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SELECTION PROCESS OF AN OFFSHORE PETROLEUM PRODUCTION SYSTEM THAT ACCOUNTS TECHNICAL, TECHNOLOGICAL, ECONOMIC, ENVIRONMENTAL AND LOGISTIC ATTRIBUTES

Laura Julieth González Castaño

University of Campinas, Faculty of Mechanical Engineering & Center for Petroleum Studies, Campinas-SP, Brazil
laura@dep.fem.unicamp.br

Celso Kazuyuki Morooka

University of Campinas, Faculty of Mechanical Engineering & Center for Petroleum Studies, Campinas-SP, Brazil
morooka@dep.fem.unicamp.br

Abstract. An offshore petroleum production system is composed by a set of equipment placed from the wellhead to the surface process FPU, including the storage and offloading system for the produced oil. Today, the design of an offshore production system is more sophisticated and complex due to the ultra water depth and the long distance from the coast to the offshore oilfield, among others. Initially, technically-feasible alternatives are built, then, the best alternative between different sets of available equipment is selected. The selection process must consider cost-effectiveness, environmental friendliness, technical effectiveness, technological confidence, and logistic simplicity of each alternative. Metrics to find attractiveness of a given alternative from economic, technological and environmental point of view were based on previous studies and a new indicator, as an attribute involving logistics, was defined and included by the author. Multi-attribute technique was used to define the total attribute for each alternative on the decision-making. The proposed selection process was applied through a real field evaluation, and discussions are shown. A comparison with the actual system in the field of study showed the good performance of the proposed selection process and improvements in the process were obtained from the inclusion of the new logistic attribute.

Keywords: floating production system, offshore petroleum, petroleum production.

1. INTRODUCTION

The growth in world energy demand has led to the premature depletion of many onshore oil reservoirs. As a result, onshore reserves have become more difficult to find, and big oil companies have risked in offshore-field development. Deep and ultradeep water fields are one of the segments of greatest growth in the offshore industry, since a great number of discoveries of considerable-size reservoirs have been accomplished. These discoveries allowed oil companies to begin strategic studies to find the most suitable offshore petroleum production systems for a given petroleum field development.

The design of an offshore production system for a given offshore petroleum field consists in determining, among others, well arrangement, use of manifold or not, type of the production platform, riser system, mooring system, separation system and storage and offloading system.

Morooka and Galeano (1999) and Dezen and Morooka (2002) show methodologies for the selection of an oil and gas production system. The main parameters for the selection process related to the reservoir, well drilling program and production plan for oil and gas are evaluated. Furthermore, ocean environment and geographical location of the offshore field are also considered.

Franco (2003) proposed a clear, organized and systematic methodology for the selection of different components of an offshore production system where technical issues were taken into account. Artificial intelligence techniques are applied and an intelligent system is presented, where knowledge, which is described through fuzzy sets, is obtained through a literature survey, and expert knowledge is demanded to assist the selection of the production system. Due to the complexity involved in determining solutions deterministically, approximate reasoning is used.

On the other hand, Castro et al. (2002) pointed out that a number of other aspects must be taken into account in the decision-making process, as well as the importance of including technological and environmental aspects besides the technical or financial ones. The utility function is employed to model those aspects and the multi-attribute concept is

The first stage of the methodology involves building a set of alternatives of offshore petroleum production systems considering technical aspects. The knowledge presented by Franco (2003) will be used, but for a different purpose. Thus, while Franco (2003) intends to find the best alternative project considering just technical aspects, the first stage of this work seeks to obtain a range of alternatives with technical feasibility.

To find each alternative is necessary select a set of components that, according with the field characteristics, could be installed together. This choice depends on numeric input data as reservoir area, reservoir depth, number of wells, daily flow per well, water depth and distance from the coast. In order to use the decision rules proposed by Franco (2003) to select alternative components, numeric input data must be transformed into linguistic terms by means of fuzzy sets. The fuzzy sets define different numeric ranges of a field characteristic and assigns a linguistic term to each range. Fuzzy Sets Theory was also used by Fonseca et al. (2005) to include the uncertainty involved in the definition of a petroleum production system, demonstrating the fuzzy sets usefulness in similar decision processes.

The decision rules combine the linguistic terms, which represent the field input data, to obtain, as output, the components that could better operate in this field characteristics. Franco (2003) used the knowledge of experts on processes and technical procedures that involve the offshore oil production to create these rules.

The second stage is based on the work developed by Castro et al. (2002) and presents the methods to compare different aspects of each alternative, including the logistic aspect proposed in this paper. The multi-attribute concept will be used to establish a standardized and systematic procedure for the selection of the best option among the alternatives.

2.1 Building Alternatives

First, it is necessary to determine the arrangement of the wells and the use or not of the manifold. The parameters used to determine the well arrangement are the reservoir area, the reservoir depth, the well type and the number of wells. To determine if a manifold is required, the parameters are the number of wells, the daily flow per well and the arrangement of the wells. The interrelationship between all these parameters forms the necessary knowledge to determine the well arrangement and manifold of a given offshore field. This knowledge is summarized and described by Franco (2003).

Then, the appropriate floating production unit, anchorage type and riser are defined. It was observed that more than one FPU alternative could be installed and operated successfully in fields with similar characteristics. In order to consider other factors in the decision, besides the technical requirements, the data base of Franco (2003) was updated by the author to obtain a set of technically possible FPU alternatives and not only the best one. This information was obtained from the floating production systems currently operating or under development showed in Barton et al. (2016). Parameters such as water depth, number of wells, the existence of infrastructure close to the FPU with availability to process the produced fluids, the arrangement of the wells and the expected production of the field are used to determine the operational limitations for installing the floating units. Only floating production units were considered (Spar, TLP, semi-submersible and FPSO) since this work is focused on water depths of over 300 meters.

For the selection of the type of anchoring and riser, the procedure proposed by Franco (2003) is used. However, as these are components that depend on the type of FPU, they are established separately for each viable FPU type.

And finally, the type of separation system and the type of storage and transport of oil are selected. For the type of separation system, the parameters used are: existence of processing infrastructure close to the FPU and the type of separation system of that infrastructure. The separation systems can be subdivided into three types: two-phase separation, three-phase separation and three-phase separation and treatment. The purpose is to always make the separation and the treatment of the produced fluids as complete as possible, even on the high seas. Therefore, if there is no available infrastructure near the field to process all the produced fluids, the FPU must be equipped with a three-phase separation plant and facilities for the oil treatment. On the other hand, if this infrastructure existed, but it is only equipped with a treatment plant, the platform must be able to separate all its production in three phases and then, send the oil to the infrastructure where it will be treated. The separation system was added as a component of the production system aiming at its use in determining the logistic attribute and because it will be necessary in the selection of the type of oil storage and transportation.

For the determination of the type of storage and transport of oil, the parameters are: FPU type, its storage capacity and type of separation system. The types of oil storage and transportation adopted in this work are basically three: pipelines (will always be an option), hydrocarbon transport system by ship (will be an option just when the FPU has the capacity to store the whole production) or transport system by ship with external storage permanently anchored in the field receiving the oil produced (when the FPU does not have the capacity to store the whole production). It is important to highlight that, for the selection of the hydrocarbon transportation and storage system, more than one option is found to be viable for each type of FPU.

2.2 Evaluating Alternatives

Technology is defined as the ability to perform a task and its development is accomplished through its usage (Nepomuceno, 1997). In order to find the value of the technological attribute of each FPU, it was assumed that if all the FPU's installed in the world were of the same type, this type of FPU would have the maximum technological attribute,

since it is said that all the experience that could be obtained on field development would be acquired in the installation and production of this specific type of FPU.

Also, the technological gain in FPU anchoring (one of the most notorious problems in deep and ultra deep waters) is measured, thus it is necessary to subdivide the deepwater classification in three bands: from 300 to 1000 meters (Medium), from 1000 to 1500 meters (Deep) and from 1500 meters onwards (Ultradeep). So, for each FPU type, the cumulative number of units that went into operation until 2016 was found, as shown in Tab. 1. The cumulative number of each FPU was normalized with the total number of FPUs operating in each water depth range to obtain the technological attribute.

Table 1. Cumulative number of FPU's for each water depth range.

FPU	FPU number 300-1000 m	FPU number 1000-1500 m	FPU number Besides 1500 m
FPSO	42	35	22
SS	21	6	11
Spar	4	11	7
TLP	18	11	1
Total	85	63	41

The economic attribute is determined by NPV calculation. The net present value of a project is defined as the sum of the input and output values of a project's cash flow discounted at a minimum attractiveness rate and referred to the beginning of the development phase of a field. The elements that vary in the calculation of each cash flow are: cost and time of building, installing, launching, connecting and mooring each FPU alternative; workover time and cost per well with dry christmas tree and wet christmas tree; cost and connection of each well to the FPU (including handling with riser), among others. Furthermore, the price of oil, the exponential decline rate of the production, the project life span, taxes and the minimum attractive rate of return (used as discount rate) are the same for all alternatives.

The NPV calculated for each alternative will be linearly proportional to the economic attribute, based on the fact that the economic attribute of the alternative with the highest NPV will have a value of 1.

The environmental attribute is based on Gonçalves (2014), who structured an environmental impact matrix for each type of floating FPU that considers the main activities in the life of an offshore oil production system: FPU installation, operational phase and decommissioning (Mariano and La Rovere, 2007), and highlighted a list of environmental elements that are involved in these activities: air, water, sediment, plankton, benthic communities, fish, fishing activity, birds, marine mammals and tourism. (Patin, 1999). Then, Gonçalves (2014) calculated the probability that such activities impacted in some way the elements of the environment and was able to determine a total environmental impact indicator for each FPU. By normalizing this indicator, the environmental attribute is generated where the alternative with the least environmental impact indicator has an attribute of 1 and the alternative with the greatest indicator has an attribute of 0.

2.2.1. Determination of the logistical attribute

Four subsystems were defined as essential for the logistic during the production stage of an offshore field: production on the platforms, oil storage, oil transportation and people and supplies transportation. For each one, a logistic management indicator is dimensioned by the parameters that influence each subsystem. These parameters were obtained by means of bibliographical research of the problems most commonly seen in the offshore production, and are discussed orderly below.

For the calculations, a value is attributed to each possible entrance parameter and the indicator value is defined by their average. Finally, the logistic attribute is calculated by the average of the indicators, assuming that all have the same importance within the logistic chain.

Production Indicator

It was evidenced that in the production subsystem the main concern of the logistics is to avoid operational losses in the FPUs, that is, to ensure that the FPU produces the oil continuously (Ono, 2007). The parameters that define this indicator are presented schematically in Fig. 2.

The FPU processing capacity could be insufficient when it is less than the production volume or sufficient if it is the other way around. So, if production is continuous, the FPU must be prepared to process the entirety of the produced fluids. If the field logistics cannot dispose oil, production will be restricted. It is here where the processing capacity of the FPU plays a very important role, because if it is insufficient, the field will require other solutions, such as transporting the unprocessed production to a nearby treatment plant, which will undoubtedly demand a representative logistical effort. The optimal solution would be that the FPU has sufficient processing capacity.

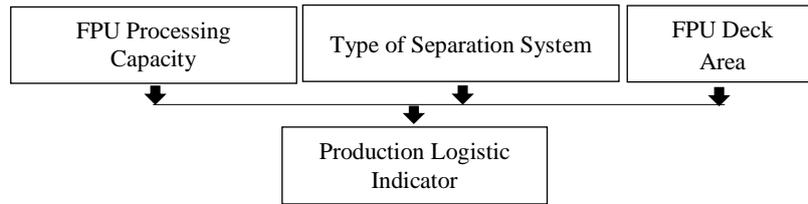


Figure 2. Parameters used to determine the production indicator.

Three types of separation system were considered: two-phase, three-phase and three-phase + treatment. When the FPU has only a two-phase separation system, additional work will be required to transport the water and oil mixture to some infrastructure that can separate and process them. Generally, the production water has all kinds of dissolved contaminants, a fact that could generate problems like corrosion and incrustations. In this sequence, if the FPU can separate water, gas and oil, but does not treat the oil, it should be drained to a nearby treatment plant, still with water and impurities, since the three-phase separation by itself is not designed to destabilize and break emulsions. Finally, if a FPU has a three-phase separation + treatment system, it does not need other infrastructure and the fluids can be transport directly to coast.

The deck area for a FPSO is very large, for an SS is large and for a TLP and Spar is medium. An FPU with a very large deck area may have greater logistic value thanks to space, as long as it is used properly. Thus, for example, this space can be used to install a more complete and sophisticated treatment plant without disrupting the other activities developed on the FPU.

According to the latter, the values attributed to each parameter in the production logistic indicator were: for the FPU processing capacity "Sufficient: 1.0" and "Insufficient: 0.0"; for the type of separation system "Three Phase + Oil Treatment: 1.0", "Three Phase: 0.5" and "Biphasic: 0.0"; And for FPU deck area "Very Large: 1.0", "Large: 0.5" and "Medium: 0.0"

Oil Storage Indicator

Using the established criteria for the production indicator, the unavailability of oil storage space implies an operational loss due to the interruption of production, and should be avoided at any level of planning. The storage type defined in the first stage and it is the only parameter included in this indicator.

Offshore units may or may not be equipped with storage tanks. The best option in logistics terms would be pipelines, so there would be no concerns about storage capacities, interconnections, time intervals and discharge rates, among others. On the other hand, if storage is done on the FPU versus an external storage, it would not require to rent or buy infrastructure for storage and the connections between the FPU and said infrastructure.

For the oil storage logistic indicator, the utilities attributed were "Pipeline: 1.0", "On the FPU: 0.5" and "External storage: 0.0".

Oil Transport Indicator

The parameters that account for the logistical difficulties to transport oil are shown in Fig. 3. The mode of oil transport has already been defined in the first stage of the methodology. As has been noted, transportation through a pipeline will always have a greater logistic function than that of a vessel. The availability of neighboring pipelines will facilitate logistical tasks only when the selected oil transportation subsystem is a pipeline. Otherwise, it means that this infrastructure is wasted and its logistical gain will be lower. The distance from the field to the coast is categorized as short, medium and long, according with the fuzzy sets proposed by Franco (2003). This parameter affects the oil transport indicator since the offloading terminals are located on the coast and their proximity to the field decreases the complexity of the logistics operations, making the construction of a pipeline more favorable or the transport by vessels faster.

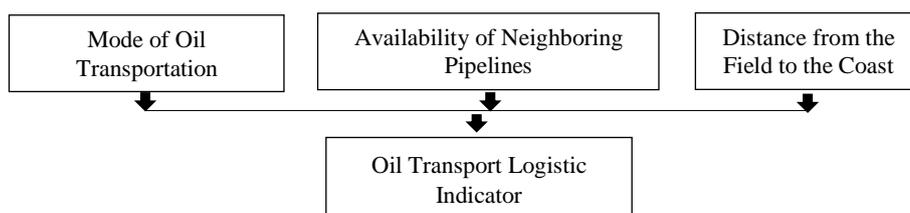


Figure 3. Parameters used to determine the transport of oil logistic indicator.

To determine the oil transportation indicator, the values attributed to the parameters are, for the type of oil transportation "Pipeline: 1.0" and "Vessel: 0.0"; for the availability of neighboring pipelines "Yes: 1.0" and "No: 0.0"; and for the distance from the field to the coast "Short: 1.0", "Medium: 0.5" and "Long: 0.0".

Transportation of People and Supplies Indicator

During the field production, oil transport is just one of many concerns referring transportation. The transportation of people and supplies is another relevant logistical problem, since new discoveries are located at greater distances from the coast and imply a great difficulty for logistical support. The parameters used to represent the logistical difficulties to transport people and supplies are shown in Fig. 4.

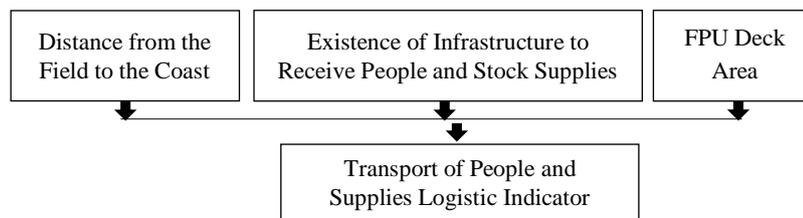


Figure 4. Parameters used to determine the transport of people and supplies logistic indicator.

Distance from the field to the coast affects the transport of people and supplies indicator, since, in the logistic chain, the coast is always the point of embarkation or disembarkation, and its proximity saves logistic efforts. For example, quick vessels or helicopters, which travel short distances, can be used for transporting passengers and supplies, thus reflecting in savings in time and fuel.

An infrastructure to receive people and stock supplies solves the problems related to the autonomy of flight of most airplanes. The most important workers and supplies could be transported in high-capacity vessels to these infrastructures and from that point they would go to the FPU's via helicopter with a lower autonomy capacity (Morais, 2013). When the distance from the coast is short, this parameter will be indifferent on the determination of the transport of people and supplies logistic indicator.

FPU deck area is used to define the indicator of transport of people and supplies. The more space there is on the FPU for stock supplies, the less trips are necessary to provision it.

In the transport of people and supplies logistic indicator, the parameters values are: for distance from the field to the coast "Short: 1.0", "Medium: 0.5" and "Long: 0,0; for the availability of infrastructure to receive people and stock supplies "Yes: 1.0" and "No: 0.0"; and for deck area "Very Large: 1.0", "Large: 0.5" and "Medium: 0.0".

Finally, according with the multi-attribute model, a weight for each attribute should be given. According to Borghini et al. (1998), in the development of a project, about 19% to 22% of the investment is directed towards the environmental aspect and, according to Paul (1998), the budget used by an average oil company on the development of new technologies is 0.05%. Based on these statistics, Castro (1999) assumed the weight of the environmental and technological attributes as 0.2 and 0.05 respectively, and for the weight of the NPV attribute, a value of 0.5. By including this weight distribution of such parameters in this methodology, the missing weight to complete the unit (0.25) is the weight of the logistic attribute.

3. RESULTS

For a better understanding of the methodology, two real field evaluations are presented and discussed. In the Tab. 2 the data input for the study fields is shown.

Following the first stage of the methodology, the alternatives whose development is considered technically feasible were found. These alternatives consist of 7 components: well arrangement, manifold, FPU type, riser type, anchorage system, type of separation system and type of storage and oil transport. The alternatives, listed in Tab. 3, were formed by all possible combinations between the selected components.

For each field, as shown in Tab. 3, well arrangement, manifold use, and type of separation system are the same. This result implies that they depend only on field conditions and their databases were combined to choose only the best option for installation.

For the FPU type, more than one could have been chosen. The number of wells of Field I limited the choice because only a FPSO can receive 67 wells. The anchorage system and type of riser are components that depend on the FPU and the field parameters, so they could be different for each field and for different FPU's in the same field. For oil storage and transportation, more than one type complies with the development characteristics of the field and with the type of FPU.

Table 2. Fields data.

Field Data	Field I	Field II
Reservoir Area (km ²)	398	59
Reservoir Depth (m)	1500	4267
Number of Wells	67	14
Wells Type	Horizontal	Horizontal
Daily Flow Rate per Well (m ³ /d)	1200	2000
Water Depth (m)	1730	896
Environmental Condition	Moderate	Mild
Existence of Processing Infrastructure	No	No
Type of Separation System of the Infrastructure	N/A	N/A
Production (MBOE/d)	375	180
Distance from the Field to the Coast	125	210
Infrastructure for Receive People and Stock Supplies	No	No
Availability of Neighboring Pipelines	Yes	No
Distance to Neighboring Pipelines (km)	57	N/A

Table 3. Alternatives.

Alternatives	Field I		Field II					
	1	2	1	2	3	4	5	6
Arrangement	Satellite	Satellite	Clustered	Clustered	Clustered	Clustered	Clustered	Clustered
Manifold	Yes	Yes	No	No	No	No	No	No
FPU	FPSO	FPSO	TLP	TLP	SS	SS	FPSO	FPSO
Mooring	Taut Leg	Taut Leg	Vertical	Vertical	Catenary	Catenary	Turret	Turret
Riser	Flexible	Flexible	Rigid	Rigid	Rigid	Rigid	Rigid	Rigid
Separation System	Three-phase + Treatment							
Type of Storage and Transport Of Oil	Pipeline	Vessel	Pipeline	Ext. Storage + Vessel	Pipeline	Ext. Storage + Vessel	Pipeline	Vessel

With the objective of evaluating the alternatives, technological, economic and environmental attributes were founded as described in the methodology and are shown on Tab. 4.

Table 4. Evaluation by attributes of the alternatives.

Alternatives		Technological Attribute	Economic Attribute	Environmental Attribute	Logistic Attribute	Total
Field I	1	0,97	1,00	0,36	0,58	0,77
	2	1,00	1,00	0,36	0,33	0,70
Field II	1	0,43	0,84	0,74	0,59	0,74
	2	0,43	1,00	0,74	0,17	0,71
	3	0,50	0,32	1,00	0,67	0,55
	4	0,50	0,49	1,00	0,25	0,53
	5	1,00	0,69	0,36	0,75	0,65
	6	1,00	0,85	0,36	0,46	0,66

To determine the technological attributes, only water depth and FPU type are needed. This means that alternatives of the same field with the same type of FPU will have the same value for the technological attribute.

To determine the economic attribute, it is necessary to calculate the NPV for each alternative. To simplify the calculation of each cash flow, it was assumed that the only variable elements among the alternatives are the FPU cost and time to construction, the perforation and completion cost for a well with wet or dry christmas tree and the cost of the storage and transport of oil. Furthermore, it was assumed that for the vessel option, its rent was paid yearly. The rent cost was 40 MUSS/day and the number of days that must be rented depended of the production and the capacity of the vessel, which was assumed to be 800 MBOE. On the other hand, to pay the pipeline, a loan was made that had to be repaid of the first fifteen years of the project. It was also assumed that the cost was 3 MMUSS/km and its length was equal to the distance from the field to the pipeline infrastructure and that the interest on the loan is included in the total amount.

With these assumptions, the cash flow and NPV for each alternative were calculated. The value of the economic attribute was determined by normalizing the NPV's, where the alternative that obtained the highest NPV has as an economic attribute of value 1.

The determination of the environmental attribute depends only on the type of FPU, since the total environmental impact indicator proposed by Gonçalves (2014) for each stationary production unit was adopted and normalized. Therefore, alternatives that have the same type of FPU have the same environmental attribute value.

Finally, for the calculation of the value of the logistic attribute, the logistic indicators must be found. These were determined according to the interrelationship of the parameters influencing them. The average of the indicators represents the value of the logistic attribute.

After having the values of the attributes for each alternative the multi-attribute concept was applied. The sum of the weight of each attribute multiplied by its value represents the total attribute. The attributes for the alternatives and the total attribute found after weighting them are presented in Tab. 4.

The best alternative for Field I is composed by satellite well arrangement with the use of manifold, a FPSO anchored by taut leg, flexible risers and a pipeline for oil transportation. On the other hand, for Field II, the best alternative is composed by clustered arrangement without manifold, a TLP with vertical anchoring, rigid risers and a pipeline for oil transportation.

For Field I, a satellite well arrangement was selected due to its ability to reach a large reservoir area more evenly. This is different for Field II, whose area is smaller.

The manifold was suggested for Field I in order to join the production of the large number of well. Individual wells (wells connected directly to the FPU) were discarded due to flowline costs and the high load capacity required by the stationary production unit to load the risers weight. Instead, for Field II, a manifold is not necessary because of the small number of wells.

Field I is categorized as ultradeep water so the selected risers are flexibles. For Field II, which is in medium water depth, a rigid riser was selected.

Although the distance from the field to the coast is medium, a pipeline was suggested as the type of oil transportation for Field I since there is pipeline infrastructure available near the field. In addition, field production is really high which would partly offset the economic impact on construction. The latter can be observed on the economic attribute, where an FPSO with pipeline presents the second highest economic return. For Field II, a pipeline was selected as the oil transportation system because the TLP platform has not storage capacity and if a vessel was used, it would be necessary to have another vessel anchored permanently next to the TLP.

Table 5 shows the components of the offshore production system currently installed in the fields and the results obtained by the application of the proposed methodology are listed. The results that differ from the installed system are highlighted.

Table 5. Results of the methodology and the system currently installed.

Components	Field I			Field II		
	System Currently Installed	Result of Methodology	Result without Logistic Attribute	System Currently Installed	Result of Methodology	Result without Logistic Attribute
Arrangement	Satellite	Satellite	Satellite	Clustered	Clustered	Clustered
Manifold	Yes	Yes	Yes	No	No	No
FPU	FPSO – SS	FPSO	FPSO	TLP	TLP	TLP
Mooring	Taut Leg	Taut Leg	Taut Leg	Vertical	Vertical	Vertical
Riser	Hybrid	Flexible	Flexible	Rigid	Rigid	Rigid
Separation System	Three-phase + Treatment	Three-phase + Treatment	Three-phase + Treatment	Three-phase + Treatment	Three-phase + Treatment	Three-phase + Treatment
Type of Storage and Transport Of Oil	Pipeline	Pipeline	Vessel	Pipeline	Pipeline	Vessel

The only difference found between the installed systems on the fields and the results of the methodology is the type of riser for the Field I. The hybrid risers installed on this field were presented as one of the main improvements of the Petrobras innovation strategy executed in 2007. Generally, in other regions of the world, a flexible riser is commonly used at that depth.

The results of the methodology without including the logistic attribute suggested the oil to be transported by a vessel, whereas with the inclusion of the logistic attribute, the use of pipeline was recommended. This means that if the logistic attribute was not considered, that is, its weight was zero, the accuracy of the selection process would be lower. The effect of the logistic attributed is really important because in fields with high production, a pipeline would significantly reduce logistics efforts in relation to the monitoring of storage, transportation and offloading capacities, the creation and optimization of offloading routes, the connections between FPUs and transport vessels, among others.

4. CONCLUSIONS

Selection processes of an offshore production system proposed by other authors were adapted and fitted so that current conditions of offshore-field development were considered. Therefore, indicators related to logistics planning were successfully included in such processes allowing the selection of the offshore petroleum production system that best meets the technical, economic, technological, environmental and logistic aspects.

The two fields evaluated demonstrated the good performance of the proposed selection process since the results were coherent with the field conditions and with the offshore production systems currently installed. This means that by just following this work methodology, without the knowledge of field development specialists, it is possible to obtain a good approximation of the equipment that should be installed for a given field conditions.

The results show that when the logistic attribute is not accounted, the type of transport and storage of oil changes, adding an additional percentage of error to the process. Consequently, the success of the methodology at analyzing the type of oil storage and transportation can be justified as an improvement by the inclusion of the logistic attribute.

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7. RESPONSIBILITY NOTICE

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