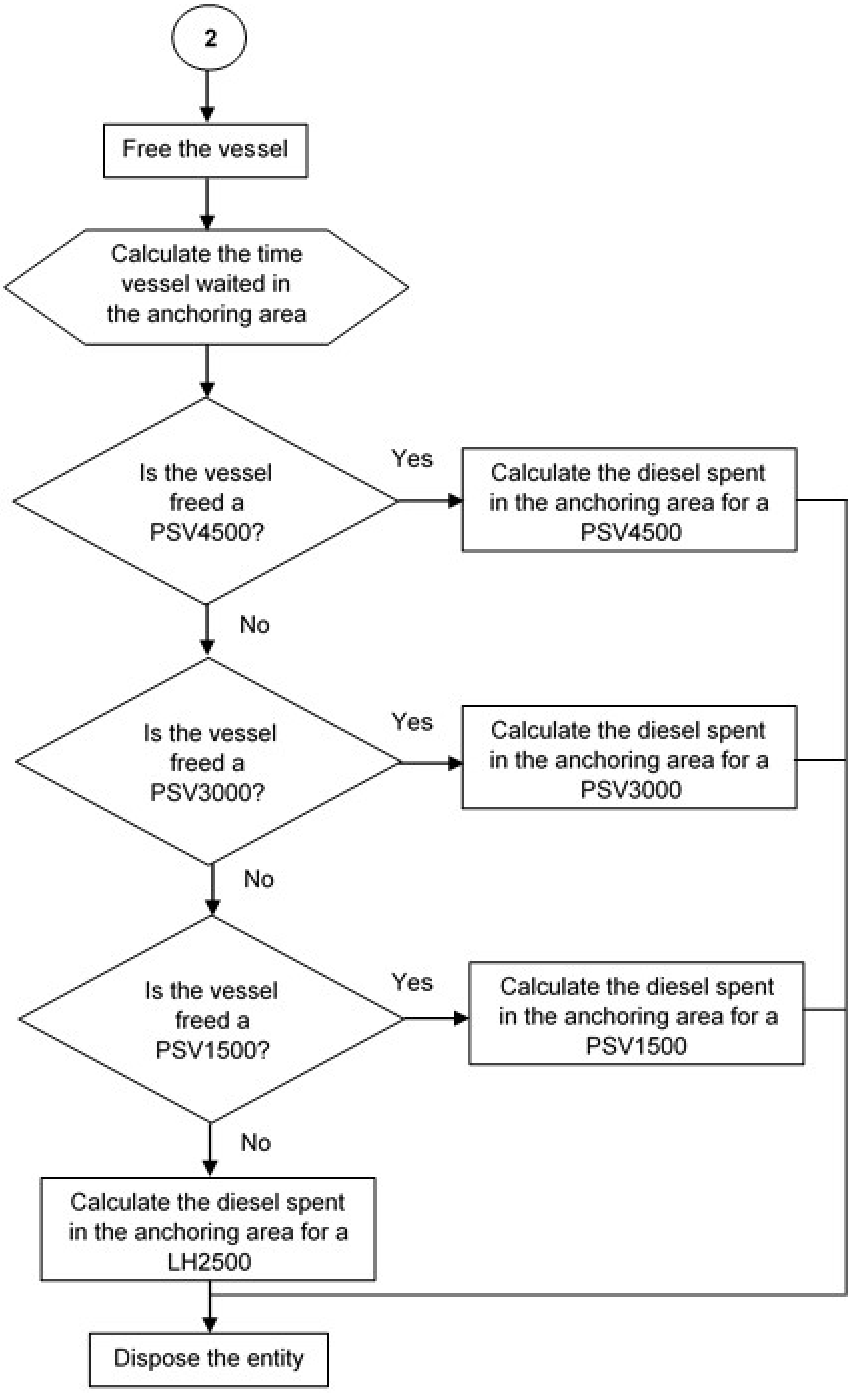
This section describes interactions taking place in the port anchoring area. All vessel downtime occurrences have been analyzed as if has been taken place in this location. Therefore, vessels stay in downtime according to the probability of breaking down based on historical indicators and distributions. 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***


Anchoring Area Station
Stop the cycle time counter
Is it a PSV4500?
Yes
Calculate Diesel cost for PSV4500
No
Is it a PSV3000?
Yes
Calculate Diesel cost for PSV3000
No
Is it a PSV1500?
Yes
Calculate Diesel cost for PSV1500
No
Calculate Diesel cost for LH2500
Is the vessel available?
No
Repair the vessel
Yes
Calculate the initial time in the anchoring area
1



1
Does the cargo come from UEP5 or UEP44?
Yes
Is there a vessel in queue waiting for programming to UEP5 or UEP44?
Yes
Hold until there is no vessel in queue
Wait cargo programming for the LH2500
No
Cargo area smaller than 270 m²?
Yes
Is there a PSV1500 vessel in queue waiting for programming?
Yes
Hold until there is no vessel in queue waiting
No
Wait cargo programming for the PSV1500
No
Cargo area smaller than 460 m²?
Yes
Is there a PSV3000 vessel in queue waiting for programming?
Yes
Hold until there is no vessel in queue waiting
No
Wait cargo programming for the PSV1500
No
Is there a PSV4500 vessel in queue waiting for programming?
Hold until there is no vessel in queue waiting
No
Wait cargo programming for the PSV4500
2




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. **Table 13** presents average values for diesel oil consumption according to the class of the vessel.

***Table 13 - Oil Diesel Consumption***

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

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.

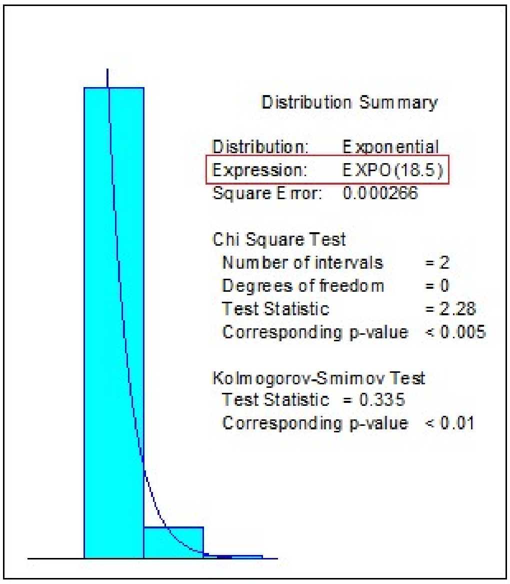
$$dieselcostvesselPSV4500 = (finalcycletime - initialtime) \times dieselconsumption\_PSV4500 \times dieselprice \quad \textbf{Equation 3}$$

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

$$Dieselcostvessel = dieselcostvessel + dieselcostvesselPSV4500 \quad \textbf{Equation 4}$$

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***




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 were 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.

$$diesel\_cost\_for\_PSV4500\_anchoring = anchoring\_time \times dieselconsumption\_PSV4500 \times dieselprice \quad \textbf{Equation 5}$$

**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.

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

| 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 |

The total Diesel consumption cost for all vessels will be calculated through the iterative variable “*Dieselcostvessel_anchoring*” as shown by **Equation 6**.

$$\mathit{dieselcostvessel\_anchoring} = \mathit{dieselcostvessel\_anchoring} + \mathit{diesel\_cost\_for\_PSV4500\_anchoring}$$ **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 time-persistent. **Figure 34** shows the data collected upon the finishing of the simulation.

***Figure 34 – Statistics Data Collected – Statistics Module***

| | Name | Type | 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 | |

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 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 model-generated 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 comparison proposed 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.

***Table 15 - Comparative Table for the Validation***

| **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% |
| 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**:

$$\textit{Average Vessel Occupancy}\ (\%) = \frac{\textit{Total of Deck Area Carried}\ (m^2)}{\sum_{i=1}^{4}(\textit{Number of Fulfiments}_i \times \textit{Vessel Deck Capacity}(m^2)_i)} \qquad \textbf{Equation 7}$$

*i*: number of vessel types

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

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

$$\boldsymbol{Average\ Vessel\ Occupancy} = \mathbf{63.9}\%$$

The values found in the table have been considered satisfying and the deviation within the 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 proved to be zero, which shows 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.

***Figure 35 – Average Port Loading Time Calculation***

Model Filename: C:\Users\Rafael Basilio\Desktop\ARENA MODELOS\Final Page 17 of 31

15:57:45 **Category Overview** junho 21, 2017

**Unnamed Project**

Replications: 20 Time Units: Hours

**Queue**

**Other**

| Number Waiting | Average | Half Width | Minimum Value | Maximum Value |
|---|---|---|---|---|
| request_LH_2500.Queue | 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 |

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.

***Table 16 - Simulation Scenarios Proposed***

| Scenario | Vessel Analyzed | Description | Sub-scenarios analyzed | Goal |
|---|---|---|---|---|

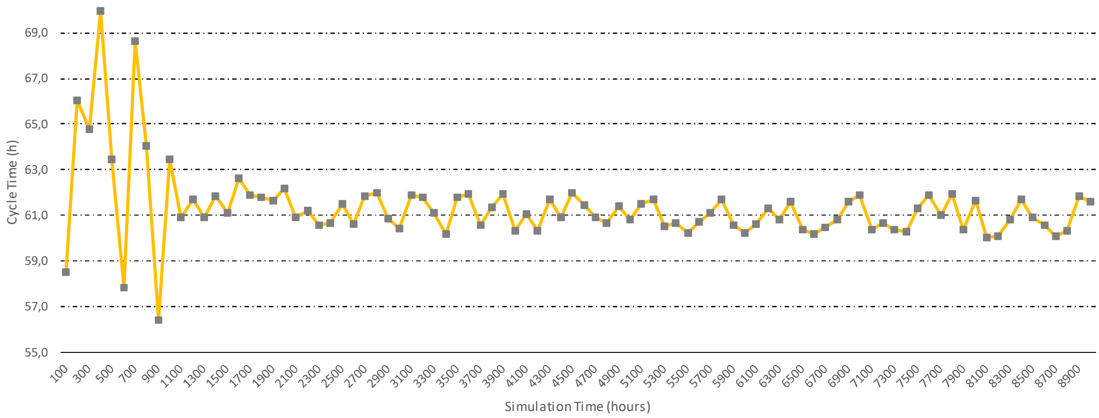
| | | | | |
|---|---|---|---|---|
| I | PSV4500 | Gradual reduction of the PSV4500 fleet | I to VIII | Analyze the impact of the reduction of the PSV4500 fleet on the indicators |
| II | PSV3000 | Gradual reduction of the PSV3000 fleet | I to IV | Analyze the impact of the reduction of the PSV3000 fleet 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 |

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 BATISTA (2005) 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 sample proposed of 20 replications. **Table 17** shows the outcome of the pilot round of 20 replications for the cycle time.

***Table 17 - Average Cycle Time for the Determination of the Minimum Number of Replications Required***

| 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 |

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 – α)* (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

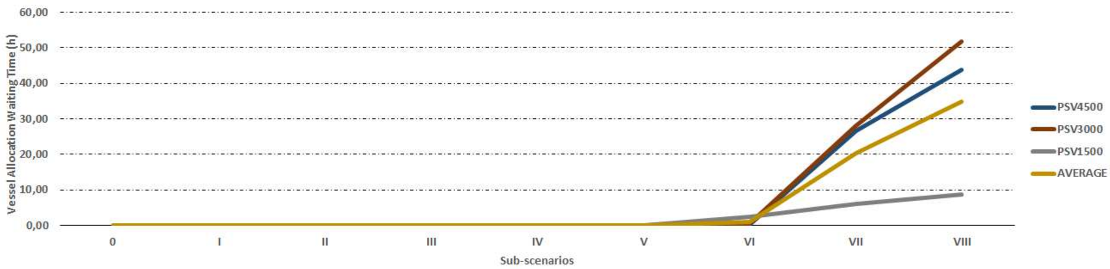
The first scenario comprehended the simulation of the downsizing only of the PSV4500 vessel fleet with the purpose of studying the influence of the fleet size for this type of vessel on parameters such as anchoring area waiting time, vessel allocating waiting time, cycle time and offshore transportation fulfilment indicator. **Table 18** shows the fleet size used in each sub-scenario simulated for the first scenario proposed by this study.

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

| Sub-scenario | 0 | I | 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 |

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).

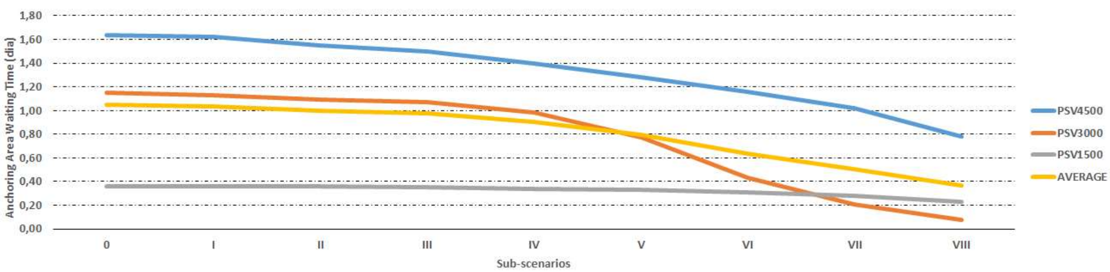
*Figure 37 - First Scenario – Vessel Allocation Waiting Time*




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.

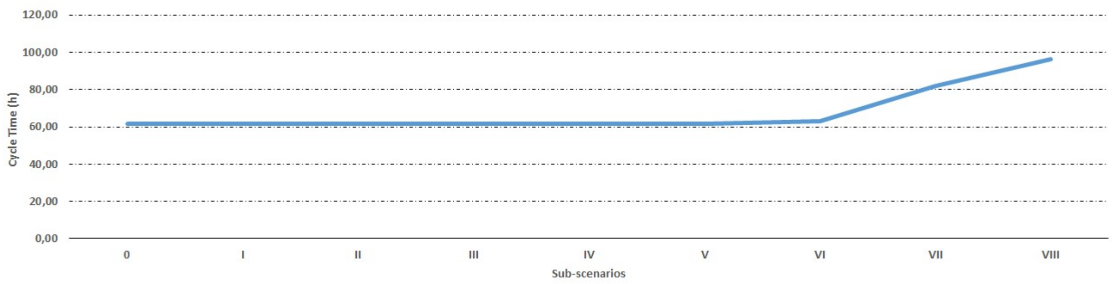
*Figure 38 - First Scenario – Anchoring Area Waiting Time*




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 respond to a stronger demand for allocation.

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

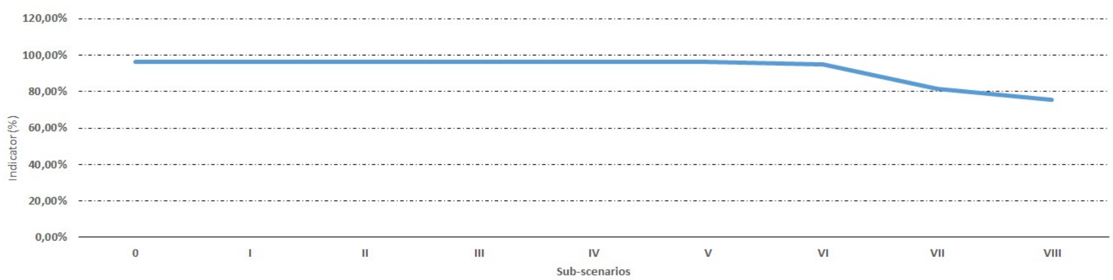
*Figure 39 - First Scenario – Cycle Time*




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.

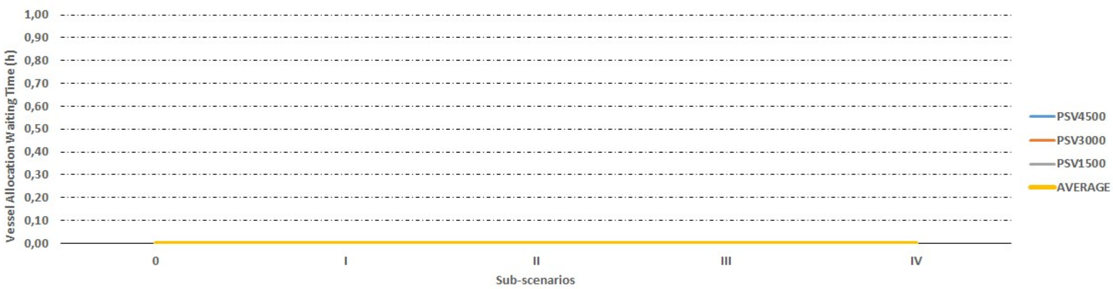
The second scenario comprehended the simulation of the downsizing only of the PSV3000 vessel fleet with the purpose of studying the influence of the fleet size for this type of vessel on parameters such as anchoring area waiting time, vessel allocating waiting time, cycle time and offshore transportation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

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

| Sub-scenario | 0 | I | 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 |

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

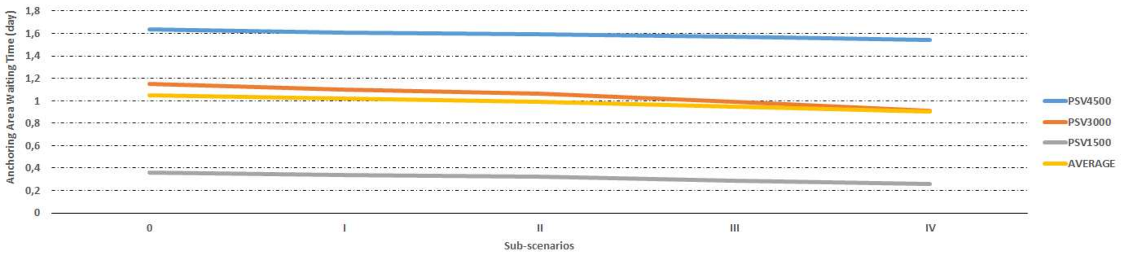
***Figure 41 - Second Scenario – Vessel Allocation Waiting Time***




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 perspective cost associated with stock out, charter and Diesel consumption has been added.

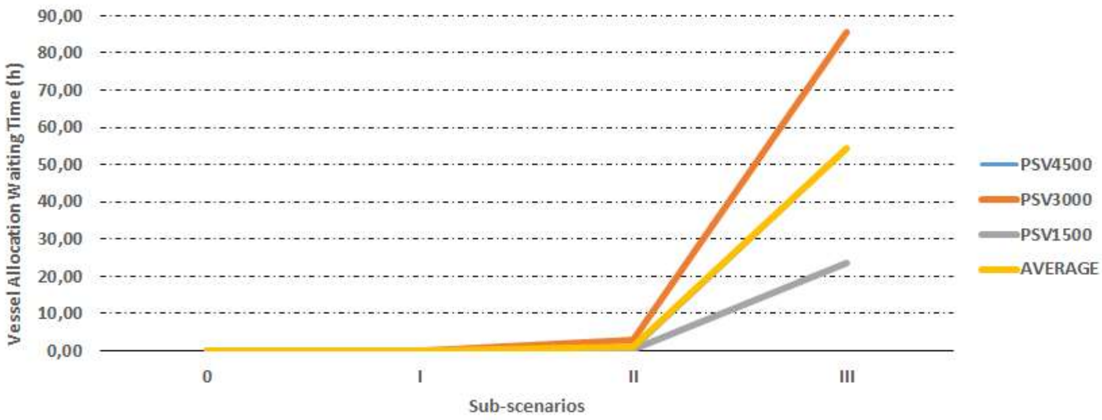
**Table 20** presents the sub-scenarios for this third scenario proposed according to proportional reduction.

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

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

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

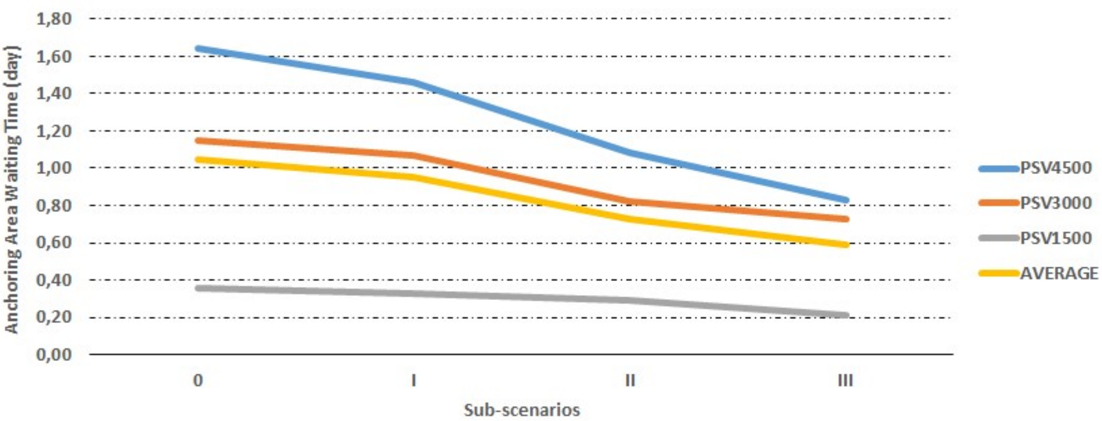
*Figure 43 – Third Scenario – Vessel Allocation Waiting Time*




As can be seen above, under the aggressive reduction of the fleet in the sub-scenario 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*

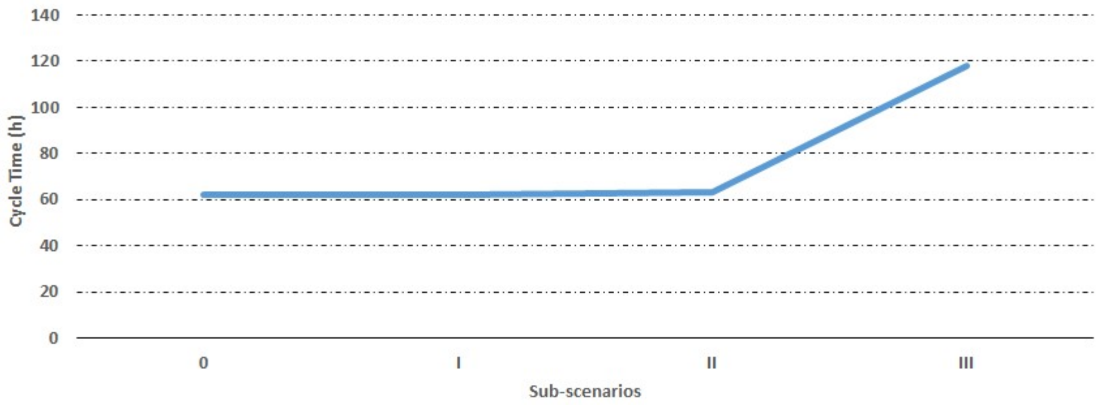
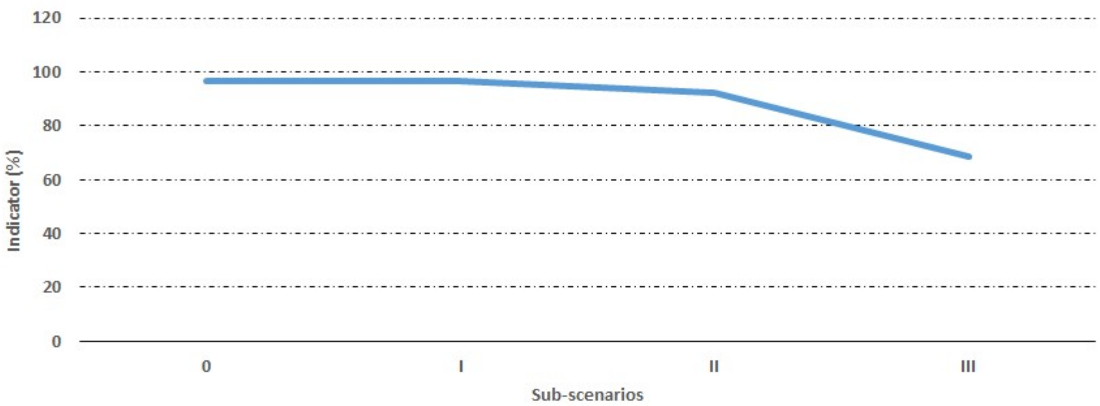



*Figure 46 – Third Scenario – Offshore Transportation Fulfilment Indicator*




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, costs related to 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**.

***Table 21 – Third Scenario – Charter Rates***

| Definition | 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 | $DT_A$ | 0.93 |

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.

$$Stockout\ Cost = 30\sum_{j=1}^{2}\left(\frac{LDRD_j \times R_j \times NC_j}{NT}\right) \times \frac{\sum_{i=1}^{3}(NFP_i \times VAWT_i)}{24}$$ ***Equation 11***

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

$LDRD_j$: Logistic-related Drill Rig Downtime Indicator

$R_j$: 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 has been created to measure the impact of the cargo delivering delay on the total downtime of a drill rig. 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 fulfilments delayed 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.

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

| Type of Units | Exclusive Clusters | Shared 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 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.

$$Stockout\ Cost = 30 \times \frac{LDRD \times CBO \times NC}{NT} \times \frac{\sum_{i=1}^{3}(NFP_i \times VAWT_i)}{24}$$

***Equation 12***

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

The same value used for *LDRD* associated to drill rigs has been used for the oil production units.

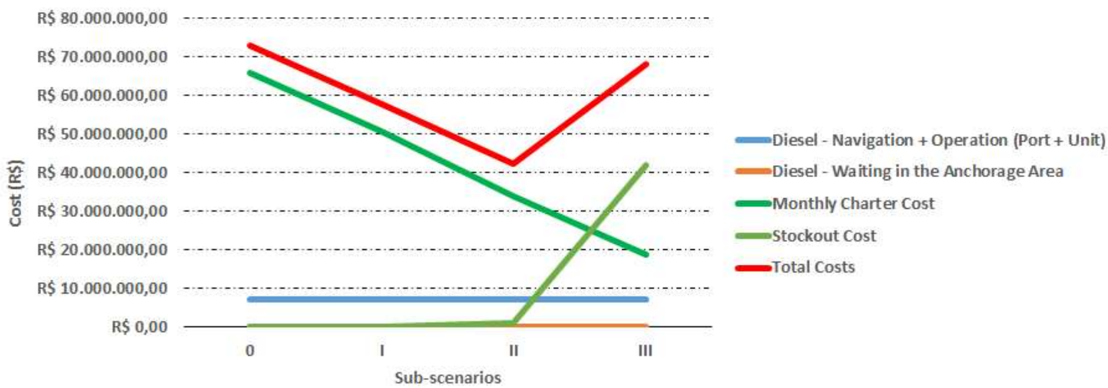
The Diesel consumption-related costs for navigation + loading (port + offshore) have been calculated by ARENA and the result is presented in **Table 25**. The Diesel consumption for navigation + loading has not varied, since regardless of the number of vessels, the time spent for navigation and loading 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.

***Table 25 – Third Scenario – Cost Table***

| 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 Anchoring 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$ 1,069,729.34 | R$ 42,123,739.04 |
| **Total Costs** | **R$ 73,052,567.50** | **R$ 57,789,037.53** | **R$ 42,197,865.16** | **R$ 67,987,501.38** |

**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 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-on-weather 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.

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. 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. Furthermore, 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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