UNIVERSIDADE ESTADUAL DE CAMPINAS
FACULDADE DE ENGENHARIA MECÂNICA
E INSTITUTO DE GEOCIÊNCIAS

LEONARDO DE PÁDUA AGRIPA SALES

SELECTION OF OFFSHORE PRODUCTION SYSTEMS CONSIDERING UNCERTAINTIES

SELEÇÃO DE SISTEMAS DE PRODUÇÃO MARÍTIMOS CONSIDERANDO INCERTEZAS

CAMPINAS

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Dissertation presented to the School of Mechanical Engineering and the Institute of Geosciences of the University of Campinas in partial fulfilment of the requirements for the degree of Master in Science and Petroleum Engineering in the area of Exploitation.

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Orientador: Prof. Dr. Celso Kazuyuki Morooka

Este exemplar corresponde à versão final da Dissertação defendida pelo aluno Leonardo de Pádua Agripa Sales e orientada pelo Prof. Dr. Celso Kazuyuki Morooka.

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DISSERTAÇÃO DE MESTRADO ACADÊMICO

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Autor: Leonardo de Pádua Agripa Sales
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A Ata da defesa com as respectivas assinaturas dos membros encontra-se no processo de vida acadêmica do aluno.

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RESUMO

O desenvolvimento de um campo marítimo petrolífero é um projeto complexo e arriscado. Um problema central nesta tarefa é a seleção de um sistema de produção que maximize a recuperação de óleo e minimize os investimentos e custos operacionais enquanto satisfaz restrições externas, econômicas, ambientais, sociais e tecnológicas em um cenário de incertezas. Diversos estudos abordam tal problema na literatura, entretanto eles não consideram incertezas nos dados de entrada, nem justificam objetivamente a alternativa escolhida dentre as demais possíveis. Aqui, é proposto selecionar um sistema marítimo de produção utilizando um sistema inteligente que considere incertezas nos dados de entrada e que selecione a melhor alternativa de maneira racional. Através da avaliação de estudos de caso e da comparação dos resultados obtidos com estudos anteriores e da situação real, conclui-se que o método pode obter a solução ótima em situações onde outros não podem.

Palavras-chave: desenvolvimento da produção do campo, inteligência artificial, sistema nebuloso.

ABSTRACT

The development of an offshore oilfield is a complex and risky project. One core problem in this task is the selection of a production system that maximizes oil recovery and minimizes investments and operational costs while meeting external, economic, environmental, societal and technological demands in a scenario of uncertainties. Several studies address this problem in the literature; however, they do not consider uncertainties in the initial data neither justify objectively the chosen alternative among other feasible ones. Here, it is proposed to select an offshore production system using an intelligent system that considers input uncertainties and chooses the best alternative in a rational manner. By evaluating case studies and comparing the results obtained with previous studies and real scenarios, it is concluded that the method can obtain the optimal solution in situations where others cannot.

Keywords: field production development, artificial intelligence, fuzzy system.

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LISTA DE ABREVIATURAS E SIGLAS

AHP	Analytic Hierarchy Process
BSR	Buoy Supported Riser
CAPEX	Capital Expenditure
EPS	Early Production System
ESA	Even Swaps Analysis
FPSO	Floating Production Storage and Offloading unit
FSO	Floating Storage and Offloading unit
GBS	Gravity Based Structures
GoM	Gulf of Mexico
GOR	Gas-oil ratio
IPR	Inflow Performance Relationship
MODU	Mobile Offshore Drilling Unit
NPV	Net Present Value
OPEX	Operational Expenditure
PI	Productivity Index
PSVM	Plutão, Saturno, Venus and Marte field
PV	Present Value
SCR	Steel Catenary Riser
SCR	Steel Catenary Riser
SPM	Single Point Mooring
SS	Semisubmersible
TDP	Touch Down Point
TLP	Tension Leg Platform
TOPSIS	Technique for Order Preference by Similarity to an Ideal Solution
VLP	Vertical Lift Performance relationship
VOIP	Volume of Oil-in-place

SUMÁRIO

1. INTRODUCTION

The selection of a production system that maximizes oil recovery and minimizes operational cost and investments while meeting economic, environmental, societal and technological demands is fundamental to any offshore field development. Methodologies were proposed in the literature to overcome such problem by analysing the problem both qualitatively (BEHRENBRUCH, 1993; COCKCROFT et al., 1994; BORGHINI et al., 1998; MOROOKA; GALEANO, 1999; RONALDS, 2002a, 2002b, 2004, 2005a; LU et al., 2006; MADDAHI; MORTAZAVI, 2011; ERLINGSEN et al., 2012) and quantitatively (DEVINE; LESSO, 1972; GRIMMETT; STARTZMAN, 1987; CASTRO; MOROOKA; BORDALO, 2002; DEZEN; MOROOKA, 2002; FRANCO, 2003; FONSECA et al., 2005; CULLICK; CUDE; TARMAN, 2007; SMYTH et al., 2010; MENTES; HELVACIOGLU, 2013; WU et al., 2016; GONZALEZ-CASTAÑO, 2017; BASILIO et al., 2018). Besides, many studies in the literature detail the selection process for offshore production systems (NAVEIRO; HAIMSON, 2015; ROACH et al., 1999; TUCKER; ROOBAERT, 1986). Although a specific and complex process, those reports help to build a knowledge base about how to select offshore production systems in an optimum manner.

In the earliest phases of field development, information related to reservoir proprieties and engineering data is usually uncertain and scarce. Even though reservoir studies or advanced seismic techniques are available to address uncertainties in these parameters (HAYASHI; LIGERO; SCHIOZER, 2007; OSYPOV et al., 2013), they are not sufficient or robust enough to face the complexity of the decisions involved in the selection of an offshore production system. Besides, production system concepts must be assessed and selected during the earlier phases of the field development to maximize economic return.

Several approaches in the literature addressed uncertainties in the selection of offshore production systems, such as in Dezen and Morooka (2002), Franco (2003), and Akeze, Sikandar, and LaForce (2009). In Franco (2003) only uncertainties in the linguistic terms used in the inference process are evaluated, ignoring uncertainties in the model's inputs. Moreover, the study does not properly explore the space of alternatives accounting ambiguities present in the process. A real options approach was employed in Dezen and Morooka (2002) to indirectly consider uncertainties through concept flexibility, addressing only a few types of equipment employed in the production system, such as the stationary production unit and the offloading system. Akeze, Sikandar, and LaForce (2009) addressed uncertainties by evaluating several field development schemes. However, the stationary production unit selection process does not follow a rational or an objective methodology. In this study, it is proposed to consider uncertainties in input data and their related ambiguities by considering fuzzy inputs in a fuzzy system. To better address this problem, a literature review about uncertainties and key aspects in the selection process is also proposed. This way, it is expected to address uncertainties deeper than other approaches in the literature.

In the following sections, the proposed methodology is presented, the model results are shown, and finally, the main conclusions are drawn.

1.1. Literature review

1.1.1. Development versus uncertainties

Field development planning is one of the main challenges of the industry. Key aspects (subsurface, drilling and completions, and surface facilities) interact iteratively in order to maximize operator's key performance indicators, including financial, strategic and risk requirements. The planning is constrained by internal (policies, portfolio and preferences) and external (political, environmental and legal) constraints over time. Field development poses as a complex and high-risk endeavour, as uncertainties in many components of a prospect are especially high at the beginning of the life cycle, when critical decisions must be made.

To reduce uncertainties, field appraisal is required. However, development costs increase the more an oilfield is appraised. Sometimes, reducing uncertainties may be expensive. For example, the cost of field appraisal that may prohibitive in deepwater. Dekker and Reid (2014) mentioned that a single deepwater appraisal well in such location is on average US$ 150 million and an early production system (EPS) over a billion dollars. An even worse scenario would be investing so much in reducing uncertainties that it is now possible to know certainly the best concept possible to implement, however there is no budget anymore due to the high investments made in field appraisal. This dilemma is illustrated in Figure 1. Because of this, in the majority of cases the company keeps questioning itself whether it is doing the right investment. Therefore, in overall the petroleum industry must make decisions under a certain level of uncertainties. However, the tools to aid the decision making do not consider uncertainties as it should, in general.

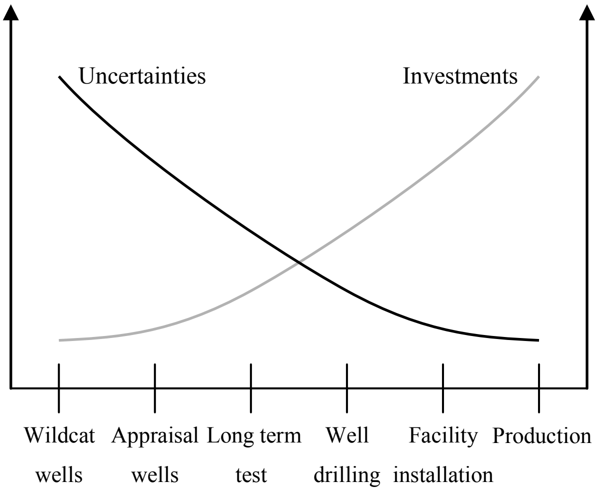


Figure 1. The dilemma of development flexibility versus uncertainty.

Uncertainties appear along the project in a different fashion. Uncertainties can be either aleatoric or epistemic. This classification is very similar to the one discussed in Ross (2010) and Ogawa *et al.* (2018). Aleatoric uncertainties are those that arise out of chance, such as tossing a dice, spinning a wheel in a lottery, or even the motion of dust particles in the air. On the other hand, epistemic uncertainties arise because of complexity, such as ignorance, or a lack of a precise measurement or statement. Both types of uncertainties happen during field development, with the second one affecting the decision making greatly, as it is everywhere and usually is poorly considered. For example, there are uncertainties regarding the riser diameter along its length, which can be clearly determined by a normal probability distribution, however uncertainties regarding the well count should not. The former arises by chance while the latter due to a complex design process. Therefore, epistemic uncertainties are ingrained into field development as both the variables and selection process are complex and hard to understand precisely in the earlier phases. Theregore, the focus of this study is tackling epistemic uncertainties and their associated ambiguities.

To deal with epistemic uncertainties, the use of fuzzy logic is required and recommended. Fuzzy logic differs from crisp logic mainly in the sense that it breaks one of the main hypothesis of the latter: fuzzy logic enables an element of a universe to belong partially to a set. Mathematically, this means that fuzzy logic usually breaks the Law of Excluded Middle of crisp logic, which defines that a set and its complement must comprise the universe of discourse, and the Law of Contradiction, which defines that an element must be in its set or its complement, as it cannot simultaneously be in both (MENDEL, 2017). Although this is a critical difference between crisp and fuzzy logic, the most important difference between a crisp and a fuzzy approach is the knowledge base, which is required in a fuzzy system. The knowledge base allows the decision maker to build a model using rules, which are ordinary statements involving key terms pertaining to the subject. Building a knowledge base is much more intuitive to a human compared to proposing a probabilistic model, which is common in crisp approaches, besides being easier to understand and trace back the decisions made by the model. These positive qualities of fuzzy systems are well tuned with the main issues of the selection of offshore production systems, making it an interesting approach to use.

However, the fuzzy logic theory should not be seen as completely opposed to crisp logic theory. Although books about fuzzy logic usually try to highlight an reinforce the difference between these theories (ROSS, 2010; MENDEL, 2017), possibly to highlight to the readers about the relevance of studying fuzzy logic theory, they have much in common. One example is the probabilistic theory, which is based on crisp logic and serves as a guideline to develop the possibilistic theory, which employs concepts based on fuzzy logic. The possibilistic theory is comparable to a large extent to probability theory because it is based on set-functions, however it differs due to the use of a pair of dual set functions instead of only one (DUBOIS; PRADE, 2015). Zimmermann (1985) sums up by stating that the comparison between the two theories is difficult primarily because such comparison could be made on many different levels, i.e. mathematically, linguistically, semantically, and so on. Besides, fuzzy logic is no longer uniquely defined mathematically, currently being a general family of theories, pretty much as probability theory.

1.1.2. Development strategy

As the industry pushes into deepwater, frontier areas emerge with high uncertainties. According to Dekker and Reid (2014), a frontier may be reservoir geology, high reservoir pressures and temperatures, or challenging reservoir fluid properties or impurities. It may also be a specific location, remoteness from an existing structure, water depth, extreme met-ocean conditions or limited operator experience in the region. Additionally, advancing frontier areas inevitably involve uncertainties related to reservoir properties, flow rates, recovery factor, project execution and reservoir management, so higher recovery factors are needed when compared with projects in known basins. Usually, these frontier aspects appear combined in a certain proportion in a project. Ignoring uncertainties in such scenarios can result in false-starts and redevelopment. Dekker and Reid (2014) also highlight that in the past 15 years the development of frontier areas was carried out especially during high oil prices. Therefore, as the development investments increase and a new wave of high oil barrel prices is uncertain, they recommend caution, discipline and risk management in order to develop new frontiers successfully.

The business-as-usual approach is to select a concept based on a number of scenarios that are created and investigated using predefined methods (HOLSEN; KING; STEINE, 1993; SATTER; VARNON; HOANG, 1994; MOROOKA; GALEANO, 1999; ASRILHANT, 2005; SAPUTELLI et al., 2008). In sum, these approaches follow a technically oriented process, where a chain of specialized disciplines provides requirements and restraints to the following discipline. They may vary on sequence, accuracy of each phase, scope, organizational culture and supply chain. As there are uncertainties in inputs, several concepts must be proposed (CULLICK; CUDE; TARMAN, 2007; XIA; D'SOUZA, 2012; WU et al., 2016; BASILIO et al., 2018). This is time-consuming (SMYTH et al., 2010), especially on a large field, requiring a high degree of interaction between subsurface, drilling and completions and surface teams, besides several levels of screening, and it may result in increased cycle time (WU et al., 2016). Besides, such approaches only consider a few scenarios, so it may lead to sub-optimal selections and thus to a higher risk of over- or under-design, as noted by Cullick, Cude and Tarman (2007). According to Dekker and Reid (2014), the development team acquires experience from several partners and experts before building a strategy. Nonetheless, the solution is good as the weakest link. Cullick, Cude and Tarman (2007) and Smyth *et. al.* (2010) agree that even though this approach is successful in obtaining optimum solutions, it can be improved. A computer-assisted approach can provide a standard method to obtain solutions quicker than manual methods and even consider the full range of scenarios, this way potentially including lower maturity or unusual concepts with higher net present value (NPV) reward. In addition, it may enable the decision-maker to trace the reasons for selecting such concept, thus giving better insights into the problem. As mentioned by Basilio *et al.* (2018), an automated and integrated computational model accelerates the design process, sparing time to improve selected concepts and to minimize uncertainties along the decision process, therefore enhancing concept design.

Wu *et al.* (2016) noted that some types of uncertainties can be modelled quantitatively or qualitatively. For example, an early concept with uncertain inputs can be qualitatively selected by comparing how flexible it is against others, or it may be quantitatively selected by performing probabilistic analysis, where uncertain inputs are assessed for their feasible outcomes, and then all concepts are weighted by its probabilities. A fuzzy method performs similarly, however it weights concepts by their membership value. Wu *et al.* (2016) emphasise that such quantitative analysis is not a foolproof decision, but an informed one.

The development strategy varies among independent, integrated and national operators. Dekker and Reid (2014) stated that independent oil companies operate around 15% of global deepwater production, while integrated and national oil companies have 50% and 35%, respectively. Independent operators usually focus on smaller projects (between 50 - 150 mmboe recoverable) and deal with uncertainties by having small experienced groups and by joining forces with other companies to spread the costs and risks. Integrated and national oil companies focus on large reservoirs (over 150 mmboe) as they have the capital required. National oil companies take a long-term view and invest in emerging technologies for basin development rather than viewing it as an individual block development.

1.1.3. Uncertainties during selection of offshore production systems

In the literature, several variables are regarded as having some level of uncertainty. The most common are related to the subsurface. As mentioned by D'Souza and Basu (2011) and Xia and D'Souza (2012), geometry, connectivity, size, rock and fluid properties have intrinsic uncertainties, and they are essential to determine well count and arrangement, drilling and completions, flow rates, production profiles and ultimate recovery, which are key parameters to field development. Predicting long-term reservoir performance and recovery is very important because it is the starting point in determining the development strategy, besides being tightly linked to the revenue success of the field. The scarcity of data in the beginning makes it hard to access the reservoir true potential, which builds up the risk of uneconomic outcomes. Besides, Dekker and Reid (2014) highlight that even on regions with the geologic setting well understood the target reservoirs may not have producing analogues nearby in order to base estimates. This is why a large number of studies in field development uncertainty focuses on mitigating subsurface uncertainties. Smyth *et al.* (2010) noted that not only reservoir uncertainties must be managed, but also these uncertainties must be properly communicated to surface teams. Failure in doing so may result in expensive retrofitting. When subsurface uncertainties are high, even after a solid appraisal plan, the decision-makers favour projects with a low well count and spread out wet-trees in the beginning, thus lowering capital expenditures (CAPEX) and cycle time, but increasing operational expenditures (OPEX) in the long term due to the cost of interventions (RONALDS, 2005a).

Surface-related uncertainties also play a key role. Greater depths bring high pressure and temperatures that may exceed drilling, completion and production system limits. Drilling and completing wells in deepwater can represent over half of development costs. In some occasions, well completions can equal or exceed drilling costs (D'SOUZA; BASU, 2011). Flow assurance problems later on are expensive to install and remediate. Besides, drilling and completion are critical for well performance and reservoir recovery, thus why well count and wet- or dry-trees selection is so important. Reid, Dekker and Nunez (2013) mention that increasing reservoir uncertainty favours wet-trees due to their flexibility, not only in well count terms but also in well completion terms. Furthermore, Mobile Offshore Drilling Units (MODUs) and specialist intervention vessels for deepwater are highly demanded. Their schedules may be even more constrained in smaller and remote fields (RONALDS, 2002a) and their operation may be delayed due to harsh met-ocean conditions, so uncertainty in their availability must be considered in concept selection (XIA; D'SOUZA, 2012).

Surface and subsurface issues influence each other, thus obfuscating the analysis of uncertainties. The main relationship between surface and subsurface is expressed through the inflow performance relationship (IPR) and the vertical lift performance relationship (VLP). The IPR curve is given by any deliverability equation and relates the well production rates and the driving force in the reservoir (i.e. the pressure difference between the average or outer boundary and the flowing bottomhole pressure). In order to estimate oil production, the reservoir deliverability must be combined with the well's VLP, which is a function of the hydrostatic pressure difference, kinetic energy pressure drop and friction pressure drop along the wellbore. Figure 2 illustrates a VLP and an IPR curve. At the intersection of both curves, that is, when a flowing bottom hole pressure satisfies both equations, the well will produce at a rate q. Thus, the oil production will depend both on the reservoir and wellbore hydraulics concurrently, as well as their uncertainties.

The installation and operation of a production system equipment must be carefully scheduled, as they may suffer delay due to harsh met-ocean conditions. Dekker and Reid (2014) mention that conditions such as hurricanes and high currents and seabed topography (steep slopes) are specific to the prospect physical location, so new technologies of installation and operation of production system equipment must have an adequate level of maturation before implementation to reduce uncertainties, particularly in such scenarios. Remoteness (that is, the distance to available infrastructure) is also a key aspect, as transporting personnel, equipment, and oil and gas over long distances are more prone to failure. An emergency response to such events also gets harder.

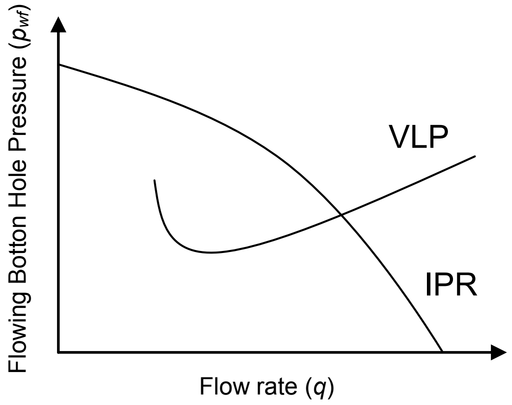


Figure 2. Combination of VLP and IPR.

Estimating costs during the concept selection phase is complex due to uncertainties involved, having an inaccuracy of around 30% (BEHRENBRUCH, 1993; BASILIO et al., 2018), so a careful planning must be conducted. To this, expert teams provided with updated databases and estimating tools are required according to Xia and D'Souza (2012). Besides, rigorous benchmarking among concept costs is needed to guarantee comparable results between competing scenarios. The main uncertainties in cost derive from subsurface. For example, production flow rate, well count, and gas-oil ratio (GOR) affect the selection and scaling of drilling campaign, completions, facilities, and export pipelines construction, which compose the main expenditures. Scheduling also plays a key role, as it deeply impacts execution costs. Delays in drilling operations that employ MODUs or operations that use highly specialized completion/workover vessels are expensive. In addition, D'Souza and Basu (2011) note that employing some specific equipment increases execution risk and therefore unexpected expenses. For example, a spar has a high execution risk as it needs more marine operations to install and commission it than an semisubmersible (SS) or a tension leg platform (TLP). If successfully employed, the use of new technology also plays a key role in managing costs.

Uncertainties on a higher level embrace political and legal framework. Oil and gas concession terms have a varied duration, which impacts directly in development strategy as described by Dekker and Reid (2014). In summary, as time pressure and complexity increases, flexible turnkey concepts are more suitable. As mentioned in Ronalds (2005b), this is due to tailored concepts requiring greater knowledge ahead of production, while turnkey concepts give a faster outcome and a high level of flexibility, at the expense of not properly fitting the exact needs of the field. Aggressive schedules are likely to under-deliver (NANDURDIKAR; KIRKHAM, 2012), so a careful planning must be conducted early. Usually, regulators expect expeditious development even when there is a long duration license in place, however they may extend the contract if extra-time is justifiable and feasible. Xia and D'Souza (2012) noted that obtaining permits for surface facility components are generally slower where precedence does not exist, which might sacrifice financial value. This is one of the reasons why floating production storage and offloading units (FPSOs) are rare in the GoM. Likewise, the lease of smaller block sizes may disrupt development strategy as a field unitization can affect facilities projects and their economics (D'SOUZA; BASU, 2011). Moreover, large blocks favour phased development with multiple host systems in order to decrease uncertainties first.

The local content is another key factor imposed by regulators. It may be beneficial to all stakeholders in the long term, however in the short term it might be uncertain if local resources will be available. An example would be the Jones Act in the United States, which limits the availability of shuttle tank exporters in the GoM (XIA; D'SOUZA, 2012). As FPSOs are in synergy with such export process, it is another reason why they are not commonly employed in the GoM.

A strategy to mitigate uncertainties is to employ an EPS. They are relatively easy and quick to deploy and decommission and support a flexible operation, this manner providing positive cash flow and reducing field uncertainties earlier (RONALDS, 2005a). This strategy is also known as CAPEX deferral (XIA; D'SOUZA, 2012) and it is very important to fields without production analogues, both small and large. An EPS can also mitigate risks in regions with uncertain political and legal framework (DEKKER; REID, 2014). Common EPS include Floating Storage and Offloading units (FPSOs) and semisubmersibles as they are easily decommissioned and relocated to other fields at a lower cost. However, this is a capital-intensive approach from the beginning that increases the time required to fully develop the field.

1.1.4. Proposed methods

An updated and extensive survey regarding integrated models applied to offshore field developments is found in Basilio *et al.* (2018). Therefore, this review will focus on models that consider uncertainty in offshore field developments. The seminal paper of Devine and

Lesso (1972), although it used deterministic methods for developing offshore fields at minimum cost, highlights that due to the real world complexity and the stochastic nature of drilling costs, economic and environmental conditions, among others, an optimal solution does not imply that the decision-maker has a perfect concept ready to implement. The authors also note that the model results are an aid and not a replacement for the decision-maker's intuition, and the purpose of such model is to enhance understanding of how field development depends upon many parameters. This observation is also fundamental in today's models.

Grimett and Startzman (1987) observed that it is hard to estimate factors linked to revenues such as oil price due to uncertainty, even though many models try to maximize NPV or other economic parameter. Estimating operational costs and taxes in the long-term plan may be equally difficult. Therefore, in their work they focused on minimizing field development investments because it is an aspect generally known with greater certainty.

Behrenbruch (1993) presented general guidelines to assess the feasibility of offshore petroleum projects. He showed graphically that uncertainties in estimates usually decrease over time, and he observed that sensitivity analyses are a useful tool to evaluate downside scenarios, as they reveal how vulnerable the concept is to variations. For example, a marginal project may prove to be very sensitive to reservoir size, so actions such as suitably positioning an appraisal well could be recommended. Besides, given the large amount of capital invested, he recommended to carry probabilistic estimates for any offshore development. Furthermore, if additional data are required, Cockcroft *et al.* (1994) and Hayashi, Ligero and Schiozer (2007) recommended to rank priorities in obtaining data based on the value of the information.

Dorgant et al. (2001) defined adaptability as the ability of tools and equipment to deal with uncertain conditions and robustness as the ability to deal with resource uncertainties, and considered them as key performance indicators for Brutus, Bonga and Nakika fields. Furthermore, Castro, Morooka and Bordalo (2002) employed utility functions and multi-attribute techniques to weight financial, technological, environment and safety attributes, among others, to select a host system considering adaptability and robustness indicators. Dezen and Morooka (2002) proposed a real option valuation model to capture the value of flexibility, this way mitigating uncertainties by selecting a flexible field development plan.

Franco (2003) proposed a fuzzy model to select offshore production systems using technical expert knowledge. With few crisp input data (reservoir area and depth, well count and type, oil production per well, water depth, environmental conditions, shore distance and pipeline availability), the fuzzy model selects a feasible set of production equipment (well arrangement, production manifold use, host system, mooring and riser system and storage and offloading), obtaining a single production system concept.

Fonseca et al. (2005) and Gonzalez-Castaño (2017) coupled the fuzzy model seen in Franco (2003) with the multi-attribute technique seen in Castro, Morooka and Bordalo (2002). The former focused on using utility functions to represent the inclination of the decision-maker to each option. The latter focused on adding a logistic attribute, which considers production performance, transportation and storage of hydrocarbons, personnel and supply mobility and their respective housing and storage. The fuzzy model is employed to compute the subjectivity and imprecision involved in selecting a concept.

Cullick, Cude and Tarman (2007) used a meta-heuristic optimization model combined with nonlinear optimization that maximizes NPV relative to its standard deviation for offshore production system concepts. The integrated framework includes uncertainty assessments for production and economics, a reservoir and network simulator, an expert system and a cost estimator. Furthermore, Smyth *et al.* (2010) introduced a procedure that evaluates and ranks hundreds of concepts. Optimization techniques that include uncertainty analysis of subsurface and economic unknowns are coupled with reservoir and surface network simulators. Following the trend of integrated design approaches, Basilio *et al.* (2018) proposed one that automatically generates and rank conceptual alternatives of field development based on key parameters such as CAPEX, OPEX, NPV, internal rate of return and payback. To this, a meta-heuristic model based on an extensive database generates many concepts, then reservoir and flow simulations are conducted for each concept. Finally, an economic assessment is conducted for each concept along with an evaluation of key parameters.

Akeze, Sikandar, and LaForce (2009) addressed uncertainties by evaluating initial field development schemes. Further uncertainty analyses were conducted for concepts in which an optimum oil and gas recovery were obtained. Finally, the host system of the selected concept was used to determine the remaining field production development design. D’Souza and Basu (2011) discussed strategies to mitigate reservoir and well performance uncertainty especially in deeper, subsalt reservoirs with scarce production analogues. Besides, Xia and

D’Souza (2012) stated that the techniques to mitigate uncertainties in increasing order of effectiveness (and cost) are drill stem tests, appraisal wells, extended well tests and phased and staged development.

Mentes and Helvacioglu (2013) proposed a coupled fuzzy Analytic Hierarchy Process (fuzzy AHP) with a fuzzy Technique for Order Preference by Similarity to an Ideal Solution (fuzzy TOPSIS) to select a host system for the Black Sea Region. This manner, the model address uncertainties in the linguistic variables present. An alternative to managing uncertainties is proposed by Wu *et al.* (2016). They combine Even Swaps Analysis (ESA), which improves concepts instead of eliminating them, with AHP, which shortlists options and improves the quantitative and qualitative aspects of the decision-making process. This way, a decision-maker is able to conduct a rigorous and objective concept selection.

In conclusion, the high number of uncertainties in a new prospect, particularly in deepwater frontier regions, hinders field development and production system’s concept selection. In addition, field appraisal is financially restricted in deepwater. To overcome these issues, a well-defined strategy must be carried out early in the development process, reducing aleatoric and epistemic uncertainties in key aspects such as subsurface, drilling and completions and surface facilities, while considering stakeholders demands to avoid unnecessary redevelopment. Finally, carefully estimating costs and scheduling concept execution is critical to avoid slippages and cost overruns. After all, ignoring uncertainties can result in false-starts and redevelopment. To achieve these objectives, both industry and academy are working on integrating the selection process and reducing uncertainties of these key aspects using different computer-based approaches and methods to obtain fully optimized solutions in a timely fashion. Therefore, in this study it is considered uncertainties and related ambiguities in an integrated way, obtaining solutions similar to the real scenario for 85% of the fields studied here, compared only to 59% in Franco (2003) study.

2. METHODOLOGY

First, a review of important key concepts in an offshore production system will be presented. Later, it is presented the proposed mathematical method.

2.1. Key aspects in the selection of offshore production systems

The current mindset for concept selection is very oriented to defining key aspects and matching them logically, as they are considered critical to a successful development. These key aspects are sometimes mentioned with different names or classifications, so they will be presented here in a general way. Approaches to select an offshore field concept must consider subsurface and surface aspects in an integrated way. Therefore, how these parameters are determined will be briefly discussed here for completeness. As the objective in this study is only to show the mathematical model, a simple model for offshore production system selection will be illustrated further below, so only some of the key aspects will be considered. However, adding more key parameters to solve real problems is possible and recommended.

Geologists and reservoir engineers develop geological and reservoir models based on seismic and well log data. The subsurface models are largely driven by the recovery scheme adopted, which is selected based on iterative economic analyses of recovered volumes. Recovering schemes may be depletion (considering reservoir production mechanisms), water and gas injection, and artificial lift. Besides, aspects such as permeability and porosity determine well count, well completions and well performance, so they must be analyzed properly to assure a profitable production.

In overall, these aspects determine oil, gas and water production curves, which can be obtained more precisely by reservoir simulation. A larger deck area is required to process high production and injection rates of water and gas, so the production curves affect the host system selection. Also, reservoir fluid properties have an impact on deck area requirements, as some may require additional processing. It may also be necessary to include secondary recovery, such as gas lift or subsea boosting to keep flow rates from decreasing sharply. This requirement has significant implications for well planning and platform topsides. However, in the applied model shown here these effects are considered negligible and only the maximum oil production output is taken into account, as it is decisive to the maximum capacity of many production system equipment.

The well count required is dependent on the reservoir characteristics such as geometry, size, connectivity, and rock and fluid properties. Well count is decreasing over time as technological innovations such as extended reach wells (ERWs), expandable tubular and multi-laterals are developed. Due to the high-pressure reservoirs found in ultra-deepwater, well production rates are greater and thus require fewer wells. Highly faulted reservoirs with large areal extent usually require more wells to achieve the same recovery rate as one with good connectivity. After an analysis of these issues is conducted, an approximate well count required is known, serving as an input to the model proposed here.

An important decision is whether the wells should be clustered or dispersed around the field. Clustering the wells is beneficial when frequent intervention is planned, and ERWs have greatly increased clustered well applications. On the other hand, the wells may be placed around the field in a distributed manner. This arrangement maximizes drainage from a minimum well count and favours the use of discovery and appraisal wells as producers or injection wells (RONALDS, 2002a). Another advantage of this architecture is that further information is gained about the reservoir, being readily able to be employed to optimise field development. As distributed wells usually require MODUs for drilling and workover, drilling fewer wells is recommended to reduce capital and operational costs. Ronalds (2005a) concluded that a shorter service life or a dispersed well arrangement favours an FPSO or a semi-submersible. In this study, it is considered (in a fuzzy way) that the well arrangement may be clustered or satellite.

Too few or too many wells will negatively impact field development. When a high well count is required, providing a drill rig on the platform can increase recovery and reduce well downtime and drilling, completion and intervention costs compared to a MODU, while it increases facility cost, schedule and execution complexity, and reduces well arrangement flexibility. However, it is important to note that FPSOs do not support drilling effectively yet, and only a fraction of semisubmersibles and spars have drilling capability (RONALDS, 2002a, 2005a). Considering only floaters without drilling capacity, the GOR influences the selection between FPSOs and semisubmersibles. As the FPSO has a higher response to environmental loads, its gas-liquid separation and export are restricted compared to a semisubmersible. Therefore, semisubmersibles are commonly employed in oilfields with high GOR while FPSOs are used in oil-dominated fields (RONALDS, 2005a). In general, a higher well count or intervention intensity favours dry-trees while the opposite favours wet-tree solutions, and a small number of complex wells favours a wet-tree system while a high number of less complex well favours a dry-tree system (REID; DEKKER; NUNEZ, 2013). Intermediate situations require a careful analysis. In the model presented here, it is considered the well count as a key parameter.

Another key aspect is the export strategy. The difficulty of installing and operating economically-feasible pipelines increases as the deeper the water column is. Also, geotechnical conditions in the region may deter the use of pipelines. Only the Gulf of Mexico (GoM) and several areas of the North Sea have an extensive pipeline network, while in other regions, shuttle tankers must be employed due to the lack of pipelines. Unless the production is intermittent or there are multiple offloading points, platforms that employ shuttle tankers as an export strategy require some form of in-field storage.

Host systems with large buffer storage such as the FPSO usually provide the best commercial value when oil transport by shuttle tankers is required. Nonetheless, it is possible (at a cost) to employ a floating storage and offloading unit (FSO) in conjunction with a spar, TLP or SS, which do not provide significant storage capability, to provide buffer storage to these hosts. This is a reason why FPSOs dominate over new provinces or in undeveloped pipeline network regions. Besides, tanker export also gives market flexibility. However, developing neighbouring fields can make pipeline export more attractive. Two separated fields may not have the budget to individually invest in a pipeline, but it may be the best option for them if used collaboratively (SMYTH et al., 2010). Gas export is commonly done by pipeline, so in this study it is considered only three alternatives for the oil export strategy: pipeline, FSO with shuttle tanker, and internal storage with shuttle tanker.

The mooring system is a critical key aspect in certain conditions. For example, the TLP is restricted to moderate depths due to its mooring: the tension forces rapidly increase in deep waters, requiring larger hulls to increase buoyancy. Although the TLP’s tendon mooring weight is close to the steel catenary mooring employed in other host systems, in harsher regions such as in the North Sea, the TLP’s tendon mooring requires high-quality manufacturing (as the fatigue loads are severe), advanced ballast control plans and rigorous inspection. The foundation piles also need to resist larger loads which may prove to be unfeasible or expensive in some geotechnical characteristics.

The catenary mooring is relatively insensitive to water depth, thus it is widely used in FPSOs and semisubmersibles in ultra-deepwater. As it hangs off the deck edges of the floater or pontoon and it does not require tensioners, thus enabling a high well count in these platforms. However, catenaries occupy a large area. In the GoM, the catenary footprint may even encroach on neighbouring leases (D'SOUZA; BASU, 2011).

The taut catenary mooring of spars and semisubmersibles is also relatively insensitive to water depth, however the air cans employed in spar's risers are, forcing them to have fewer risers in ultra-deepwater regions. The taut catenary mooring limits horizontal excursions and thus riser draw-down, so they are regarded as an excellent option for ultra-deepwater mooring (RONALDS, 2002a). Besides, by reducing the mooring footprint and weight, it enables a higher rigid riser count and possibly dry-trees in semisubmersibles in ultra-deepwater.

The spread-moored can be employed in FPSOs and semisubmersibles and it is the mooring system most suited to major fields, as it is able to support both large topsides and riser count. In FPSOs, it is only employed in mild or highly directional met-ocean regions. An FPSO may also be moored by a single point mooring (SPM) about which the hull weathervanes. The turret is the most common SPM and it must be installed on the hull internally or externally, so it increases cycle time (RONALDS, 2005b). Some floaters in harsh environments employ thrusters to assist station-keeping and to intervene close wells, and some FPSOs that have such system are able to disconnect from their turret in adverse weather, therefore requiring a lighter mooring system. However, dynamic positioning in host systems increases OPEX and the risk of malfunctioning. In the model presented here, it is considered only the main mooring systems specific to each host system.

There is a wide array of met-ocean conditions, ranging from hurricanes in the GoM, harsh storms in the North Sea, to the moderate Brazilian conditions and the calm environment off West Africa. Here, they are simply categorized as mild, moderate and severe. Floaters are not recommended in harsh environments and very shallow water because there is insufficient riser compliance. Jackets have fatigue challenges in deeper waters and high well count, so concrete gravity based structures (GBSs) are preferred in harsh environments, besides having the benefit of oil storage, inshore integration, and larger topside weight capacity. FPSO's ship-shaped hull generates considerable motions and by aligning the long axis with the environmental action (weathervaning), these motions are reduced. Nonetheless, weathervaning has a limited effect for harsher met-ocean conditions, and production downtime may happen. The semisubmersible and spar have improved motion characteristics, being far from significant wave energy natural periods due to their geometry. Deep draft semi-submersibles offer an advantage in harsh environments compared to traditional semi-submersibles. The TLP hull is sometimes based on the semisubmersible shape, however its motions are even more restrained by the mooring tendons. Compliant towers offer transparency and stiffness through the water column, thus having reduced deflections. Met-ocean conditions also impact drilling and installation operations when strong persistent currents are present and may also delay schedule and operations such as resupply and offloading.

Even though the industry is international, an important key aspect is the geographical location. Due to relatively calm met-ocean conditions found in Brazilian coast, FPSOs and semisubmersibles are heavily utilised offshore Brazil, and most of them are conversions. The phased field development starting with an EPS is also common in this region. Besides, there is a higher availability of VLCCs for conversion because double hull host systems are not required in the region, and semisubmersible rigs can be redesigned from their traditional drilling role. Also, there is a current trend of replacing and choosing more FPSOs than semisubmersibles nowadays due to the dramatic improvements in FPSO mooring and thus better performance in ultra-deepwater (RONALDS, 2002a). On the other hand, new-built are much more prevalent than conversions in the North Sea, where greenwater on deck and fatigue favour a purpose-designed hull (RONALDS, 2002a). The harsh environment in the region also favours the transition of dry-tree to wet-tree systems at much lower water depths, as the fatigue is harder to control.

Natural, political, industrial and experiential issues vary widely around the world. For example, political issues affect the disposal of associated gas, the minimum local content, and the use of FPSOs in a different manner in different regions. Previous company experience in the region may favour specific decisions regarding oilfield development, therefore building up specialized regional infrastructure (in both expertise and equipment) for all development phases. Company’s experience with particular equipment and techniques, their strategic desire to pursue specific technologies, as well as market pressures contribute to the selection process. For example, there is a strong bias to employ wet-tree systems in Brazil while in GoM it is more commonly employed dry-tree systems (RONALDS, 2002a). Besides, contracting and mobilizing MODUs or intervention vessels may be difficult, time-consuming and expensive in some regions. Companies with sufficient presence in the region usually benefit from easier access to equipment and vessels for all phases of field development. Therefore, operators may have more flexibility in selecting a specific production system on regions they traditionally operate. Political issues such as local content enforcement affect development and local supply. For example, as in GoM the use of FPSOs is restricted by the Jones Act, jackets dominate, making platform construction cheap, with a variety of standardized equipment available to choose (RONALDS, 2005a). This is why jackets in GoM outweigh floaters in moderate water depths. Regarding natural issues, they include harsh met-ocean conditions (e.g. high currents and hurricanes), seabed topography (e.g. canyons, furrows, and steep slopes) and shallow hazards (e.g. slumps, shallow water, gas flows, and vents).

In remote and underdeveloped regions, the selection of offshore production concepts that minimize marine operations is favoured (XIA; D'SOUZA, 2012). Heavy lifting of components is discouraged due to the risk and the high costs involved in mobilizing such vessels in unusual locations. For example, even though spars are recommended in deeper waters, TLPs have construction and installation advantages over them, as they have a lighter hull and their topside can be integrated inshore. The GBS has installation advantages in remote regions compared to jackets, as they do not require an extensive mobilization of heavy-lift vessels.

Remoteness also drives concept selection towards robust equipment and rigorous integrity management, as the lack of supporting infrastructure translates into an increased time to repairments. In remote regions the high reliability required along with the risks involved in personnel evacuation and the mitigation of oil spills drive the platform design to survive 10,000-year return cyclonic storms. The complexity of exporting hydrocarbons over long distances using pipelines or shuttle tankers also adds risk to the project.

Another important issue is access to qualified people willing to work in remote regions. The simultaneous growth of the deepwater industry, onshore unconventionals and a lack of young professionals cause significant risk related to adequately staffing projects (DEKKER; REID, 2014). The access to experienced contractors may prove to be difficult too. When these resources are short, concept selection favours standard and conventional projects.

Riser selection is another relevant key parameter. Risers are used to transport products, gas, chemicals and power, and are categorized as rigid, flexible, hybrid (tower and buoy supported), and steel catenary riser (SCR). Their selection is based mainly on product service, host system, economics, water depth, installation vessels, and insulation requirements (MADDAHI; MORTAZAVI, 2011). Currently, there is increased focus on SCRs and hybrid risers due to the increasing water depths, so they will receive a more detailed analysis here.

Rigid risers are essentially vertical steel tubes connecting the well to the topside, so they lack material and geometric compliance, being unable to withstand relevant vertical displacements. Therefore, in compliant towers and jackets, the rigid riser is attached in their substructure through the lateral guides. In floaters, they are tensioned to support environmental loads and their weight.

Through a combination of geometric compliance (a curved shape underwater) and material compliance (layers of helically wound wires and thermoplastic sheaths), flexible risers show excellent bending flexibility and superior insulation properties compared to steel pipes, despite being expensive and inefficient in resisting high hydrostatic pressures. Specific fluid properties may challenge the use of flexible risers, such as high temperatures, high pressures and sour service. They may be matched with all host systems, but they are especially useful for platforms with considerable motions.

In ultra-deepwater, rigid risers may be employed in catenary configuration as there is an increased tolerance to hull motions due to the riser's longer length through the water column. As flexible risers have restrained diameters in such depths, there is the benefit of lower material cost and larger diameters, besides dismissing top-tensioners. This special type of rigid riser is called steel catenary riser and it is commonly employed in import and export functions due to these benefits. SCRs lack the material compliance, so they are less suitable to several combinations of environmental conditions, host systems and water depth, and may have fatigue issues on its touch down point (TDP), near the bottom or near the topside connection. In shallower depths, they are restricted to mild met-ocean conditions and host systems with low deflections. Semisubmersibles may employ SCRs in harsher environments and shallower waters than FPSOs. A general configuration of BSRs along with its components is illustrated in Figure 3.

Riser towers and buoy supporting risers (BSRs) are designed to provide compliance only near the host system, where it is critical. They are composed of a rigid riser held by buoyancy, spanned from sea bottom up to near sea surface, with one or more compliant catenaries linking it to the platform (flexible risers can have larger diameters in shallower regions, so they do not bottleneck the flow). This manner, they reduce riser loads on the topside, as the buoy supports the weight of the rigid riser, and avoids fatigue in it. Therefore, their use is recommended for host systems with high motion response and harsh met-ocean conditions. However, they are harder to install and less reliable compared to SCRs.

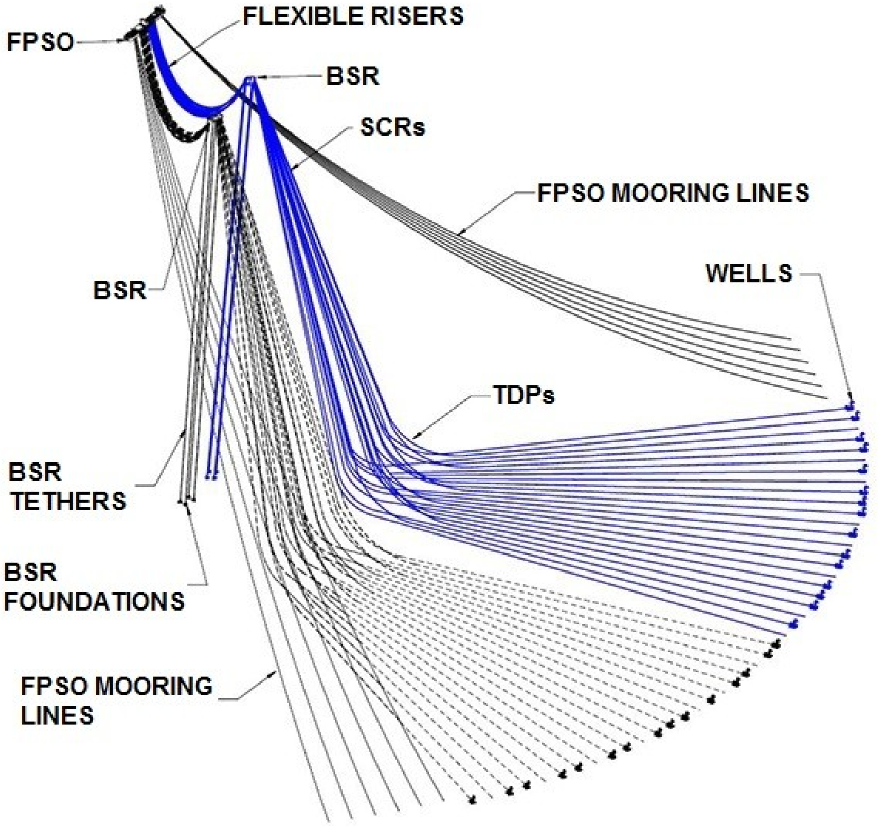


Figure 3. Buoy supported riser system. Source: adapted from 2H Offshore (2016).

Flexibles, SCRs, and riser towers are usually combined with subsea trees, both distributed and clustered, while rigid risers are commonly associated with surface trees (RONALDS, 2002a). Although the first combination is more expensive than the second one in shallow to deep waters, the ultra-deepwater alters these relationships, as the motion-compensating devices increase in cost, size and complexity, and towers and SCRs gets more suitable. Compliant towers, spars and TLPs are commonly combined with surface trees and rigid risers, as the motions in all sea-states can be accommodated. Reducing the motion response of semisubmersibles and FPSOs would be valuable as it would assist in overcoming SCR’s limitations. Almost all host systems can be feasibly matched with all riser and well types; however there are clear preferences in most scenarios. For example, semisubmersibles and FPSOs are regularly matched with subsea trees and flexibles, towers or SCRs, which are compliant. An exception occurs at water depths lower than 70 meters, when there is insufficient riser compliance to accommodate motions of floater platforms (RONALDS, 2004). Risers may be installed in S-lay, J-lay and reel-lay configurations, as shown in Figure 4. In this study, it is considered only rigid (which includes supported, top tensioned and SCRs), hybrid (which is a more general term for riser towers and BSRs), and flexible risers, as illustrated in Figure 5.

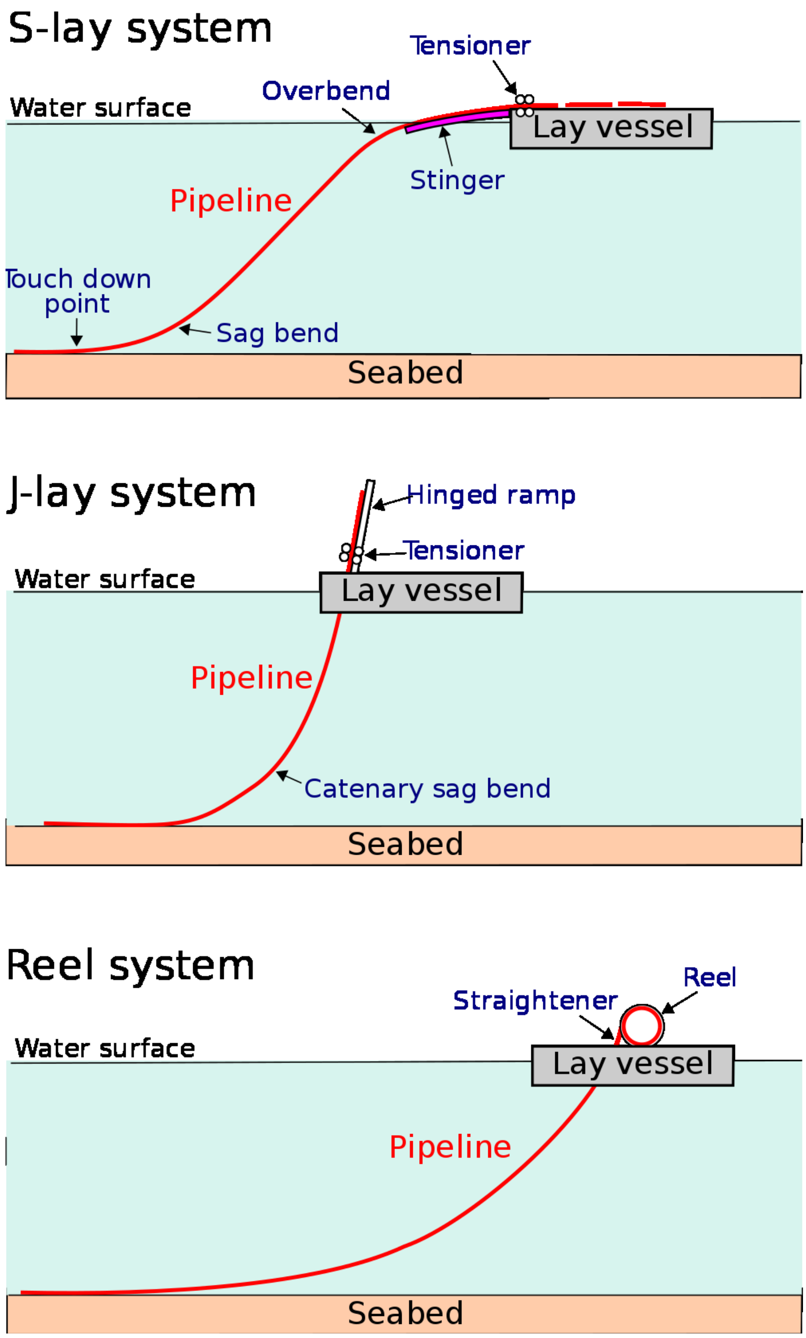


Figure 4. Riser installation systems. Source: Lusilier (2013).

While the well count is heavily dependent on reservoir characteristics, riser count depends on production system architecture. Generally, there is one riser to each surface well, while the ratio of risers to subsea wells is less, equal or greater than one. The ratio may be less than one due to manifolding and riser bundling and greater than one due to the use of twin risers, gas lift risers and flowlines to ease pigging. In increased water depths, riser weight is an important consideration, so the riser count is constrained in floaters due to the large hull buoyancy requirement. Passive riser support systems such as jackups and compliant towers substructures allow a high riser count attached to them, providing a low risk of interference and a close space setting under extreme environmental loading.

Riser accommodation in the host system is important to determine the number of risers employed and the host system. The risers, umbilicals and mooring converge into a single point in turret FPSOs, resulting in congestion. In a spread-moored FPSO, the risers are hung off along the deck edge, allowing twice the riser count compared to a turret FPSO (RONALDS, 2002a). Spars also have a limited well count, as the risers must be supported through the single column. Besides, spars have difficulties dealing with too many risers in deep waters due to the huge-sized air cans required, unless the hull diameter is increased considerably. On the other hand, the semisubmersible supports many risers along the deck edge or pontoon with the benefit of having an efficient load distribution. Although the TLP has a large moonpool which can accommodate a large number of rigid risers, the riser count may be restricted to avoid clashing in deepwater and to limit the required space of the top-tensioning system. The riser count may be reduced by manifolding on the seabed and riser bundling, although increasing seabed, monitoring and well intervention complexity.

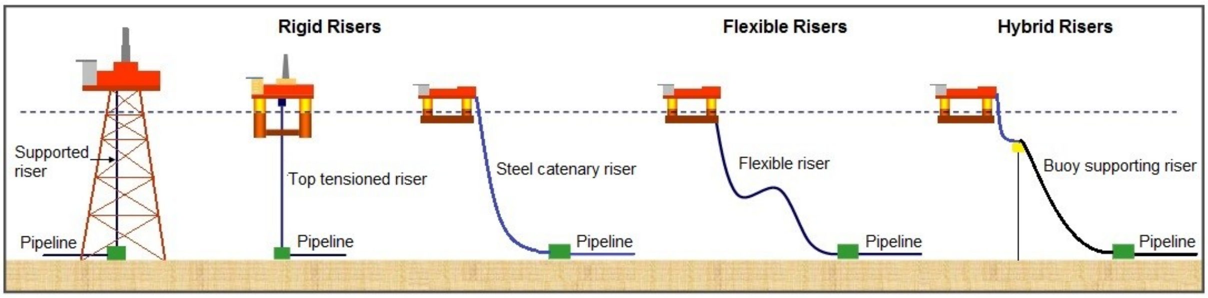


Figure 5. Riser types. Source: adapted from Acona (2014).

The use of manifolds is currently discussed for many subsea arrangement projects. First, the manufacture, installation, commissioning, productive life and demobilization of it must be considered. Besides, as they usually weight a few hundred tons in deep waters, it is required special heavy lift vessels, which have low availability in the global market and expensive daily rates. For example, in the Pre-Salt area of Brazil, Petrobras is being challenged with a high manifold installation demand, high installation costs and lower than expected oil prices (COSTA; LIMA, 2017). This made the company launch initiatives to both reduce manifold use and their installation costs, as it is the case of the Santos Basin Pre-Salt projects. There, the development is based on production satellite wells individually connected to the host system, performing well in this scenario because 1) the wells have a high production rate, 2) there is the possibility of having wells with different productivity index (PI), which would limit themselves if manifolds were used, and 3) it allows a higher flexibility to optimize the wellheads' location (CEZAR et al., 2015). Here, it is considered if production manifolds are employed in the field or not.

An important factor for selection of an offshore production system is the oil production rate. The only host system ideally suited to major fields is the spread-moored FPSO, as it supports large topsides, high oil production rates and riser count. Producing at high rates is possible by extensive modifications of FPSOs, jackups and semisubmersibles conversions, and thus their production capacity may vary widely. The production capacity is directly linked to the deck area. GBSs have greater topsides compared to jackets because the concrete structure gives greater flexural stiffness and fatigue durability (RONALDS, 2004). Ronalds (2002a) observed that there is an inverse trend regarding riser count and topside capacity. FPSOs and spars have limited riser count capacity, but less so in topside capacity. In contrast, TLPs and semisubmersibles support larger riser counts, however enlarging the hull is necessary to process the production of such high number of risers. A lower production rate, greater uncertainties and shorter field life suit subsea solutions. To minimize the chances of under- or overdesign platform capacity, staged developments are recommended.

The host system’s water depth range is limited by economic and operational issues. For example, fixed host systems (jackups, jackets, and GBS) are very sensitive to water depth regarding CAPEX. Tension forces in the tendon mooring of a TLP increase quickly in deeper waters, requiring larger hulls and restricting their use to shallow waters. Spars are less sensitive to water depth due to their taut catenary mooring and their self-supported risers with air cans. Semisubmersibles and FPSOs are also less sensitive to water depths, with the benefit of a semisubmersible having a lighter hull than TLPs and spars. The most common dry-tree host systems (spars, compliant towers and TLPs) can be differentiated by their operating water depth and well count (RONALDS, 2002a). Subsea satellites are feasible over all the current water depth range. Generally, multiple small platforms are favoured in shallow waters compared to extended reach wells from a single platform with a drilling centre (RONALDS, 2005a; MADDAHI; MORTAZAVI, 2011). The water depth also affects production, as in deeper water columns robust artificial lift equipment and flow assurance studies are required. Figure 6 shows several host systems illustrated according to their usual operating water depth. In this study, the water depth is a key parameter, affecting multiple decision components.

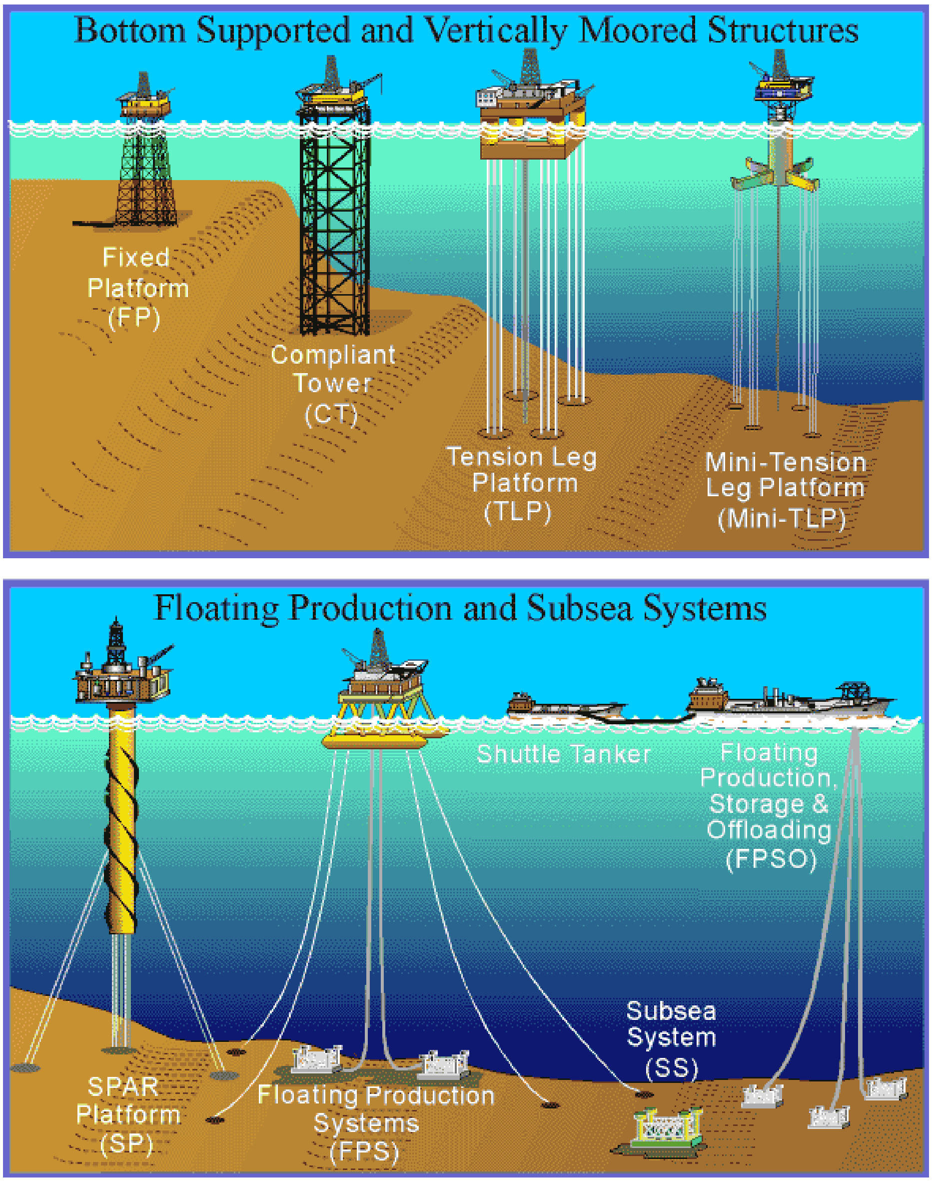


Figure 6. Fixed and floating host systems. Source: BSEE (2008).

According to IHS Markit (2016), US$ 2.4 billion will be required to decommission approximately 600 installations between 2017 and 2020, being half of that spent in the North Sea and most of the other half in the GoM. It is also expected to decommission more than 2,000 offshore production systems between 2021 and 2040, where US$ 13 billion will be required. Much of these expenditures could be reduced if a solid decommissioning plan had been proposed from the beginning of the development plan.

According to Bohi and Toman (1984), the decommissioning phase starts when the field is completely exhausted, physically or economically. When the reservoir is completely depleted from hydrocarbons, complete physical exhaustion is attained. Except for gas fields, few fields can attain complete physical exhaustion. When the hydrocarbons are not completely depleted due to economic issues, incomplete physical exhaustion is attained and the remaining hydrocarbons in the reservoirs are left behind. This is the most common scenario.

One of the most employed methods to determine if the field is economically exhausted is analyzing the production curves of oil, gas, and water (generated by reservoir simulation), and the expected future cash flow. Oil and gas prices and return rates must be estimated, and employing secondary and tertiary recovery techniques should be considered. Then, the uneconomical period can be determined for a given field, that is, the period where the production is unprofitable or too risky, even with advanced recovery techniques. Many studies proposed methods to determine this uneconomical period under different assumptions of production, hydrocarbon price and taxes (RUIVO, 2001). However, the date of decommissioning cannot be predicted exactly due to the uncertainties mentioned in Section 1. In practice, the field operator will determine the start of decommissioning considering economic, strategic and technical factors, which include field geology, remaining reserves, field strategy, other functions of the host system in the region (such as processing and export), subsea tiebacks, oil and gas prices, operation costs and legal requirements. The decommissioning process is a critical part of selecting an offshore production system as it affects the project investments. Therefore, the decommissioning process is considered in this study. However, as the time to decommission depends on precise estimations of oil and gas prices and production rates, it will not be estimated here.

The volume of oil-in-place (VOIP) is important during production system selection. Small VOIPs favour small and rigless host systems which are relatively easy to decommission, such as semisubmersibles, FPSOs or subsea tiebacks. High VOIPs, even though presented as a single and large reservoir or a cluster of small reservoirs, favours large floating hubs, possibly with trunk lines to the pipeline grid. This concept also usually have the flexibility to gather neighbouring subsea tiebacks as production declines from the primary reservoirs. Very large oilfields may be split into regions with different production systems, starting development in the most prolific parts of the field, and adding production systems consecutively as in Lula field (Brazil). A high VOIP usually requires a high well count, so this must be taken into account during platform selection. Large reservoirs extensively dispersed in a large area require multiple and dispersed drill centres for optimum depletion and thus wet-trees are suitable.

In order to install an offshore production system, placing equipment on the seabed and surface piercing structures are required. The installation and operation of this equipment not only disturb the seabed, but generates noise, heat transfer and possibly water discharges. Depending on the specific area where the production system will be installed, the environmental footprint may be a key aspect.

The seabed topography and geotechnical conditions may also prove to be an issue. Difficult or irregular seabed conditions may hinder drill centres directly below the platform, thus favouring wet-trees. Seabed topography may also alter flowline routing or the location of the host system. Difficult or irregular seabed conditions and irregular reservoir areal footprint are the largest de-selection criteria for dry-tree host systems (REID; DEKKER; NUNEZ, 2013) and cause a notable impact on platform design due to the challenges in foundation design. For example, the calcareous soils of the Northwest Australia challenge designing foundations to spread-moored spars and semisubmersibles, and severely restrain the use of TLPs, as their foundations hardly resist the large and static tension loads (XIA; D'SOUZA, 2012). Seismicity is also a challenge to many prolific regions.

2.2. Mathematical method

In order to select the best concept for a given field considering uncertainties involved, a fuzzy system that takes uncertain (i.e. vague, ambiguous, or imprecise) field parameters as input, and returns the most appropriate alternatives to the field as output is proposed. As the input parameters are vague and the model considers ambiguity, multiple concepts can satisfy the given criteria. Therefore, a single solution must be selected somehow. Here, it is proposed a method to arrive at the best concept alternative possible, which is named here as the refine method. The overall view of the proposed methodology is schematically illustrated in Figure 7. An offshore production system solution is composed of M decisions, each one considering N or fewer input values. In each decision, one or more equipment E_i is selected, where i is the equipment index. After the refine method, a single optimal solution is obtained.

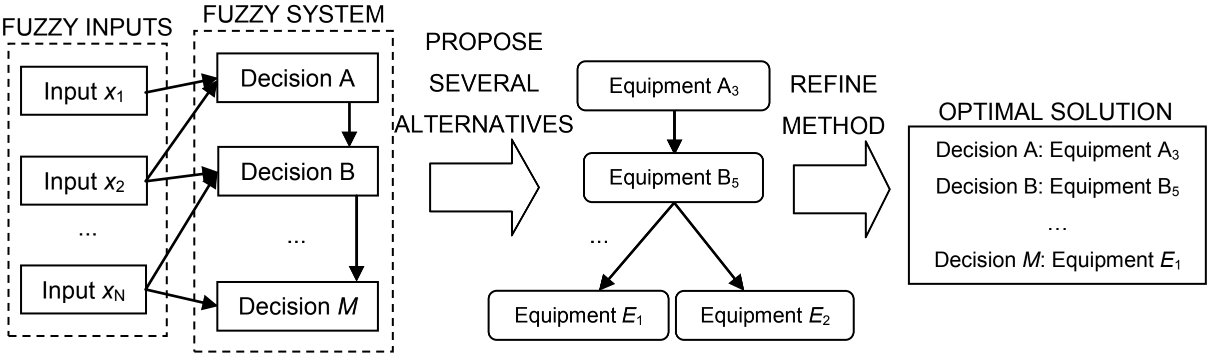


Figure 7. General methodology.

2.3. Fuzzy system

A fuzzy system, as presented in Figure 8, is composed of four main components, as follows: fuzzifier, rules, inference and output processor. It can have crisp values as inputs (e.g. *clustered*, *yes*, *2 m³/s*, *10 wells*) or fuzzy ones (e.g. *approximately 5 wells*, *slightly large reservoir area*). In this study, all output values are linguistic terms (e.g. *FPSO*, *pipeline*, *flexible*) and they can be easily translated into crisp numbers if needed by applying defuzzification methods.

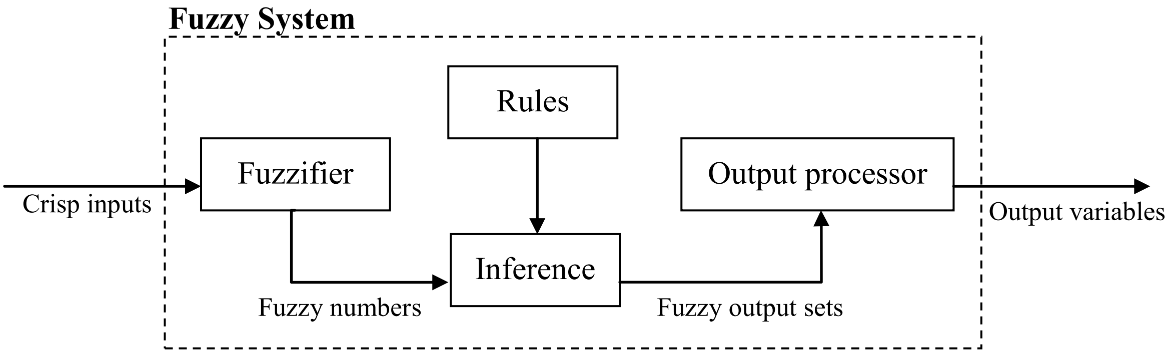


Figure 8. A general fuzzy system.

For crisp sets, an element $x \in X$ is either a member of a set A or not. That is, its membership function can be represented mathematically as $\mu_A(x) = \begin{cases} 1, & x \in A \\ 0, & x \notin A \end{cases}$. Zadeh, on his seminal paper (ZADEH, 1965), extended this notion of binary membership by considering various degrees of membership on the real continuous interval $[0, 1]$. This manner, the element x pertains at some level to the now-called *fuzzy* set $\underset{\sim}{A}$. The analyst must decide how the membership function of $\underset{\sim}{A}$ maps the x elements to the continuous interval $[0, 1]$.

Here, it is considered fuzzy input values instead of crisp ones, which is a novel approach to the literature. Thus, a decision maker can enter ambiguous, vague, and imprecise values in the intelligent system here proposed, such as “the reservoir size is approximately 40 km²”, “maybe there will be an oil pipeline available for use” and “the reservoirs are 2000 and 2500 meters below mudline”. Those uncertainties are modelled using fuzzy sets (also named fuzzy numbers) which can be associated with membership functions of any shape. Here, it is used trapezoidal and triangular membership functions, commonly employed in the literature (ROSS, 2010).

Figure 9 shows examples of membership functions for a given fuzzy number $\underset{\sim}{A}$, being σ_i the spread of the fuzzy number $\underset{\sim}{A}$ around the most likely value a_i. Larger spreads imply in larger uncertainties present. When $\sigma_i \to 0$, then the fuzzy input reduces to a crisp input. The transformation of a crisp numbers a_i into a fuzzy number $\underset{\sim}{A}$ is called fuzzification, which is done by the fuzzifier component of the fuzzy system. Singleton fuzzifiers map crisp inputs to crisp sets (which are equivalent to singleton fuzzy sets), while non-singleton fuzzifiers map crisp inputs to fuzzy sets. In the present work, non-singleton fuzzifiers are used.

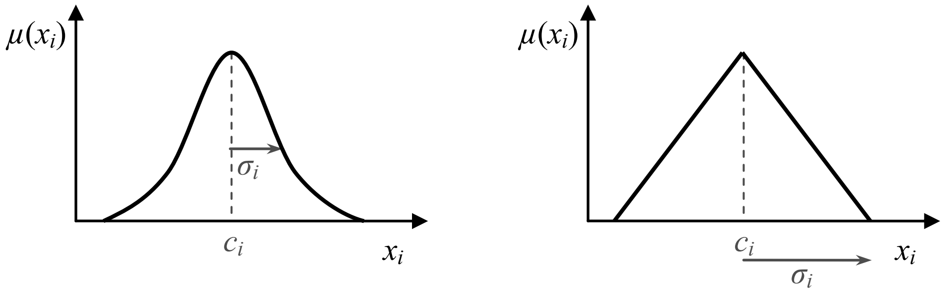


Figure 9. Gaussian (left) and triangular (right) membership functions.

The rules are logical implications, e.g. IF antecedent; THEN consequent, and they represent the knowledge of the system being simulated. Among the two main canonical rule structures (ZADEH, 1965; TAKAGI; SUGENO, 1985; SUGENO; KANG, 1988), in the present work Zadeh (1965) was considered more suitable for the objectives. The use of one or another is very much application dependent (Mendel 2017).

The fuzzy inference engine along with the fuzzifier plays a key role in this study, as they are fundamental to address vagueness and ambiguousness. Here, a Mamdani fuzzy inference engine is employed, as it is more suitable for this application. In this work, there is no need to process fuzzy outputs, therefore there is no output processor. More details of fuzzy system components and the mathematical methods used can be found in Mendel (2017).

Now it will be presented the proposed model. Given a fuzzy system with n inputs and a rule base of m rules, we have:

$$R^l: F_1^l \times F_2^l \times \cdots \times F_n^l \rightarrow G^l = F^l \rightarrow G^l, l = 1, 2, \cdots, m \tag{1}$$

Where F^l is the rules' antecedent, and G^l the rules' consequent. The membership grade of R^l is calculated using Mamdani (also known as engineering) implication

$$\begin{aligned} \mu_{F^l \rightarrow G^l}(\mathrm{x}, y) &= \mu_{F^l}(\mathrm{x}) \star \mu_{G^l}(y) \\ &= \mu_{F_1^l \times F_2^l \times \cdots \times F_n^l}(\mathrm{x}) \star \mu_{G^l}(y) \end{aligned} \tag{2}$$

Where $\star$ is the t-norm operation. Being separable multivariable membership functions,

$$\begin{aligned} \mu_{F^l \rightarrow G^l}(x, y) = \mu_{R^l}(x, y) &= \mu_{F_1^l \times F_2^l \times \cdots \times F_n^l}(x) \star \mu_{G^l}(y) \\ &= \mu_{F_1^l}(x_1) \star \mu_{F_2^l}(x_2) \star \cdots \star \mu_{F_n^l}(x_n) \star \mu_{G^l}(y) \\ &= \left[T_{i=1}^n \mu_{F_i^l}(x_i)\right] \star \mu_{G^l}(y) \end{aligned} \tag{3}$$

where T is the T-norm operator.

Now, presenting the mathematical equations related to the input data as the separable set membership function A_x,

$$\begin{aligned} A_{\mathrm{x}} &\subseteq X_1 \times X_2 \times \cdots X_n \\ \mu_{A_{\mathrm{x}}}(\mathrm{x}) &= \mu_{X_1 \times X_2 \times \cdots \times X_n}(\mathrm{x}) \\ &= T_{i=1}^n \mu_{X_i}(x_i) \end{aligned} \tag{4}$$

The most common method to match input data (premise) with the rule's antecedent in crisp logic is the *modus ponens*. In fuzzy logic, the *modus ponens* is extended for approximate matches, and it is called *generalized modus ponens*, stated as:

Premise: x is A_x
Implication: IF x is F^l *THEN y is* G^l
Consequence: y is B^l

where fuzzy set A_x does not have to exactly match fuzzy set F^l, and fuzzy set B^l does not have to exactly match fuzzy set G^l. The matching degree is the degree that the rule can be applied. The unknown term B^l is determined using the fuzzy relational equation:

$$B^l = A_x \circ R^l \tag{5}$$

The aim here is to determine the membership grade of the output variable y in B^l. By manipulating the resultant membership function, we find that

$$\begin{aligned} \mu_{B^l}(\mathrm{x},y) &= \mu_{A_{\mathrm{x}}\circ R^l}(\mathrm{x},y) \\ &= \sup_{\mathrm{x}\in \mathrm{X}}[\mu_{A_{\mathrm{x}}}(\mathrm{x}) \star \mu_{R^l}(\mathrm{x},y)] \\ &= \sup_{\mathrm{x}\in \mathrm{X}}\left[T_{i=1}^{n}\mu_{X_i^l}(x_i) \star \left[T_{i=1}^{n}\mu_{F_i^l}(x_i)\right] \star \mu_{G^l}(y)\right] \\ &= \sup_{\mathrm{x}\in \mathrm{X}}\left[T_{i=1}^{n}\left[\mu_{X_i^l}(x_i) \star \mu_{F_i^l}(x_i)\right] \star \mu_{G^l}(y)\right] \\ &= \sup_{x_1\in X_1}\left[\mu_{X_1^l}(x_1) \star \mu_{F_1^l}(x_1)\right] \star \cdots \star \sup_{x_n\in X_n}\left[\mu_{X_n^l}(x_n) \star \mu_{F_n^l}(x_n)\right] \star \mu_{G^l}(y) \end{aligned} \tag{6}$$

The last line follows from the fact that $\mu_{X_i^l}(x_i) \star \mu_{F_i^l}(x_i)$ is only a function of x_i, so that each supremum is over just a scalar variable, x_i. Finally, we obtain

$$\mu_{B^l}(\mathrm{x},y) = T_{i=1}^{n}\left[\sup_{x_i\in X_i}\left[\mu_{X_i^l}(x_i) \star \mu_{F_1^l}(x_i)\right]\right] \star \mu_{G^l}(y), y \in Y \tag{7}$$

Examining Equation (7), we note that the interactions inside the brackets involve only the fuzzified input ($\mu_{X_i^l}$) and its respective antecedent ($\mu_{F_1^l}$). After all these interactions are computed, the result is then t-normed against the consequent (μ_{G^l}). Thus, we can define the inner bracketed term as

$$\mu_{X_i^l}(x_i) \star \mu_{F_1^l}(x_i) \equiv \mu_{P_i^l}(x_i) \tag{8}$$

The maximum value of $\mu_{P_i^l}(x_i)$ occurs at $x_i = x_i^{max}$, where both $\mu_{X_i^l}$ and $\mu_{F_1^l}$ maximize their value. Therefore, we can write Equation (7) as

$$\mu_{B^l}(\mathrm{x},y) = T_{i=1}^{n}\mu_{P_i^l}(x_i^{max}) \star \mu_{G^l}(y), y \in Y \tag{9}$$

When we are considering only fuzzy singletons, $\mu_{X_i^l}(x_i^{max}) = 1$, this reduces Equation (8) to

$$\mu_{P_i^l}(x_i) = \mu_{F_1^l}(x_i) \tag{10}$$

In our study, since we deal only with categorical variables as outputs, and considering that a rule consequent refers to the categorical variable itself,

$$\mu_{G^l}(y) = \begin{cases} 1, if\ y = T(G^l) \\ 0, otherwise \end{cases}, y \in Y \tag{11}$$

where $T(G^l)$ is the linguistic term of G^l. That is, there is only one categorical output variable that can activate the rule, and it is equal to the linguistic term of the consequent fuzzy set G^l. For a given $y' = T(G^l)$, then

$$\mu_{B^l}(\mathrm{x}, y') = T_{i=1}^{n} \mu_{P_i^l}(x_i^{max}) \tag{12}$$

Equation (12) determines the degree that rule l can be applied, or in other words, the level which rule l will fire. Note that, differently from crisp systems, more than one rule can have a non-zero value for $\mu_{B^l}(\mathrm{x}, y')$, meaning that more than one rule can be fired simultaneously.

Therefore, the next step in a fuzzy system is to somehow combine those rules to obtain an overall conclusion about them. To do this, an output processor is employed. Even though it is not known how the rules are combined in a human perspective (if indeed they are) (MENDEL, 2017), the most usual way to combine them in a Mamdani fuzzy system is by disjunctive aggregation:

$$\mu_B(\mathrm{x}, y) = \max_{l=1,2,\cdots,m} T_{i=1}^{n} \mu_{P_i^l}(x_i^{max}) \star \mu_{G^l}(y), y \in Y \tag{13}$$

When more than one alternative (i.e. a variable output y) has a non-zero membership grade, ambiguity (or contradiction, which will be explained further below) happens at some degree. A measure of ambiguity is proposed by Siler and Buckley (2005):

$$\text{Ambiguity} = \alpha = \frac{\sum_i \mu_i}{\max_i \mu_i} \tag{14}$$

where μ_i is the membership grade of alternative i, and $1 \leq \alpha \leq n$, being n the number of alternatives. An ambiguity of one means that only one member is valid (no ambiguity), while an ambiguity of n means that all alternatives are equivalent (maximum ambiguity). In this study, it is defined that $\lfloor \alpha + 0.5 \rfloor$ alternatives will be selected in a given decision, where $\lfloor x \rfloor$ is the floor function of x. For example, in a decision with four alternatives with an ambiguity equal to 2.44, it is selected the $\lfloor 2.44 + 0.5 \rfloor = \lfloor 2.94 \rfloor = 2$ alternatives with the greatest grades of membership as potential solutions (see Appendix A). All ties are also selected, if they exist. Then, they are treated as an ambiguity or a contradiction, as shown further in the refine method.

2.4. Choosing the most adequate alternative (refine method)

In a given decision, if only one alternative can satisfy it, alternatives are considered mutually exclusive and therefore a contradiction (e.g. a stationary production unit cannot be addressed as both a jackup and an FPSO). On the other hand, if more than one alternative can be selected (e.g. a variable that measures production rate can have membership in both medium and high rates), they are not mutually exclusive and thus there is an ambiguity (SILER; BUCKLEY, 2005). In offshore production systems, alternatives usually employ different technologies to attain similar objectives, therefore in our study a decision between alternatives will be considered as contradictions unless stated otherwise.

Siler and Buckley (2005) presented several ways to resolve contradictions. Based on them, it is built a tailored version for the offshore production systems' perspective. First, it is needed to recognize that the fuzzy system does not produce final results, but preliminary ones. The first step to resolve contradictions is to analyse if the succeeding decision steps undermine the alternative, as there may be subsequent alternatives that have a non-zero membership grade in the impossible fuzzy set. These alternatives must be removed followed by all subsequent alternatives below them (e.g. between a contradiction of host systems A and B, if the results indicate that it is quite impossible to install a riser in host system B, the decisions all the way up to the host system B and the host system B itself should be not considered as alternatives anymore).

The second step is to review the membership functions and rules employed so far. The addition or modification of MFs and rules can drive the model to one of the alternatives or even to not previously considered, although better, alternatives. If the second step is unfeasible or did not solve the contradiction, then the next step is to consider additional variables to distinguish the contradictions, as the addition of relevant variables can endorse or discourage each alternative.

The fourth step is to conduct a cost evaluation for each possible solution. The cost evaluation will point to the most economically competitive alternative. Usually, studies in the literature employ the NPV to determine the most economically competitive solution. In this study, however, determining the NPV would be 1) misleading, since there are present many uncertainties regarding cash inflows in the proposed scenario, and 2) unnecessary, since we are mainly considering the differences among the candidate solutions. Thus, the main result of this analysis is the Present Value (PV), presented in Equation (15) and defined as the sum of the present values of cash outflows:

$$PV = \sum_{t} \frac{CO_t}{(1+i)^t} \tag{15}$$

where CO_j is the cash outflow (US$) at time period t (here considered in years), and i is the discount rate (% per year). This cash outflow includes the investments in equipment and facilities.

Ultimately, if none of the former steps resolved the contradictions (which is very unlikely), the alternative with the greatest membership grade should be selected. However, it must be kept in mind that this step does not imply that the alternative with the greatest membership grade is the most appropriate, thus it is recommended to apply it only if the former steps are completely inconceivable.

Regarding ambiguities, it is recommended to retain them in the decision process to avoid completely wrong solutions (SILER; BUCKLEY, 2005). In an ambiguity, by selecting only the alternative with the greatest membership grade, we transmit an incomplete picture to later reasoning stages or to the end user, and we may overlook some very relevant solutions along the way. That said, retaining ambiguities in fact increase the system robustness (SILER; BUCKLEY, 2005).

2.5. Problem modelling

In order to have a consistent model for the design of an offshore production system, the first step is to define the order of components for decision. In this study, decision components presented in Franco (2003) were adapted, as the offloading system is decided before the stationary production unit, and the following decision components are proposed: *well arrangement*, *manifold use*, *offloading system*, *stationary production unit*, *mooring and risers systems*, *storage capacity* and *storage system*. Here, few decision components are considered, as the objective of this study is only to validate the proposed model. In real model scenarios, it is suggested to consider more decision components to obtain a full and integrated offshore production system concept.

The *well arrangement* determines if the wells are clustered around drill centres or strategically spread around the reservoir, in a satellite configuration. The *manifold use* basically defines the employment of this equipment in the field which depends, for example, of the well arrangement decision. The transportation method for the produced oil through pipelines or shuttle tankers is decided in the *offloading* decision component. The stationary production unit may be a barge, a jackup, a jacket, a gravity-based platform, a compliant tower, a spar, a tension leg platform, a semisubmersible or an FPSO.

The *mooring system* is specific to each stationary production unit alternative, as the first four do not use mooring lines, the compliant tower may be guyed by mooring lines, the tension leg platform is tethered by anchored lines, while the spar, semisubmersible and FPSO can be conventionally moored. The FPSO may also be moored through a turret. *Risers* might be rigid, flexible or hybrid.

In *storage capacity*, the average capacity to store oil in the host system is considered. Finally, the *storage system* is decided according to the availability of an export submarine pipeline, the use of stationary production unit or a floating storage unit. Figure 10 shows the relation among decision components. The arrows point to decision components that depend on the former component.

Furthermore, relevant field aspects must be considered as input variables in each decision component. Some of them are reservoir area and depth, number and type of wells, water depth and environmental conditions. Table 1 presents the input variables with their name, the linguistic terms used to label them, along with their relation with each decision component and some observations. In comparison with previous work (Franco, 2003), the *reservoir depth* and *storage capacity* input variables were removed to fit for the present objectives. It must be observed that some output values from decision components become input variables to further decision components.

Furthermore, membership functions (MFs) must be defined for each variable. This process can be intuitive or employ algorithms or logical operations based on given data. Ross (2010) presents various methods of developing MFs, and Mendel (2017) presents a method to determine MFs through survey results. In this study, it is employed the membership functions presented in Figure B1, which were based on expert knowledge.

Lastly, a rule base must be elaborated to each decision component using the variables introduced in the former steps. As in developing MFs, it is possible to determine rules intuitively or through an automated fashion, as shown in Ross (2010). However, it must be clear that even though it is possible to derive MFs and rules from input-output data, this form of knowledge has the same utility as the one derived by human understanding (ROSS, 2010). Here, rule bases were also developed using expert knowledge, being updated from Franco (2003). Several modifications to support nowadays ultra-deepwater fields were included, and improvements in the embedded knowledge were carried out which led to a large database with 1390 rules, which are shown in Table B1 through Table B9.

In each decision component, there may be several alternatives available. The first decision component is analyzed, and their ambiguities solved. After, it is analysed the next decision component, and these steps are repeated until the last decision component.

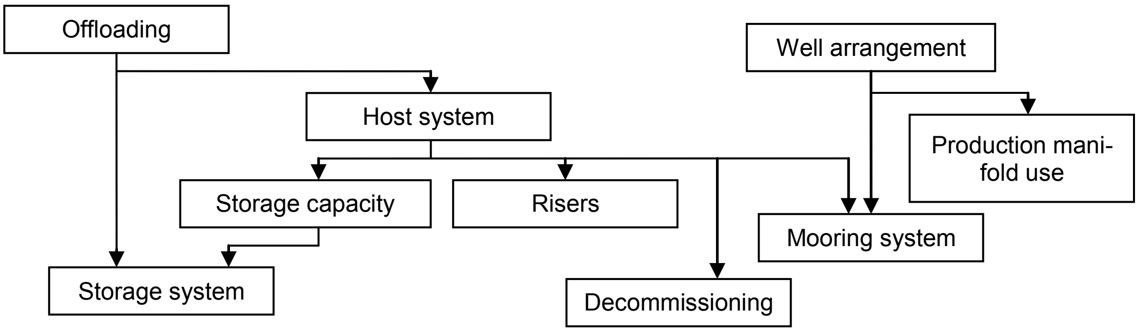


Figure 10. Order of decision components in this study.

Table 1. Input variables considered in this study.

Name	Linguistic terms	Required to	Observations
Reservoir area	Small, Medium, Large	Well arrangement	--
Well count	Few, Low, Medium, High	Well arrangement, Production manifold use, Host system, Mooring, Offloading, Storage system	The number of active producers and injectors in the field
Well type	Vertical, Directional	Well arrangement	Directional wells are either classified as vertical or directional in a crisp manner
Oil production rate per well	Low, Medium, High	Production manifold use, Host system, Offloading, Storage system	--
Water depth	Very shallow, Moderately shallow, Shallow, Medium, Deep, Ultra-deep	Host system, Riser, Decommissioning	The water depth where the host system will be installed
Environmental conditions	Mild, Moderate, Severe	Host system, Riser	This parameter is based on the overall scenario of the field
Shore distance	Small, Medium, Large	Offloading, Decommissioning	--
Export pipeline available	Yes, No	Offloading	Only yes if neighbouring export pipelines are available to offload the produced oil

2.6. Comprehensive example

Here, it will be determined the membership grade of the alternatives of the well arrangement decision component as an example. This procedure is recursively applied to all decision components. A simpler example of this procedure is present in Appendix A. It will be used the same input data of the Sapinhoá field case study, which is presented in the next section in Table 12.The information used in this example is summarized in Table 2.

First, it is calculated the membership grade of each variable related to the decision component (in this example, they are reservoir area, well count and well type) for each linguistic term, using the membership functions in Figure B1. Figure 11 shows the intersection of the fuzzy input of reservoir area and its membership functions. The values obtained from these intersections are shown in Table 2 for all related variables.

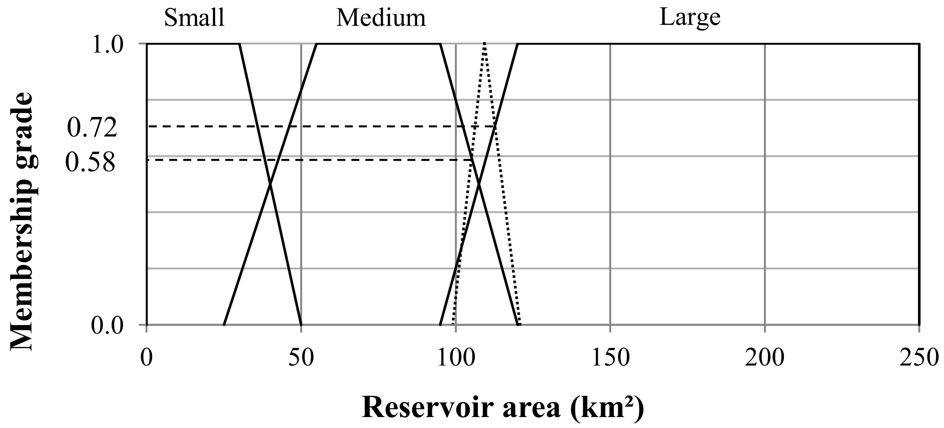


Figure 11. Membership grades for reservoir area.

Table 2. Membership grades of each variable of well arrangement.

Variable	Value	Spread	Linguistic term	Membership grade
Reservoir area	110 km²	±10%	Small	0.00
			Medium	0.58
			Large	0.72
Well count	15	±10%	Few	0.38
			Low	0.08
			Medium	1.00
			High	0.00
Well type	Directional	--	Vertical	0.00
			Directional	1.00

These membership grades will fire each rule of Table B1 differently. Here, only 18 rules fired (out of 72). Equation (13) is then employed to combine those rules to obtain a single membership grade for each alternative. Thus, we obtain that:

$$\begin{aligned} \mu_{Clustered} &= \max\{[(0 \star 1)_1 \star (1 \star 1)_2 \star (0 \star 1)_3]_1, \cdots, [(1 \star 1)_1 \star (1 \star 1)_2 \\ &\quad \star (0.58 \star 1)_3]_8, \cdots, [(0 \star 0)_1 \star (0 \star 0)_2 \\ &\quad \star (0.58 \star 0)_3]_{13}, \cdots, [(0 \star 0)_1 \star (0 \star 0)_2 \star (0 \star 0.72)_3]_{24}\} \\ &= \max\{[0]_1 \cdots [0.58]_8 \cdots [0]_{24}\} \\ &= 0.58 \end{aligned} \tag{16}$$

$$\begin{aligned} \mu_{Satellite} &= \max\{[(0 \star 0)_1 \star (1 \star 0)_2 \star (0 \star 0)_3]_1, \cdots, [(0 \star 1)_1 \star (0 \star 1)_2 \\ &\quad \star (0.58 \star 1)_3]_{13}, \cdots, [(1 \star 1)_1 \star (1 \star 1)_2 \\ &\quad \star (0.72 \star 1)_3]_{22}, \cdots, [(0 \star 1)_1 \star (0 \star 1)_2 \star (0.72 \star 1)_3]_{24}\} \\ &= \max\{[0]_1 \cdots [0.72]_{22} \cdots [0]_{24}\} \\ &= 0.72 \end{aligned} \tag{17}$$

Evaluating the ambiguity between these two alternatives, we have

$$\alpha = \frac{0.58 + 0.72}{0.72} = 1.81 \tag{18}$$

$$\lfloor \alpha + 0.50 \rfloor = \lfloor 1.81 + 0.50 \rfloor = 2 \tag{19}$$

Therefore, we have two feasible concepts for well arrangement: a clustered or a satellite one. This is considered a contradiction in this study, so it must be resolved as seen in Section 2.4. After, we head over to the next decision component, repeating this process for all decision components.

3. RESULTS

A database containing 34 oilfields was used to evaluate the performance of the proposed method. The database, shown in Table 6, is similar to Franco (2003) in its content, although nine very old fields were replaced with new fields developed after 2003, and information about all fields was updated. The green shaded cells show updated values from Franco (2003), and red shaded cells highlight mismatches of the proposed model compared to the real scenario. The fuzzy system was coded in C language and ran on an Intel Core i7-3770 processor with 24 GB of RAM. The fuzzy systems runs almost instantly (less than a second for all fields), allowing real-time results and quick sensitivity analyses.

First, a sensibility analysis is conducted in order to evaluate the impacts of the input uncertainties. For each oilfield, the spread in each numerical input was increased from 0% to 35% in steps of 5%, relative to its most likely value. Table 3 presents if there was a change in the proposed solution for each increase in spread. A zero means that there were no changes in the results compared to the former step increase, while a one means the opposite. For every other field considered, there were no changes. Only 18 oilfields (53%) presented some sensibility to a spread change, and only five fields (15%) shown a high sensitivity to the spread change.

Table 3. Sensitivity analysis of input uncertainties for all oilfields.

	5%	**10%**	**15%**	**20%**	**25%**	**30%**	**35%**	**Total**
Agbami	0	0	1	0	1	1	1	4
Albacora Leste	0	0	1	0	1	1	1	4
Baldpate	0	0	1	0	1	1	1	4
Malikai	0	0	1	0	1	1	1	4
Triton	0	0	1	1	1	0	1	4
Albacora	0	1	0	0	0	0	1	2
Balder	1	1	0	0	0	0	0	2
Barracuda	1	0	0	0	0	0	1	2
Alba	1	0	0	0	0	0	0	1
Andrew	0	1	0	0	0	0	0	1
Argyll	0	0	1	0	0	0	0	1
Britannia	1	0	0	0	0	0	0	1
Ekofisk	0	1	0	0	0	0	0	1
Girassol	0	0	0	0	0	0	1	1
Griffin	0	1	0	0	0	0	0	1
Gullfaks	0	0	1	0	0	0	0	1
Kraken	0	0	0	0	0	0	1	1
Roncador	0	0	0	0	0	0	1	1

Then, it was evaluated the sensitivity of each numerical variable of the first eight oilfields in Table 3 (which presented the most sensitivity). The spread in each numerical variable was increased from 0% to 35% in steps of 5%, relative to its most likely value, while the spreads from other variables were kept null and constant. Table 4 presents the total sum of changes in the results for each increase in spread. Water depth, oil production rate per well and well count were the most sensitive parameters. This is expected, as they are the most important key parameters in offshore production system concept selection.

Table 4. Sensitivity analysis of input uncertainties for numerical variables.

Reservoir area	2
Well count	11
Oil production rate per well	12
Water depth	19
Shore distance	2

After, an overall comparison to the real scenario production systems is conducted, adding a spread of 10% in each numerical variable in order to consider uncertainties in their measurement during the early phases of development. In 85.3% of the cases, the solutions obtained for the offshore production system using the fuzzy system met with the actual field production system. This is greater than the 58.8% found in previous work (FRANCO, 2003). Table 5 presents the comparison of each decision component performance. It was observed that the fuzzy system found the expected solution more times, missing less critical components such as manifold use, mooring and storage and offloading process. It can be concluded that the proposed system is well-calibrated giving good response in verifications done along field production developments in the database.

Table 5. Performance of fuzzy systems for each decision component.

Decision component	**Franco (2003)**	**Our fuzzy system**
Well arrangement	97.0%	100.00%
Manifold	100.0%	97.06%
Stationary production unit	70.6%	97.06%
Mooring	70.6%	97.06%
Riser	100.0%	100.00%
Storage and offloading	100.0%	94.12%
All decision components	58.8%	85.30%

The main reason for the good performance of the fuzzy system is perhaps the proper selection of the alternatives while considering input uncertainties and ambiguities. For example, in the actual scenario of Marlim, Albacora and Roncador fields, stationary production units are a semisubmersible and an FPSO. If only exact inputs and no ambiguities are considered as in Franco (2003), the only solution is the use of an FPSO.

Even though the fuzzy method provides feasible solutions for the stationary production units, sometimes decisions are not fully aligned. For example, in the Albacora field, the present method recommended the use of an FSO or pipelines with a semisubmersible, although such FSO may be unnecessary as there is an FPSO in the field. Thus, further studies are recommended to consider design scenarios with multiple production systems at the same time.

Although the actual production scenario is taken as the reference for comparisons, in some cases, the proposed model clearly selected a better solution than the actual one. For example, in the Argyll field, no temporary storage was available in the semisubmersible employed, therefore, wells could not flow production if a shuttle tanker was not connected to the offloading buoy. This harmed the production system availability down to 70% (HAMMETT; JOHNSON; WHITE, 1977). As a huge CAPEX cost was identified due to downtime, the semisubmersible was later replaced by one with internal storage, which solved the problem (METHVEN, 1993). The fuzzy system solution suggested a semisubmersible with internal storage from the beginning, which clearly reduces the total costs of the project.

Here, three case studies will be presented. The first one is regarding the Veslefrikk field, which will mainly serve as a performance comparison to Franco (2003) method. The second one is the Plutão, Saturno, Venus and Marte (PSVM) field, which will show some limitations of the method, and the third one is the Sapinhoá field, in which the proposed method performs accurately.

Table 6. Validation results of the proposed method.

		Abana	**Agbami**	**Alba**	**Albacora Leste**	**Albacora**	**Andrew**	**Aquila**	**Argyll**	**Balder**	**Baldpate**
Input parameters	Reservoir area (km²)	46	182	14	141	118	27	13	24	80	43
	Reservoir depth (m)	3000	3140	1830	1500	2805	2430	3500	3500	1760	4145
	Well count	17	38	23	30	18	12	2	16	16	7
	Well type	Directional	Directional	Directional	Directional	Directional	Directional	Directional	Directional	Directional	Directional
	Oil production rate per well (m³/d)	93.5	1046	700	943	786	1060	1350	400	850	1136
	Water depth (m)	4.8	1372	138	1230	850	117	850	80	125	500
	Environmental conditions	Mild	Moderate	Severe	Mild/Moderate	Mild/Moderate	Severe	Mild	Moderate	Moderate	Moderate
	Shore distance (km)	9	110	210	120	100	230	50	320	165	222
	Export pipeline available	Yes	No	No	No	No	Yes	No	No	No	Yes
Fuzzy system	Well arrangement	Clustered	Clustered	Clustered	Satellite	Clustered	Clustered	Clustered	Clustered	Clustered	Clustered
	Manifold	No	Yes	Yes	No	Yes	No	No	Yes	Yes	No
	Host system	Barge	FPSO	Jacket	FPSO	FPSO/SS	Jacket	FPSO	SS	FPSO	Compliant Tower
	Mooring	Conventional	Conventional	Nothing	Conventional	Turret/Conventional	Nothing	Turret	Conventional	Turret	Lead Cable
	Riser	Flexible	Flexible	Rigid	Flexible	Flexible	Rigid	Flexible	Flexible	Flexible	Rigid
	Storage and offloading	Pipeline	Internal storage	FSO	Internal storage	Internal storage	Pipeline	Internal storage	FSO or Internal storage	Internal storage	Pipeline
Real scenario	Well arrangement	Clustered	Clustered	Clustered	Satellite	Clustered	Clustered	Clustered	Clustered	Clustered	Clustered
	Manifold	No	Yes	Yes	No	Yes	No	No	Yes	No	No
	Host system	Barge	FPSO	Jacket	FPSO	FPSO/SS	Jacket	FPSO	SS	FPSO	Compliant Tower
	Mooring	Conventional	Conventional	Nothing	Conventional	Turret/Conventional	Nothing	Turret	Conventional	Turret	Lead Cable
	Riser	Flexible	Flexible	Rigid	Flexible	Flexible	Rigid	Flexible	Flexible	Flexible	Rigid
	Storage and offloading	Pipeline	Internal storage	FSO	Internal storage	Internal storage	Pipeline	Internal storage	No storage	Internal storage	Pipeline

Table 6. Validation results of the proposed method (Continuation).

		Barracuda	**Britannia**	**Brutus**	**Ekofisk**	**Girassol**	**Griffin**	**Gullfaks**	**Hebron**	**Hibernia Grand Banks**	**Kraken**
Input parameters	Reservoir area (km²)	233	250	53	35	180	40	50	64	68	68
	Reservoir depth (m)	1500	4000	4500	3197	1200	2700	2000	2275	3050	1334
	Well count	34	41	8	56	40	12	106	40	50	25
	Well type	Directional	Directional	Directional	Directional	Vertical	Vertical	Directional	Directional	Directional	Directional
	Oil production rate per well (m³/d)	790	194	2200	120	1000	1,126	830	588	450	994
	Water depth (m)	850	140	910	70	1350	130	140	93	80	120
	Environmental conditions	Mild	Severe	Severe	Severe	Mild	Moderate	Severe	Severe	Severe	Moderate
	Shore distance (km)	160	210	266	300	150	68	175	350	315	125
	Export pipeline available	No	Yes	Yes	Yes	No	No	No	No	No	No
Fuzzy system	Well arrangement	Satellite	Clustered	Clustered	Clustered	Satellite	Clustered	Clustered	Clustered	Clustered	Clustered
	Manifold	No	Yes	No	Yes	Yes	Yes	Yes	No	Yes	Yes
	Host system	FPSO	Jacket	TLP	Jacket	FPSO	FPSO	GBS	GBS	GBS	FPSO
	Mooring	Conventional	Nothing	Tethered	Nothing	Conventional	Turret	Nothing	Nothing	Nothing	Turret
	Riser	Flexible	Rigid	Rigid	Rigid	Hybrid	Flexible	Rigid	Rigid	Rigid	Flexible
	Storage and offloading	Internal storage	Pipeline	Pipeline	Pipeline	Internal storage	Internal storage	Internal storage	Internal storage	Internal storage	Internal storage
Real scenario	Well arrangement	Satellite	Clustered	Clustered	Clustered	Satellite	Clustered	Clustered	Clustered	Clustered	Clustered
	Manifold	No	Yes	No	Yes	Yes	Yes	Yes	No	Yes	Yes
	Host system	FPSO	Jacket	TLP	Jacket	FPSO	FPSO	GBS	GBS	GBS	FPSO
	Mooring	Conventional	Nothing	Tethered	Nothing	Conventional	Turret	Nothing	Nothing	Nothing	Turret
	Riser	Flexible	Rigid	Rigid	Rigid	Hybrid	Flexible	Rigid	Rigid	Rigid	Flexible
	Storage and offloading	Internal storage	Pipeline	Pipeline	Pipeline	Internal storage	Internal storage	Internal storage	Internal storage	Internal storage	Internal storage

Table 6. Validation results of the proposed method (Continuation).

		Lucius	**Malikai**	**Marlim**	**Mars**	**Oseberg**	**Perdido**	**PSVM**	**Roncador**	**Sapinhoá**	**Siri**
Input parameters	Reservoir area (km²)	25	92	15	59	27	83	50	65	110	66
	Reservoir depth (m)	4100	1420	2300	4267	2500	4500	1450	1360	5500	2070
	Well count	8	24	17	26	72	22	48	27	15	7
	Well type	Directional	Directional	Directional	Directional	Directional	Directional	Directional	Directional	Directional	Directional
	Oil production rate per well (m³/d)	1,987	397	520	620	96	723	520	980	432	1150
	Water depth (m)	2170	500	850	896	101	2337	1925	1360	2140	60
	Environmental conditions	Moderate	Severe	Mild/Moderate	Severe	Severe	Severe	Mild	Moderate	Mild	Severe
	Shore distance (km)	390	100	110	241	115	320	115	125	310	220
	Export pipeline available	Yes	Yes	No	Yes	Yes	Yes	No	No	No	No
Fuzzy system	Well arrangement	Clustered	Clustered	Clustered	Clustered	Clustered	Clustered	Clustered	Clustered	Satellite	Clustered
	Manifold	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	No	No
	Host system	Spar	TLP	FPSO/SS	TLP	Jacket/GBS	Spar	FPSO	FPSO/SS	FPSO	Jackup
	Mooring	Conventional	Tethered	Turret/Conventional	Tethered	Nothing	Conventional	Conventional	Conventional/Conventional	Conventional	Nothing
	Riser	Rigid	Rigid	Flexible	Rigid	Rigid	Rigid	Hybrid	Flexible	Hybrid	Rigid
	Storage and offloading	Pipeline	Pipeline	Internal storage	Pipeline	Pipeline	Pipeline	Internal storage	Internal storage/FSO	Internal storage	Internal storage
Real scenario	Well arrangement	Clustered	Clustered	Clustered	Clustered	Clustered	Clustered	Clustered	Clustered	Satellite	Clustered
	Manifold	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	No	No
	Host system	Spar	TLP	FPSO/SS	TLP	Jacket	Spar	FPSO	FPSO/SS	FPSO	Jackup
	Mooring	Conventional	Tethered	Turret/Conventional	Tethered	Nothing	Conventional	Turret	Conventional/Conventional	Conventional	Nothing
	Riser	Rigid	Rigid	Flexible	Rigid	Rigid	Rigid	Hybrid	Flexible	Hybrid	Rigid
	Storage and offloading	Pipeline	Pipeline	Internal storage	Pipeline	Pipeline	Pipeline	Internal storage	Internal storage/FSO	Internal storage	Internal storage

Table 6. Validation results of the proposed method (Continuation).

		Snorre	**Stag**	**Triton**	**Veslefrikk**	**Arkutun-Dagi**
Input parameters	Reservoir area (km²)	31	22	61	25	155
	Reservoir depth (m)	2500	812	3400	2925	1784
	Well count	23	20	20	23	45
	Well type	Directional	Directional	Directional	Directional	Directional
	Oil production rate per well (m³/d)	837	240	700	32	300
	Water depth (m)	335	47	90	185	35
	Environmental conditions	Moderate/Severe	Mild	Moderate	Moderate	Severe
	Shore distance (km)	210	65	195	145	25
	Export pipeline available	No	No	No	Yes	Yes
Fuzzy system	Well arrangement	Clustered	Clustered	Clustered	Clustered	Clustered
	Manifold	Yes	No	Yes	No	No
	Host system	SS/TLP	Jacket	FPSO	SS	GBS
	Mooring	Conventional/Tethered	Nothing	Turret	Conventional	Nothing
	Riser	Flexible	Rigid	Flexible	Flexible	Rigid
	Storage and offloading	Pipeline	Internal storage	Internal storage	Pipeline	Pipeline
Real scenario	Well arrangement	Clustered	Clustered	Clustered	Clustered	Clustered
	Manifold	Yes	No	Yes	No	No
	Host system	SS/TLP	Jacket	FPSO	SS	GBS
	Mooring	Conventional/Tethered	Nothing	Turret	Conventional	Nothing
	Riser	Flexible	Rigid	Flexible	Flexible	Rigid
	Storage and offloading	Pipeline	FSO	Internal storage	Pipeline	Pipeline

3.1. Case study: Veslefrikk field

Located in the Norwegian Sea, about 145 km offshore Bergen, Norway, in an average water depth of 185 meters, the Veslefrikk field was the first in Norway to host an offshore floating production unit. Solberg (1990) provides technical information and challenges in developing this oilfield. Franco (2003) model selected a jacket platform for this field, whoever in the real scenario, while it is true that a jacket drilled the wells, the production platform is a semisubmersible.

To fully compare both methods in this case study, the method proposed here used the same input data, decision components, rule bases and membership functions as the one presented in Franco (2003). However, in the input data of the proposed method, it is added a spread of 10% relative to the most likely value of the numerical input variables to consider uncertainty in their measurement in the early phases of development. The input data is presented in Table 7. Through this case study, it is shown that the model proposed here correctly selects the semisubmersible in this scenario, while showing why Franco (2003) model cannot obtain this solution.

Table 7. Input data of Veslefrikk field. Source: adapted from Franco (2003).

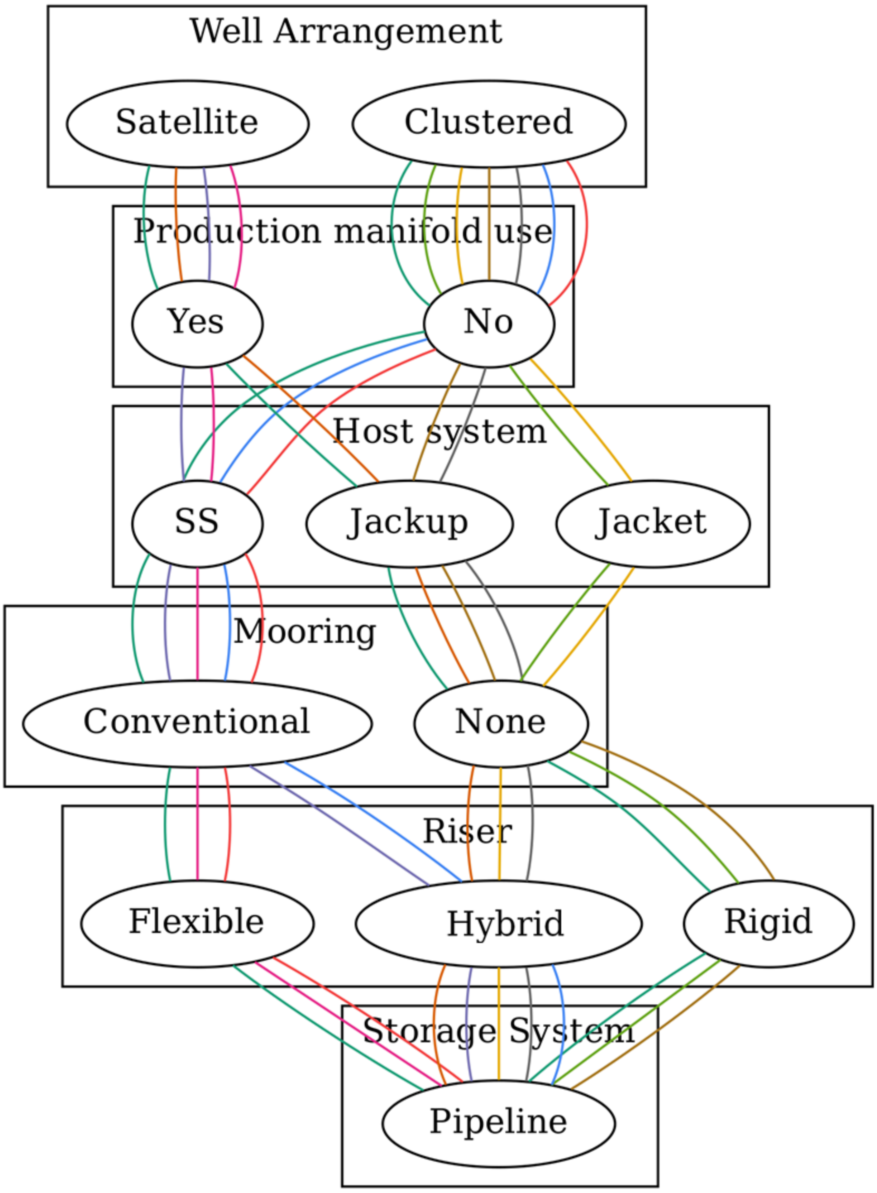
Variable	**Most likely value (x_i')**	**Spread (relative to x_i')**
Reservoir area	25 km²	±10%
Reservoir depth	2925 m	±10%
Well count	23	±10%
Well type	Directional	–
Oil production rate per well	32 m³/d	±10%
Water depth	185 m	±10%
Environmental conditions	Moderate	–
Shore distance	145 km	±10%
Export pipeline available	Yes	–

Table 8 presents the membership grades for each linguistic term. The bolded membership grades highlight the ambiguities present. It is noted that even without considering measurement uncertainty in the input data, there are ambiguities in the water depth and the reservoir depth variables. These ambiguities were overlooked in Franco (2003) model due to the criteria of always selecting the linguistic term with the highest membership grade. When we consider measurement uncertainty, these ambiguities increase and others arise, such as the one in the oil production rate per well.

The fuzzy decision tree of the proposed method is shown in Figure 12. There are ten distinct solutions, which are shown in Table 10 for the sake of clearness. The squares represent each decision component, the oval shapes represent each decision component alternative in this scenario, and the edges connect the elements of each solution, which are traced in different colours. First, it was noted that all solutions obtained would be technologically feasible to deploy in this field. The uncertainties in the input data made the semisubmersible a feasible alternative. Solution 2 is the one obtained by Franco (2003), which has the highest cost among the other solutions, and Solution 10 is the one actually employed in the field.

As stated in Section 2.4, we now must resolve the contradictions. In this case study, there are no succeeding decision steps that undermine the alternatives (step 1), neither adding rules, membership functions (step 2) nor additional variables (step 3) are conceivable. Thus, a cost evaluation is run for each alternative (step 4). There are four aspects that influence the cost competitiveness of each solution: production manifolds (employing it or not), host systems (jackup, jacket, and semisubmersible), and risers (rigid, hybrid and flexible). Other aspects are superfluous to the analysis, so they are not considered here.

Table 9 shows the estimated values for the equipment. All prices are estimations for a given water depth of 174 m and an oil production capacity of 100,000 bbl/d (0.18 m^3/s), which include full material and installation costs. Considering that all this equipment will be acquired today ($t = 0$), we obtain the following present values in Table 10. We see that Solution 10 is the most cost competitive one, thus it is selected as the final solution to the Veslefrikk production system.



Veslefrikk oilfield

Figure 12. Veslefrikk field fuzzy decision tree.

Table 8. Resultant membership grades.

Variable	**Linguistic term**	**Membership grade**	
		Franco (2003) input data	This study (inputs with uncertainties)
Reservoir area	Small	1.00	1.00
	Medium	0.00	0.00
	Large	0.00	0.00
Reservoir depth	Shallow	0.00	0.00
	Medium	**0.53**	**0.63**
	Deep	**0.30**	**0.41**
Number of wells	Low	0.00	0.00
	Medium	0.93	0.94
	High	0.00	0.00
Well daily production	Low	0.00	0.00
	Medium	0.36	**0.49**
	High	0.10	**0.29**
Water depth	Shallow	**0.24**	**0.34**
	Medium	**0.34**	**0.39**
	Deep	0.00	0.00
	Ultra-deep	0.00	0.00
Distance to coast	Small	0.00	0.00
	Medium	0.83	0.86
	Large	0.00	0.00

Table 9. Estimated values for equipment costs.

Equipment	**Price (million US$)**	**Reference**
Manifold	9.00	Mata (2010)
Jacket	451.00	Interpolation between Bullwinkle (2011) and Buzzard (2012) jacket platforms
Jackup	461.00	Kaiser and Snyder (2012)
Semisubmersible	356.60	González Castaño (2017)
Conventional mooring (catenary)	0.30	Martinelli, Ruol, and Cortellazzo (2012)
Rigid riser	2.10	Hatton (1995)
Flexible riser	8.91	Estimation based in Hatton (1995), Offshore Magazine (2000) and Hill (2017)
Hybrid riser	12.00	Estimation based in Hatton and Brownridge (1995)

Table 10. Feasible solutions for the Veslefrikk field.

Decision component	**Real scenario**	**Solution 1**	**Solution 2**	**Solution 3**	**Solution 4**	**Solution 5**	**Solution 6**	**Solution 7**	**Solution 8**	**Solution 9**	**Solution 10**
Well arrangement	Clustered	Satellite	Satellite	Satellite	Satellite	Clustered	Clustered	Clustered	Clustered	Clustered	Clustered
Manifold	No	Yes	Yes	Yes	Yes	No	No	No	No	No	No
Host system	SS	Jackup	Jackup	SS	SS	Jacket	Jacket	Jackup	Jackup	SS	SS
Mooring	Conventional	None	None	Conventional	Conventional	None	None	None	None	Conventional	Conventional
Riser	Flexible	Rigid	Hybrid	Hybrid	Flexible	Rigid	Hybrid	Rigid	Hybrid	Hybrid	Flexible
Storage and offloading	Pipeline	Pipeline	Pipeline	Pipeline	Pipeline	Pipeline	Pipeline	Pipeline	Pipeline	Pipeline	Pipeline
Present Value (million US$)	N/A	472.08	482.00	377.85	374.77	453.08	463.00	463.08	473.00	368.85	365.77

3.2. Case study: PSVM field

The PSVM field, located about 400 km offshore Angola, Luanda, is composed of four relatively small reservoirs, which are developed together: Plutão, Saturno, Vênus e Marte. In an average water depth of 1925 meters, it is a recently developed field, as its production started in 2013. Its input data is presented in Table 11.

Table 11. Input data of PSVM field.

Variable	**Most likely value (x'_i)**	**Spread (relative to x'_i)**
Reservoir area	50 km²	±10%
Well count	48	±10%
Well type	Directional	–
Oil production rate per well	520 m³/d	±10%
Water depth	1925 m	±10%
Environmental conditions	Mild	–
Shore distance	115 km	±10%
Export pipeline available	No	–

The results obtained using the method proposed here are shown in Figure 13. Here, no other solutions were obtained even when considering uncertainties. The method selected the components very similarly to the real scenario, except the mooring. This is because a great number of manifolds were used to reduce the total number of risers in the real scenario, and a turret moored FPSO was taken as the solution in the actual scenario. The model recommended the use of conventional mooring for the FPSO due to a large number of wells in the field, and also correctly predicted the use of manifolds. However, the vagueness of this statement cannot predict the size and number of manifolds. As a future improvement in the model, perhaps the number and size of manifolds could be employed in a fuzzy manner (a few, a lot, an average, among other linguistic terms) which will require more precise data from the early development phase of the field.

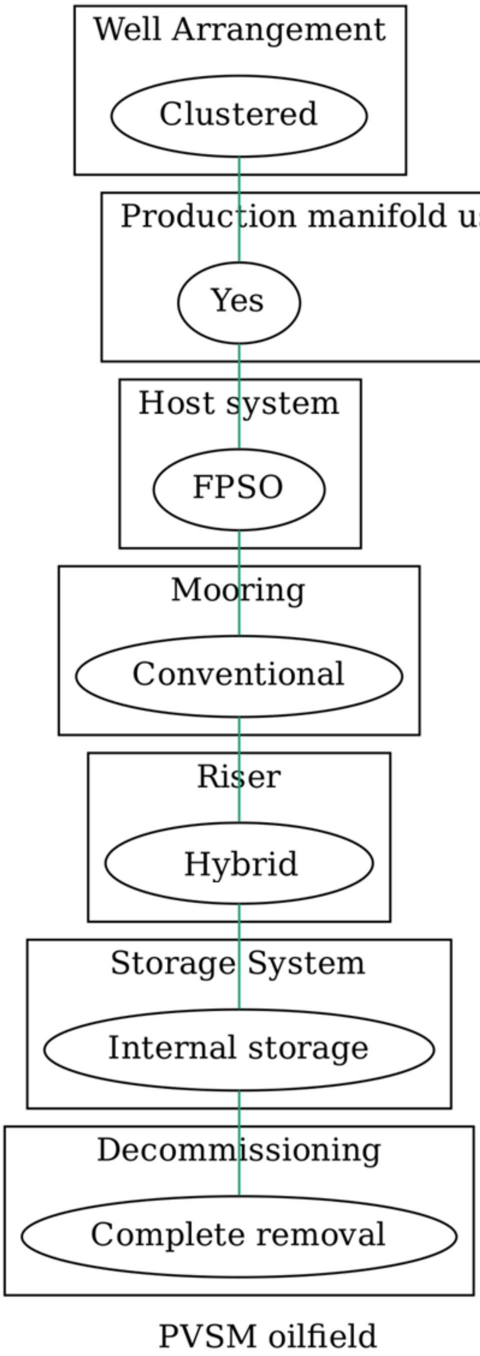


Figure 13. PSVM fuzzy decision tree.

3.3. Case study: Sapinhoá field

The Sapinhoá field, localized on the central Santos Basin, Brazil, is 310 km away from the coast in a water depth of 2,140 meters, and nowadays is one of the most prolific oilfields in Brazil. Naveiro and Haimson (2015) provide technical information and challenges in developing this oilfield. Its input data is presented in Table 12.

Table 12. Input data of Sapinhoá field.

Variable	**Most likely value (x_i')**	**Spread (relative to x_i')**
Reservoir area	110 km²	±10%
Well count	15	±10%
Well type	Directional	–
Oil production rate per well	432 m³/d	±10%
Water depth	2140 m	±10%
Environmental conditions	Mild	–
Shore distance	310 km	±10%
Export pipeline available	No	–

In Figure 14, it is presented the fuzzy decision tree for Sapinhoá field. There are four possible concepts, being the green one (the third line from left to right) employed in the real scenario. Naveiro and Haimson (2015) noted that due to the wells having different productivity index and very high flowrates, production manifolds should not be used. As the installation of spread-moored FPSOs in the Santos Basin has shown good results (ANDRADE et al., 2015), one could argue that the solution employed in the real scenario is the best one and could stop the selection process here. On the other hand, one could use the refine method and conduct detailed economic analyses as explained in Section 2.4 and applied at the Vesle-frikk case study in Section 3.1 to make sure this decision concept is the optimum one.

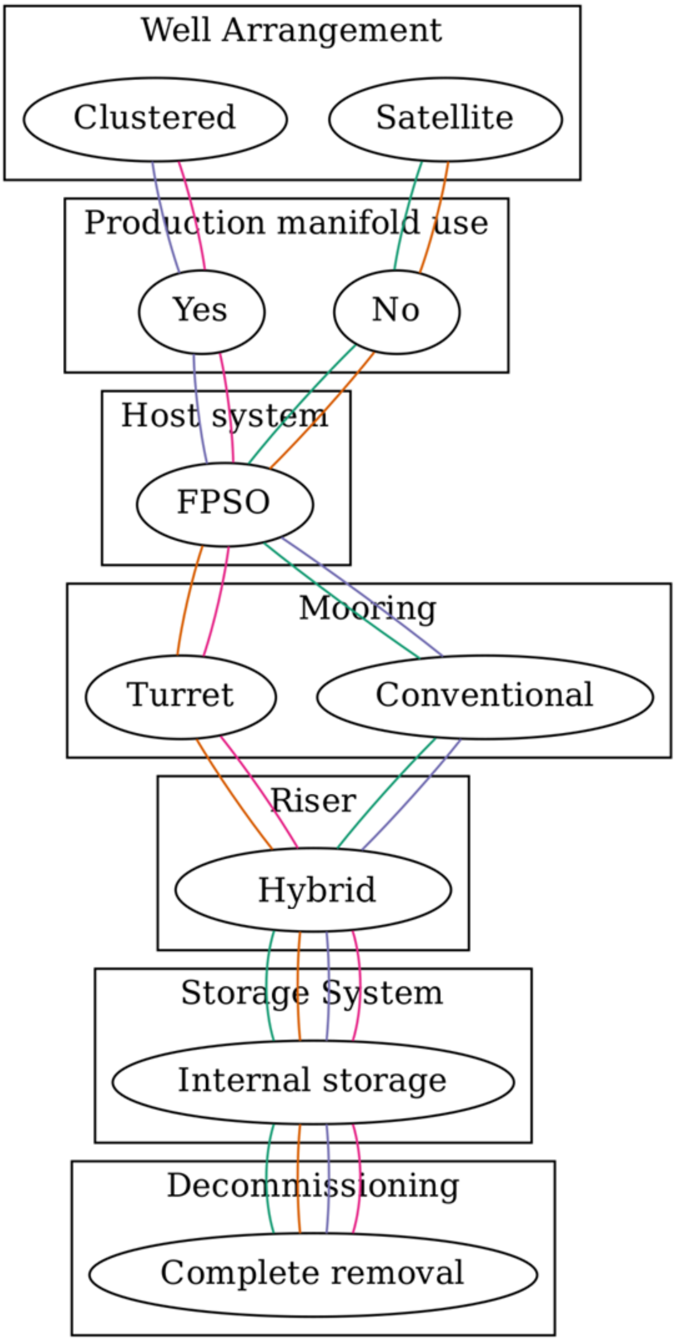


Figure 14. Sapinhoá field fuzzy decision tree.

4. DISCUSSION

Based on Franco (2003) membership functions, rules, decision components and input data, the Veslefrikk field was studied and the results of both methods were compared. The solution obtained here was identical to the currently employed in the field, contrary to Franco (2003) study that recommends a more expensive solution for this field. The semisubmersible appeared as an alternative in our model because there were uncertainty and ambiguities about some aspects (mainly in the oil production rate per well). This happened because the model fired more rules as a hedge against uncertainties, thus being prone to consider more alternatives. This is a phenomenon well known in the literature (MENDEL, 2017), and it allows maximum information about possible outcomes, thus providing more knowledge about the decision problem and enhancing the decision making. Therefore, with the proposed method, optimum solutions can be reached which are not possible by previous methods.

Membership functions, rules, decision components, input data and oilfield database were updated from previous work (FRANCO, 2003) and improved with additional data. The proposed fuzzy system led to solutions very similar to those currently present in the actual fields. As the actual solutions are considered to be well-engineered over the years, it is expected that the proposed method is able to accomplish interesting and valuable solutions for green fields.

The sensitivity analysis shown that only half of the oilfield concepts' results are influenced by input uncertainties, and even fewer (15%) are deeply affected by it. Nonetheless, it is important to consider them as concluded above. Besides, even a small change in the selected concept may or may not severely improve the solution. Water depth, oil production rate per well, and well count are critical in oilfields sensitive to uncertainties, so they must be kept in mind during field appraisal.

On the other hand, the model does not still fully integrate with the overall field development. For example, the model can fail when political or highly environmental or social-oriented solutions are demanded. Moreover, the model only addresses the first (feasibility study) and the second (preliminary project) cycles of the design spiral of the field development as in Morooka and Galeano (1999), i.e. the method does not provide information regarding the installation phase and further steps of field development. The lack of a thorough model may result in not finding solutions identical to the real scenario, such in the PSVM oilfield. Finally, the model does not determine revenues generated of the proposed solution, and further studies are desirable to evaluate the feasibility of addressing them.

Although a type-2 fuzzy system provides a greater assessment of uncertainties, the objective of this study was to provide fundamental insights about the input uncertainties that involve offshore production systems. Besides, the results obtained by a type-2 fuzzy system are harder to understand and its method is less intuitive, so it may prove to be impractical to use for many decision-makers, unless these results are somehow translated into practical information that brings important insights about the problem. Therefore, as future improvements in the study, it is suggested to enhance evaluations including other key parameters as seen in the literature review and try to improve uncertainty analysis by employing type-2 fuzzy systems in a relevant way.

5. CONCLUSIONS

To summarize, this work has the following improvements compared to Franco (2003):

- the overall performance of the method is improved, obtaining solutions similar to the real scenario for 85% of the fields studied here, compared only to 59% in Franco (2003) study;
- the proposed model now considers input uncertainties and ambiguities appropriately;
- the uncertainties in offshore production systems, along with key aspects in them, were revisited and updated, pushing the discussion about these subjects to a greater level;
- the knowledge database and field information was updated, now considering present facts, challenges and definitions of the petroleum industry.

Other contributions are:

- a survey was conducted to review the main issues in concept selection and to catalogue the existing methods;
- to address input uncertainties, it was employed fuzzy values in a Mamdani fuzzy system that considers the uncertainties through its fuzzifier;
- to address ambiguities, it was proposed a refine method similar to Siler and Buckley (2005) tailored to offshore production systems that resolves contradictions and retain other ambiguities. Later, it was observed that contradictions can be easily resolved through expert knowledge, such as demonstrated in Sapinhoá case study.

Regarding limitations and further research:

- the model does not fully integrate with the overall field development, neither directly determine revenues generated of the proposed solution;
- it is suggested to improve uncertainty analysis by employing type-2 fuzzy systems in a relevant way.

REFERENCES

2H OFFSHORE. **Subsea 7 EPCI Deepwater Riser System**. 2016. JPEG format. Available at: <https://web.archive.org/web/20190313172445if_/https://2hoffshore.com/wp-content/uploads/2016/01/SS7-EPCI-Deepwater-Riser-crop.jpg>

ACONA. **Riser types**. 2014. PNG image. Available at: <https://web.archive.org/web/20190313201608/https://aces.acona.com/ACES/Help/ACESmanual2014_files/image016.png>

AKEZE, A. C.; SIKANDAR, A. S.; LAFORCE, T. Uncertainty evaluation in field development and export planning. In: EUROPEC/EAGE ANNUAL CONFERENCE AND EXHIBITION. Amsterdam, The Netherlands: Society of Petroleum Engineers, 2009. https://doi.org/10.2118/121993-MS

ANDRADE, A. M. T. DE; VAZ, C. E. M.; RIBEIRO, J.; LOPREATO, L. G. R.; NASCIMENTO, R. F. S. DO. Offshore production units for Pre-Salt projects. In: OFFSHORE TECHNOLOGY CONFERENCE. Houston, United States of America: Offshore Technology Conference, 4 May 2015. https://doi.org/10.4043/25691-MS

ASRILHANT, B. A program for excellence in the management of exploration and production projects. In: OFFSHORE TECHNOLOGY CONFERENCE. Houston, United States of America: Offshore Technology Conference, 2005. https://doi.org/10.4043/17421-MS

BASILIO, L.; NORONHA, C.; PASSOS, M.; CALAZA, D.; NOVA, A. L. DA; DALY, R. Integrated design computational model applied to O&G offshore field development. In: OFFSHORE TECHNOLOGY CONFERENCE. Houston, United States of America: Offshore Technology Conference, 2018. https://doi.org/10.4043/28664-MS

BEHRENBRUCH, P. Offshore oilfield development planning. **Journal of Petroleum Technology**, v. 45, n. 08, p. 735–743, Aug. 1993. https://doi.org/10.2118/22957-PA

BOHI, D. R.; TOMAN, M. A. Analyzing nonrenewable resource supply. 1. ed. Washington, United States of America: RFF Press, 1984.

BORGHINI, S.; BARTOLOMEO, M.; MOLINARI, M.; RATTI, S. The role of environmental costs and liabilities in the decision making process of oil & gas exploration and production companies. In: SPE INTERNATIONAL CONFERENCE ON HEALTH, SAFETY AND ENVIRONMENT IN OIL AND GAS EXPLORATION AND PRODUCTION. Caracas, Venezuela: Society of Petroleum Engineers, 1998. https://doi.org/10.2118/46654-MS

BUREAU OF SAFETY AND ENVIRONMENTAL ENFORCEMENT (BSEE). **Deepwater Development Systems**. 2008. GIF image. Available at:

<https://web.archive.org/web/20161226191224/https://www.bsee.gov/sites/bsee.gov/files/photos/deepsys.gif?n=9972>

CASTRO, G. T.; MOROOKA, C. K.; BORDALO, S. N. Decision-making process for a deepwater production system considering environmental, technological and financial risks. In: SPE ANNUAL TECHNICAL CONFERENCE AND EXHIBITION. San Antonio, United States of America: Society of Petroleum Engineers, 2002. https://doi.org/10.2118/77423-MS

CEZAR, A. S. P.; PEREIRA, A. R.; DANIEL, L. L.; OAZEN, E. V.; TROVOADO, L. C.; ALMEIDA, M. C. DE. Subsea solutions in the Pre-Salt development projects. In: OFFSHORE TECHNOLOGY CONFERENCE. Houston, United States of America: Offshore Technology Conference, 4 May 2015. https://doi.org/10.4043/25773-MS

COCKCROFT, P. J.; GRANT, J. N.; MOORE, K. S.; WARNOHARDJO, G. N. Development planning: a systematic approach. In: SPE ASIA PACIFIC OIL AND GAS CONFERENCE. Melbourne, Australia: Society of Petroleum Engineers, 1994. https://doi.org/10.2118/28782-MS

COSTA, L. T.; LIMA, U. A. DE. Installation of manifolds - a success story. In: OTC BRASIL. Rio de Janeiro, Brazil: Offshore Technology Conference, 24 Oct. 2017. https://doi.org/10.4043/27967-MS

CULLICK, A. S.; CUDE, R.; TARMAN, M. Optimizing field development concepts for complex offshore production systems. In: OFFSHORE EUROPE. Aberdeen, United Kingdom: Society of Petroleum Engineers, 2007. https://doi.org/10.2118/108562-MS

DEKKER, M.; REID, D. Deepwater development strategy. In: OFFSHORE TECHNOLOGY CONFERENCE. Houston, United States of America: Offshore Technology Conference, 5 May 2014. https://doi.org/10.4043/25135-MS

DEVINE, M. D.; LESSO, W. G. Models for the minimum cost development of offshore oil fields. **Management Science**, v. 18, n. 8, p. B378–B387, 1972.

DEZEN, F.; MOROOKA, C. K. Real options applied to selection of technological alternative for offshore oilfield development. In: SPE ANNUAL TECHNICAL CONFERENCE AND EXHIBITION. San Antonio, United States of America: Society of Petroleum Engineers, 2002. https://doi.org/10.2118/77587-MS

DORGANT, P. L.; BALINT, S. W.; RODENBUSCH, G.; LUYTIES, W. H.; RAINEY, R. M. System selection for deepwater production installations. In: OFFSHORE TECHNOLOGY CONFERENCE. Houston, United States of America: Offshore Technology Conference, 2001. https://doi.org/10.4043/12966-MS

D'SOUZA, R.; BASU, S. Field development planning and floating platform concept selection for global deepwater developments. In: OFFSHORE TECHNOLOGY CONFERENCE.

Houston, United States of America: Offshore Technology Conference, 2011. https://doi.org/10.4043/21583-MS

DUBOIS, D.; PRADE, H. Possibility Theory and Its Applications: Where Do We Stand? In: KACPRZYK, J.; PEDRYCZ, W. (Eds.). **Springer Handbook of Computational Intelligence**. Springer Handbooks. Berlin, Heidelberg: Springer Berlin Heidelberg, 2015. p. 31–60.

ERLINGSEN, E.; STRAT, T.; GUNNERUD, V.; NYGREEN, B.; DUEÑAS DÍES, M. Decision support in long term planning of petroleum production fields. In: SPE INTELLIGENT ENERGY INTERNATIONAL. Utrecht, The Netherlands: Society of Petroleum Engineers, 2012. https://doi.org/10.2118/148861-MS

FONSECA, T. C. DA; MENDES, J. R. P.; MOROOKA, C. K.; GUILHERME, I. R. Definition of an offshore petroleum production system by using fuzzy sets and utility functions. **Journal of Advanced Computational Intelligence and Intelligent Informatics**, v. 9, n. 6, p. 684–692, 2005. https://doi.org/10.20965/jaciii.2005.p0684

FRANCO, K. P. M. Desenvolvimento de um sistema inteligente para auxiliar a escolha de sistema para produção no mar. MS thesis—Campinas, Brazil: University of Campinas, 2003.

GONZALEZ-CASTAÑO, L. J. Avaliação do aspecto logístico na seleção de um sistema marítimo de produção de petróleo. MS thesis—Campinas, Brazil: University of Campinas, 2017.

GRIMMETT, T. T.; STARTZMAN, R. A. Optimization of offshore field development to minimize investment. In: SPE HYDROCARBON ECONOMICS AND EVALUATION SYMPOSIUM. Dallas, United States of America: Society of Petroleum Engineers, 1987. https://doi.org/10.2118/16297-MS

HAMMETT, D. S.; JOHNSON, J. S.; WHITE, J. L. First floating production facility - Argyll. In: OFFSHORE TECHNOLOGY CONFERENCE. Houston, United States of America: Society of Petroleum Engineers, 1977. https://doi.org/10.4043/2821-MS

HATTON, S. Rigid risers for tanker FPSO’s. In: FPSO WORLD CONFERENCE. 1995.

HATTON, S. A.; BROWNRIDGE, J. Hybrid risers: a cost effective deepwater riser system? In: DEEPTEC ’95. Aberdeen, United Kingdom: 1995.

HAYASHI, S. H. D.; LIGERO, E. L.; SCHIOZER, D. J. Decision-making process in development of offshore petroleum fields. In: LATIN AMERICAN & CARIBBEAN PETROLEUM ENGINEERING CONFERENCE. Buenos Aires, Argentina: Society of Petroleum Engineers, 2007. https://doi.org/10.2118/107737-MS

HILL, T. When to use flexible pipe. 2017. Available at: <https://web.archive.org/web/20190126220659/http://www.ocean-flow.com/ofi-blog/2017/7/19/when-to-use-flexible-pipe>

HOLSEN, M.; KING, S. D. J.; STEINE, G. Use of economic measures as the criteria for optimising functional blocks and the selection of development concepts. In: OFFSHORE EUROPE. Aberdeen, United Kingdom: Society of Petroleum Engineers, 1993. https://doi.org/10.2118/26692-MS

IHS MARKIT. Decommissioning of aging offshore oil and gas facilities increasing significantly, with annual spending rising to $13 billion by 2040. 29 Nov. 2016. Available at: <https://web.archive.org/web/20181104055741/https://news.ihsmarkit.com/press-release/energy-power-media/decommissioning-aging-offshore-oil-and-gas-facilities-increasing-si>

KAISER, M. J.; SNYDER, B. F. Newbuild and replacement cost functions. 2012. Available at: <https://web.archive.org/web/20190126221246/https://www.ogj.com/articles/ogfj/print/volume-9/issue-9/features/newbuild-and-replacement-cost-functions.html>

LU, W.; YANG, Y.; LIU, J.; JIA, Z.; WANG, H. Comparison of different offshore oil field development concepts. In: SEVENTH ISOPE PACIFIC/ASIA OFFSHORE MECHANICS SYMPOSIUM. Dalian, China: International Society of Offshore and Polar Engineers, 2006.

LUSILIER. **Simplified drawings of three common systems used for the construction and installation of subsea pipelines (not to scale): S-lay, J-lay and reel.** 3 November 2013. PNG image. Available at: <https://commons.wikimedia.org/wiki/File:SubmarinePipelinesConstruction_Laybarge%26Towsystems.svg>

MADDAHI, M.; MORTAZAVI, S. J. A review on offshore concepts and feasibility study considerations. In: SPE ASIA PACIFIC OIL AND GAS CONFERENCE AND EXHIBITION. Jakarta, Indonesia: 2011. https://doi.org/10.2118/147875-MS

MARTINELLI, L.; RUOL, P.; CORTELLAZZO, G. On mooring design of wave energy converters: the seabreath application. **Coastal Engineering Proceedings**, v. 1, n. 33, p. 3, 15 Oct. 2012. https://doi.org/10.9753/icce.v33.structures.3

MATA, O. R. Model for economical analysis of oil and gas deepwater production concepts: comparisons of life cycle cost of subsea production systems vs. floating structures with dry wellheads. MS thesis—Stavanger, Norway: University of Stavanger, 2010.

MENDEL, J. M. Uncertain rule-based fuzzy systems: introduction and new directions. 2. ed. Los Angeles, California: Springer International Publishing, 2017.

MENTES, A.; HELVACIOGLU, I. H. An offshore platform selection approach for the Black Sea region. In: ASME 32ND INTERNATIONAL CONFERENCE ON OCEAN, OFFSHORE AND ARCTIC ENGINEERING. Nantes, France: American Society of Mechanical Engineers, 2013. https://doi.org/10.1115/OMAE2013-11319

METHVEN, J. O. The Argyll field life cycle with cost control as the operator’s Ethos. In: OFFSHORE EUROPEAN CONFERENCE. Aberdeen, United Kingdom: Society of Petroleum Engineers, 1993. https://doi.org/10.2118/26690-MS

MOROOKA, C. K.; GALEANO, Y. D. Systematic design for offshore oilfield development. In: NINTH INTERNATIONAL OFFSHORE AND POLAR ENGINEERING CONFERENCE. Brest, France: The International Society of Offshore and Polar Engineers, 1999.

NANDURDIKAR, N. S.; KIRKHAM, P. M. The economic folly of chasing schedules in oil developments and the unintended consequences of such strategies. In: SPE HYDROCARBON ECONOMICS AND EVALUATION SYMPOSIUM. Calgary, Canada: Society of Petroleum Engineers, 2012. https://doi.org/10.2118/162878-MS

NAVEIRO, J. T.; HAIMSON, D. Sapinhoá field, Santos Basin Pre-Salt: from conceptual design to project execution and results. In: OFFSHORE TECHNOLOGY CONFERENCE BRASIL. Rio de Janeiro, Brazil: 2015. https://doi.org/10.4043/26320-MS

OFFSHORE MAGAZINE. Reeled rigid riser installation can cut Roncador development costs. 2000. Available at: <https://web.archive.org/web/20190126222006/https://www.offshore-mag.com/articles/print/volume-60/issue-1/news/general-interest/reeled-rigid-riser-installation-can-cut-roncador-development-costs.html>

OGAWA, Y.; BAI, W.; HAUTECLOCQUE, G. DE; DHAVALIKAR, S.; FANG, C.-C.; FONSECA, N.; HÄNNINEN, S.; JOHANNESSEN, T. B.; LIEN, V.; MOROOKA, C.; MUMM, H.; PRPIC-ORSIC, J.; HYUN SONG, K.; TIAN, C.; UĞURLU, B.; WANG, S. Loads. In: 20TH INTERNATIONAL SHIP AND OFFSHORE STRUCTURES CONGRESS. Amsterdam, The Netherlands: IOS Press, 2018. https://doi.org/10.3233/978-1-61499-862-4-101

OSYPOV, K.; IVANOVA, N.; YANG, Y.; FOURNIER, A.; NICHOLS, D.; BACHRACH, R.; YARMAN, C. E.; NIKOLENKO, D. Assessing E&P and drilling risks with seismic uncertainty analysis. In: INTERNATIONAL PETROLEUM TECHNOLOGY CONFERENCE. Beijing, China: International Petroleum Technology Conference, 2013. https://doi.org/10.2523/IPTC-16817-MS

REID, D.; DEKKER, M.; NUNEZ, D. Deepwater development: wet or dry tree? In: OFFSHORE TECHNOLOGY CONFERENCE BRASIL. Rio de Janeiro, Brazil: Offshore Technology Conference, 2013. https://doi.org/10.4043/24517-MS

ROACH, W. J. F.; KNIGHT, V. C.; LOCHTE, G. E.; KIBBEE, S. E.; MACKINTOSH, N. Morpeth field development overview. In: OFFSHORE TECHNOLOGY CONFERENCE. Beijing, China: Offshore Technology Conference, 1999. https://doi.org/10.4043/10854-MS

RONALDS, B. F. Deepwater facility selection. In: OFFSHORE TECHNOLOGY CONFERENCE. Houston, United States of America: Offshore Technology Conference, 2002a. https://doi.org/10.4043/14259-MS

RONALDS, B. F. Surface production system options for deepwater. In: 21ST INTERNATIONAL CONFERENCE ON OFFSHORE MECHANICS AND ARCTIC ENGINEERING. Oslo, Norway: American Society of Mechanical Engineers, 2002b. https://doi.org/10.1115/OMAE2002-28143

RONALDS, B. F. Production facility choices for moderate water depths. In: 23RD INTERNATIONAL CONFERENCE ON OFFSHORE MECHANICS AND ARCTIC ENGINEERING. Vancouver, British Columbia, Canada: American Society of Mechanical Engineers, 2004. https://doi.org/10.1115/OMAE2004-51053

RONALDS, B. F. Applicability ranges for offshore oil and gas production facilities. **Marine Structures**, v. 18, n. 3, p. 251–263, 2005a. https://doi.org/10.1016/j.marstruc.2005.06.001

RONALDS, B. F. Reducing cycle time to first oil for deepwater field developments. In: 24TH INTERNATIONAL CONFERENCE ON OFFSHORE MECHANICS AND ARCTIC ENGINEERING. Halkidiki, Greece: ASME, 2005b. https://doi.org/10.1115/OMAE2005-67016

ROSS, T. J. Fuzzy logic with engineering applications. 3. ed. Chichester, England: John Wiley & Sons, 2010.

RUIVO, F. DE M. Descomissionamento de sistemas de produção offshore. MS thesis—Campinas, Brazil: University of Campinas, 2001.

SAPUTELLI, L. A.; LUJAN, L.; GARIBALDI, L.; SMYTH, J.; UNGREDDA, A.; RODRIGUEZ, J.; CULLICK, S. How integrated field studies help asset teams make optimal field development decisions. In: SPE WESTERN REGIONAL AND PACIFIC SECTION AAPG JOINT MEETING. Bakersfield, California: Society of Petroleum Engineers, 2008. https://doi.org/10.2118/110250-MS

SATTER, A.; VARNON, J. E.; HOANG, M. T. Integrated reservoir management. **Journal of Petroleum Technology**, v. 46, n. 12, p. 1,057-1,064, 1994. https://doi.org/10.2118/22350-PA

SILER, W.; BUCKLEY, J. J. Fuzzy expert systems and fuzzy reasoning. 1. ed. Hoboken, New Jersey: John Wiley & Sons, 2005.

SMYTH, J.; RUSIN, P.; GARCIA, J.; CULLICK, S. Rapid optimization of development scenarios for multiple exploration prospects using integrated asset modeling. In: SPE LATIN AMERICAN AND CARIBBEAN PETROLEUM ENGINEERING CONFERENCE. Lima, Peru: Society of Petroleum Engineers, 2010. https://doi.org/10.2118/138431-MS

SOLBERG, L. Veslefrikk field development concept. In: OFFSHORE TECHNOLOGY CONFERENCE. Houston, United States of America: Offshore Technology Conference, 1990. https://doi.org/10.4043/6303-MS

SUBSEAIQ. Bullwinkle. 2011. Available at: <https://web.archive.org/web/20101113165939/http://www.subseaiq.com/data/Project.aspx?project_id=136&AspxAutoDetectCookieSupport=1>

SUBSEAIQ. Buzzard. 2012. Available at: <http://www.subseaiq.com/data/Project.aspx?project_id=237>

SUGENO, M.; KANG, G. T. Structure identification of fuzzy model. **Fuzzy Sets and Systems**, v. 28, n. 1, p. 15–33, 1988. https://doi.org/10.1016/0165-0114(88)90113-3

TAKAGI, T.; SUGENO, M. Fuzzy identification of systems and its applications to modeling and control. **IEEE Transactions on Systems, Man, and Cybernetics**, v. SMC-15, n. 1, p. 116–132, 1985. https://doi.org/10.1109/TSMC.1985.6313399

TUCKER, R. L.; ROOBAERT, N. C. Geisum field development. In: OFFSHORE TECHNOLOGY CONFERENCE. Houston, United States of America: Offshore Technology Conference, 1986. https://doi.org/10.4043/5093-MS

WU, Y.; LU, R.; WANG, T.; VIJAYARAGHAVAN, V.; EIDE, R. Hull, mooring and riser concept selection for deepwater field development in offshore Northwest Australia. In: OFFSHORE TECHNOLOGY CONFERENCE. Houston, United States of America: Offshore Technology Conference, 2016. https://doi.org/10.4043/26907-MS

XIA, J.; D'SOUZA, R. Floating production platform selection for developing deepwater gas fields off North West Australia. In: SPE ASIA PACIFIC OIL AND GAS CONFERENCE AND EXHIBITION. Perth, Australia: Society of Petroleum Engineers, 2012. https://doi.org/10.2118/158717-MS

ZADEH, L. A. Fuzzy sets. **Information and Control**, v. 8, n. 3, p. 338–353, 1965. https://doi.org/10.1016/S0019-9958(65)90241-X

ZIMMERMANN, H. J. Possibility Theory vs. Probability Theory. In: **Fuzzy Set Theory — and Its Applications**. International Series in Management Science/Operations Research. Dordrecht, Netherlands: Springer Netherlands, 1985. p. 103–118.

APPENDIX A – A SIMPLE FUZZY EXAMPLE

For the sake of clarity, it will be presented a comprehensive example of the use of this method. The objective is to determine what sport is more appropriate to do today. We may model this problem as a single decision component with a rule base consisting of four rules:

$$\begin{gathered}
R_1\!: IF\ x_1 = \ temperature\ is\ F_1^1 = cold\ and\ x_2 = weather\ is\ F_2^1 \\
= clear, THEN\ y = sport\ is\ G^1 = skiing \\
R_2\!: IF\ x_1 = temperature\ is\ F_1^2 = cold\ and\ x_2 = weather\ is\ F_2^2 \\
= rainy, THEN\ y = sport\ is\ G^2 = basketball \\
R_3\!: IF\ x_1 = temperature\ is\ F_1^3 = warm\ and\ x_2 = weather\ is\ F_2^3 \\
= \text{clear}, THEN\ y = sport\ is\ G^3 = swimming \\
R_4\!: IF\ x_1 = \ temperature\ is\ F_1^4 = warm\ and\ x_2 = weather\ is\ F_2^4 \\
= rainy, THEN\ y = sport\ is\ G^4 = basketball
\end{gathered} \tag{A1}$$

First, let's consider that this rule base is part of 1) an expert system with crisp inputs, 2) a fuzzy system with crisp inputs and 3) a fuzzy system with fuzzy inputs. In the first model, no uncertainties are taken into account and even a very light rain could abruptly and completely change the sport recommended. In the second model, the system can gradually change the recommendation as a human would do; however, uncertainties in temperature and weather forecast (i.e. measurement uncertainty) are not considered. The third both considers gradual changes and input uncertainties better than the first two, making it more robust.

Equations (20) through (23) describe the membership functions of each antecedent. Here, the initial input is crisp, given by $\boldsymbol{x} = (24°C, 0\ mm/hour)$.

$$\mu_{Cold}(x_1) = \begin{cases} (26 - x_1)/11\,, if\ 15 \le x_1 \le 26 \\ 1, if - 20 \le x_1 < 15 \\ 0, if\ x_1 > 26\ or\ x_1 < -20 \end{cases} , x_1 \in Temperature\ (°C) \tag{A2}$$

$$\mu_{Warm}(x_1) = \begin{cases} (x_2 - 15)/11\,, if\ 15 \le x_1 \le 26 \\ 1, if\ 26 < x_1 \le 50 \\ 0, if\ x_1 > 50\ or\ x_1 < 15 \end{cases} , x_1 \in Temperature\ (°C) \tag{A3}$$

$$\mu_{Clear}(x_2) = \begin{cases} (8 - x_2)/7\,, if\ 1 \le x_2 \le 8 \\ 1, if\ 0 \le x_2 < 1 \\ 0, if\ x_2 > 8\ or\ x_2 < 0 \end{cases} , x_2 \in Weather\ (mm/hour) \tag{A4}$$

$$\mu_{Rain}(x_2) = \begin{cases} (x_1 - 2)/8, if\ 2 \leq x_2 \leq 10 \\ 1, if\ 10 < x_2 \leq 50 \\ 0, if\ x_2 > 50\ or\ x_2 < 2 \end{cases}, x_2 \in Weather\ (mm/hour) \tag{A5}$$

Using the fuzzifier, we obtain the following membership grades: $\mu_{\text{Cold}}(x_1) = 0.18$, $\mu_{\text{Warm}}(x_1) = 0.82$, $\mu_{\text{Clear}}(x_2) = 1$, $\mu_{\text{Rain}}(x_2) = 0$. The ambiguity in the alternatives is then calculated as

$$\alpha = \frac{\sum_i \mu_i}{\max_i \mu_i} = \frac{0.18 + 0 + 0.82 + 0}{0.82} = 1.22 \tag{A6}$$

As $\lfloor \alpha + 0.5 \rfloor$ alternatives are selected, we select $\lfloor 1.22 + 0.50 \rfloor = 1$ alternative with the highest membership grade, which is swimming. There is no ambiguities: it is a clear and warm day, thus swimming is recommended. Now, if we were uncertain about whether it would rain or not, we could enter a triangular fuzzy input with full membership at 4.8 mm/hour with a spread of 3 mm/hour:

$$\mu_{\text{X}_2}(x_2) = \begin{cases} (x_2 - 1.8)/3, if\ 1.8 \leq x_2 \leq 4.8 \\ (7.8 - x_2)/3, if\ 4.8 < x_2 \leq 7.8 \\ 0, if x_2 > 7.8\ or\ x_2 < 1.8 \end{cases} \tag{A7}$$

Then, we would obtain the following membership grades: $\mu_{\text{Cold}}(x_1) = 0.18$, $\mu_{\text{Warm}}(x_1) = 0.82$, $\mu_{\text{Clear}}(x_2) = 0.62$, $\mu_{\text{Rain}}(x_2) = 0.53$. The ambiguity is then calculated as

$$\alpha = \frac{0.18 + 0.18 + 0.62 + 0.53}{0.62} = 2.44 \tag{A8}$$

As $\lfloor \alpha + 0.5 \rfloor$ alternatives are selected, we select $\lfloor 2.44 + 0.50 \rfloor = 2$ alternatives with the highest membership grade, which are swimming and basketball. As these two alternatives have almost the same membership grade due to an uncertainty in the weather variable, we cannot simply choose one over another.

The first step to resolve this contradiction is to review the membership functions and rules used so far to evaluate if we can generate scenarios with fewer uncertainties. In this scenario, we could easily add linguistic terms for the weather variable, such as light rain, medium rain and heavy rain, and add rules regarding these new terms. This manner, we would have specific decisions for light, medium and heavy rain, and the contradiction about the sport would certainly disappear.

If reviewing the membership functions and rules is unfeasible, the next step is to obtain additional data to distinguish among contradictions. For example, if swimming is on the beach, we could add variables such as the average wave size, the number of friends that are going to either sport, the crowdedness of the basketball court or the beach, among others. One or more of such variables could lean the decision to one alternative or another.

The third step would be determining what is the cheapest option for us. Perhaps the basketball court is too far away, and even if rains a bit while swimming, it would worth the savings in transportation. Finally, the last resort for a contradiction is choosing the alternative with the highest grade, keeping in mind that it may not be the best option.

APPENDIX B – KNOWLEDGE BASE

Figures

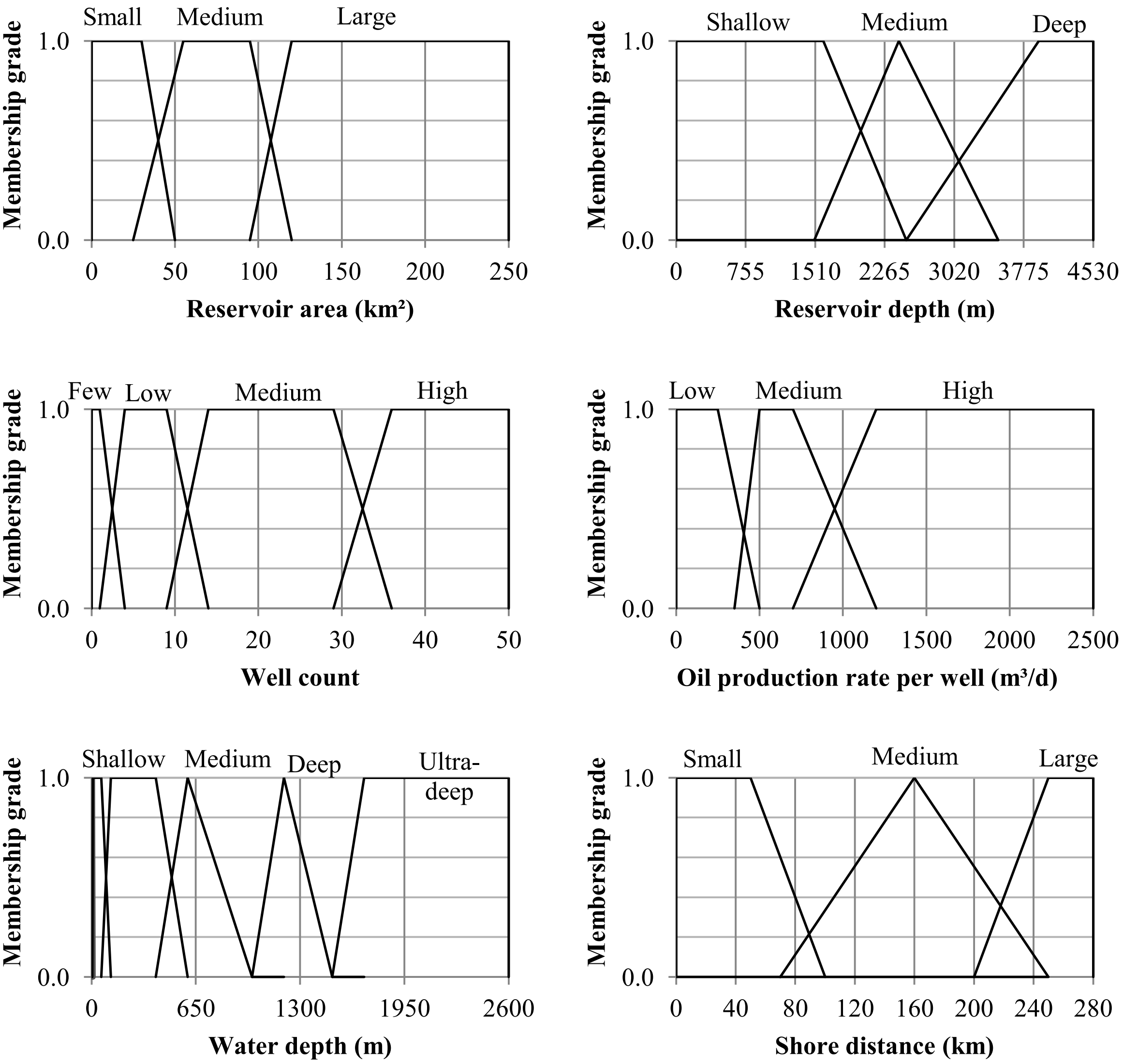


Figure B1. Membership functions of the input functions considered in this study.

Tables

Table B1. Rule base for the well arrangement decision component.

Well count	Well type	Reservoir area	Well arrangement
Few Low, Medium or High Low or Medium	Vertical or Directional Vertical Directional	Medium or Large Medium or Large Large	Satellite
Few Low or Medium Low or Medium High High	Vertical or Directional Vertical Directional Vertical Directional	Small Small Small or Medium Small Small, Medium or Large	Clustered

Table B2. Rule base for the storage capacity decision component.

Host system	Storage capacity
Barge Compliant tower	Low
Jackup Jacket TLP SS	Medium
GBS Spar FPSO	High

Table B3. Rule base for the production manifold use decision component.

Well arrangement	Water depth	Reservoir area	Well count	Oil production rate per day	Production manifold use
Satellite	Mod. Shallow, Shallow or Medium	Small, Med. or Large	High	Low, Med. or High	Yes
Satellite	Medium	Small, Med. or Large	Medium	High	
Satellite	Deep	Small	Medium	Medium or High	
Satellite	Deep	Small, Med. or Large	High	Low or Medium	
Satellite	Deep	Medium or Large	Med. or High.	High	
Satellite	Ultra-deep	Small, Med. or Large	Medium	High	
Satellite	Ultra-deep	Small, Med. or Large	High	Low, Med. or High	
Clustered	Mod. Sha.	Small	High	Low, Med. or High	
Clustered	Mod. Sha.	Large	Med. or High.	High	
Clustered	Mod. Sha.	Large	High	Low or Medium	
Clustered	Shallow	Small or Medium	Med. or High	Med. or High	
Clustered	Shallow	Large	Low, Med. or Hi.	Low, Med. or High	
Clustered	Shallow	Small or Medium	High	Low	
Clustered	Shallow	Large	Low, Med. or Hi.	Low, Med. or High	
Clustered	Shallow	Small	Medium or High	Low, Med. or High	
Clustered	Medium	Small	High	Medium or High	
Clustered	Medium	Medium or Large	Medium or Large	Low, Med. or High	
Clustered	Deep	Small	Medium or High	Low, Med. or High	
Clustered	Deep	Medium	Medium or High	Medium or High	
Clustered	Deep	Medium	Low	High	
Clustered	Deep	Medium	High	Low	
Clustered	Deep	Large	Few	Medium or High	
Clustered	Deep or Ultra-deep	Large	Low, Med. or Hi.	Low, Med. or High	
Clustered	Ultra-deep	Small or Medium	Low	Medium or High	
Clustered	Ultra-deep	Small or Medium	Medium or High	Low, Med. or High	
Clustered	Ultra-deep	Large	Few	High	

Table B3. Rule base for the production manifold use decision component (Continuation).

Well arrangement	**Water depth**	**Reservoir area**	**Well count**	**Oil production rate per day**	**Production manifold use**
Satellite or Clustered	Very shallow	Small, Med. or Large	Few, Low, Med. or Hi.	Low, Med. or High	No
Satellite or Clustered	Mod. shallow, Shallow	Small, Med. or Large	Few, Low or Medium	Low, Med. or High	
Satellite	Medium	Small or Medium	Few, Low or Medium	Low, Med. or High	
Satellite	Medium	Large	Few or Low	Low, Med. or High	
Satellite	Medium	Large	Medium	Low or Medium	
Satellite	Deep or Ultra-deep	Small, Med. or Large	Few or Low	Low, Med. or High	
Satellite	Deep	Small, Med. or Large	Medium	Low	
Satellite	Deep	Small	High	High	
Satellite	Deep	Medium or Large	Medium	Low or Medium	
Satellite	Ultra-deep	Small, Med. or Large	Medium	Low or Medium	
Clustered	Mod. Shallow	Large	Medium	Low or Medium	
Clustered	Shallow	Small or Medium	Few or Low	Low, Med. or High	
Clustered	Shallow	Small or Medium	Medium	Low	
Clustered	Shallow	Large	Few	Low, Med. or High	
Clustered	Medium	Small, Med. or Large	Few or Low	Low, Med. or High	
Clustered	Deep	Small	Few or Low	Low, Med. or High	
Clustered	Deep	Medium	Few	Low, Med. or High	
Clustered	Deep	Medium	Low	Low or Medium	
Clustered	Deep	Medium	Medium	Low	
Clustered	Deep	Large	Few	Low	
Clustered	Ultra-deep	Small	Few	Low, Med. or High	
Clustered	Ultra-deep	Small	Low	Low	
Clustered	Ultra-deep	Medium	Few	Low, Med. or High	
Clustered	Ultra-deep	Medium	Low	Low	
Clustered	Ultra-deep	Large	Few	Low or Medium	

Table B4. Rule base for the host system decision component.

Water depth	**Offloading**	**Environmental conditions**	**Well count**	**Oil production rate per well**	**Host system**
Very shallow	Pipeline or Shuttle tanker	Mild, Moderate or Severe	Few, Low, Medium or High	Low, Medium or High	Barge
Moderately shallow	Pipeline	Mild	Few	Low, Medium or High	Jackup
Moderately shallow	Pipeline	Mild	Low	Low or Medium	
Moderately shallow	Pipeline	Mild, Moderate or Severe	Medium	Low	
Moderately shallow	Pipeline	Moderate	Few	Low, Medium or High	
Moderately shallow	Pipeline	Moderate	Low	Low or Medium	
Moderately shallow	Pipeline	Severe	Few or Low	Low or Medium	
Moderately shallow	Shuttle tanker	Moderate	Few	Low, Medium or High	
Moderately shallow	Shuttle tanker	Moderate	Low	Low or Medium	
Moderately shallow	Shuttle tanker	Moderate or Severe	Medium	Low	
Moderately shallow	Shuttle tanker	Severe	Few or Low	Low, Medium or High	
Moderately shallow	Pipeline	Mild or Moderate	Low	High	Jacket
Moderately shallow	Pipeline	Moderate	Medium	Medium	
Moderately shallow	Pipeline	Mild	Medium	Medium or High	
Moderately shallow	Pipeline	Mild	High	Low, Medium or High	
Moderately shallow	Pipeline	Severe	Few or Low	High	
Moderately shallow	Pipeline	Severe	Medium	Medium or High	
Moderately shallow	Pipeline	Severe	High	Low, Medium or High	
Moderately shallow	Shuttle tanker	Mild	Few, Low or Medium	Low	
Moderately shallow	Shuttle tanker	Moderate or Severe	Medium	Medium	
Moderately shallow	Shuttle tanker	Moderate	Low	High	
Moderately shallow	Shuttle tanker	Severe	Medium	High	
Moderately shallow	Shuttle tanker	Severe	High	Low, Medium or High	
Shallow	Pipeline	Mild	Few or Low	Low, Medium or High	
Shallow	Pipeline	Mild	Medium	Low or Medium	
Shallow	Pipeline	Moderate	Few	Low, Medium or High	
Shallow	Pipeline	Moderate	Low	Low or Medium	
Shallow	Pipeline	Severe	Few or Low	Low, Medium or High	
Shallow	Pipeline	Severe	Medium or High	Low	
Shallow	Shuttle tanker	Moderate	Few or Low	High	
Shallow	Shuttle tanker	Severe	Few or Low	Low, Medium or High	
Shallow	Shuttle tanker	Severe	Medium	Low or Medium	
Shallow	Shuttle tanker	Severe	High	Low	

Table B4. Rule base for the host system decision component (Continuation).

Water depth	**Offloading**	**Environmental conditions**	**Well count**	**Oil production rate per well**	**Host system**
Shallow	Shuttle tanker	Mild	High	Medium or High	GBS
Shallow	Shuttle tanker	Moderate	Medium	High	
Shallow	Shuttle tanker	Moderate or Severe	High	Medium or High	
Shallow	Shuttle tanker	Severe	Medium	High	
Shallow	Shuttle tanker	Severe	High	Medium or High	
Shallow	Pipeline	Moderate	Low, Medium and High	High	Compliant Tower
Shallow	Pipeline	Moderate	High	Medium	
Medium	Shuttle tanker	Severe	Few and Low	High	Spar
Medium	Shuttle tanker	Severe	Medium	Medium and High	
Deep	Pipeline	Severe	Few or Low	High	
Deep	Pipeline	Severe	Medium	Medium or High	
Deep	Shuttle tanker	Moderate	Few or Low	High	
Deep	Shuttle tanker	Severe	Few	Medium	
Deep	Shuttle tanker	Severe	Few or Low	High	
Deep	Shuttle tanker	Severe	Medium	Medium or High	
Ultra-deep	Pipeline	Moderate	Few or Low	High	
Ultra-deep	Pipeline	Moderate	Medium	High	
Ultra-deep	Pipeline	Severe	Few or Low	High	
Ultra-deep	Pipeline	Severe	Medium	Medium or High	
Ultra-deep	Shuttle tanker	Moderate	Few or Low	High	
Ultra-deep	Shuttle tanker	Moderate	Medium	Medium or High	
Ultra-deep	Shuttle tanker	Severe	Few or Low	High	
Ultra-deep	Shuttle tanker	Severe	Medium	Medium or High	
Shallow	Pipeline	Severe	Medium or High	Medium or High	TLP
Medium	Pipeline	Severe	Few, Low, Medium or High	Low, Medium or High	
Medium	Shuttle tanker	Severe	Few	Low or Medium	
Medium	Shuttle tanker	Severe	Low	Low	
Medium	Shuttle tanker	Severe	Low	Medium	
Medium	Shuttle tanker	Severe	Medium	Low	
Medium	Shuttle tanker	Severe	High	Low, Medium or High	
Deep	Pipeline	Severe	Few	Low or Medium	
Deep	Pipeline	Severe	Low	Low or Medium	
Deep	Pipeline	Severe	Medium	Low	
Deep	Pipeline	Severe	High	Low, Medium or High	

Table B4. Rule base for the host system decision component (Continuation).

Water depth	**Offloading**	**Environmental conditions**	**Well count**	**Oil production rate per well**	**Host system**
Moderately shallow	Pipeline	Moderate	Medium	High	SS
Moderately shallow	Pipeline	Moderate	High	Low, Medium or High	
Moderately shallow	Shuttle tanker	Moderate	Medium	High	
Moderately shallow	Shuttle tanker	Moderate	High	Low, Medium or High	
Shallow	Pipeline	Mild	Medium	High	
Shallow	Pipeline	Mild	High	Low, Medium or High	
Shallow	Pipeline	Moderate	Medium	Low or Medium	
Shallow	Pipeline	Moderate	High	Low	
Shallow	Shuttle tanker	Moderate	Few or Low	Low	
Shallow	Shuttle tanker	Moderate	Few	Medium	
Shallow	Shuttle tanker	Moderate	Low	Medium	
Shallow	Shuttle tanker	Moderate	Medium	Low	
Medium	Pipeline	Mild	Medium	High	
Medium	Pipeline	Mild	High	Low, Medium or High	
Medium	Pipeline	Moderate	Few, Low, Medium or High	Low, Medium or High	
Medium	Shuttle tanker	Moderate	Few, Low, Medium or High	Low, Medium or High	
Deep	Pipeline	Moderate	Few, Low, Medium or High	Low, Medium or High	
Deep	Shuttle tanker	Moderate	Few or Low	Low or Medium	
Deep	Shuttle tanker	Moderate	Medium	Low or High	
Ultra-deep	Pipeline	Mild	Few, Low, Medium or High	Low, Medium or High	
Ultra-deep	Pipeline	Moderate	High	Low or Medium	

Table B4. Rule base for the host system decision component (Continuation).

Water depth	**Offloading**	**Environmental conditions**	**Well count**	**Oil production rate per well**	**Host system**
Moderately shallow	Shuttle tanker	Mild	Few, Low or Medium	Medium or High	FPSO
Moderately shallow	Shuttle tanker	Mild	High	Low, Medium or High	
Shallow	Shuttle tanker	Mild	Few, Low or Medium	Low, Medium or High	
Shallow	Shuttle tanker	Mild	High	Low	
Shallow	Shuttle tanker	Moderate	Medium	Medium	
Shallow	Shuttle tanker	Moderate	High	Low	
Medium	Pipeline	Mild	Few or Low	Low, Medium or High	
Medium	Pipeline	Mild	Medium	Low or Medium	
Medium or Deep	Shuttle tanker	Mild	Few, Low, Medium or High	Low, Medium or High	
Deep	Pipeline	Mild	Few, Low, Medium or High	Low, Medium or High	
Deep	Shuttle tanker	Moderate	Medium	Medium	
Deep	Shuttle tanker	Moderate	High	Low, Medium or High	
Deep	Shuttle tanker	Severe	Few or Low	Low	
Deep	Shuttle tanker	Severe	Low	Medium	
Deep	Shuttle tanker	Severe	Medium	Low	
Ultra-deep	Pipeline	Moderate	Few	Low	
Ultra-deep	Pipeline	Moderate	Few or Low	Medium	
Ultra-deep	Pipeline	Moderate	Low or Medium	Low	
Ultra-deep	Pipeline	Moderate	Medium	Medium	
Ultra-deep	Pipeline	Moderate	High	High	
Ultra-deep	Pipeline	Severe	Few or Low	Low or Medium	
Ultra-deep	Pipeline	Severe	Medium	Low	
Ultra-deep	Pipeline	Severe	High	Low, Medium or High	
Ultra-deep	Pipeline	Mild	Few, Low, Medium or High	Low, Medium or High	
Ultra-deep	Shuttle tanker	Moderate	Few or Low	Low or Medium	
Ultra-deep	Shuttle tanker	Moderate	Medium	Low	
Ultra-deep	Shuttle tanker	Moderate	High	Low, Medium or High	
Ultra-deep	Shuttle tanker	Severe	Few or Low	Low or Medium	
Ultra-deep	Shuttle tanker	Severe	Medium	Low	
Ultra-deep	Shuttle tanker	Severe	High	Low, Medium or High	

Table B5. Rule base for the riser decision component.

Host system	Water depth	Environmental conditions	Riser
Jackup, Jacket or Compliant tower	Moderately shallow, Shallow, Medium	Mild, Moderate or Severe	Rigid
Jacket	Deep	Mild, Moderate or Severe	
GBS	Moderately shallow, Shallow, Medium	Mild, Moderate or Severe	
Compliant tower	Deep	Mild, Moderate or Severe	
Spar	Medium	Mild or Moderate	
Spar	Deep or Ultra-deep	Mild, Moderate or Severe	
TLP	Shallow	Mild or Moderate	
TLP	Medium, Deep or Ultra-deep	Mild, Moderate or Severe	
SS	Ultra-deep	Moderate or Severe	
FPSO	Ultra-deep	Moderate	
SS or FPSO	Deep or Ultra-deep	Mild	Hybrid
Barge	Very shallow	Mild	Flexible
Spar	Medium	Severe	
TLP	Shallow	Severe	
SS or FPSO	Moderately shallow, Shallow, Medium	Mild, Moderate or Severe	
SS or FPSO	Deep	Moderate or Severe	
FPSO	Ultra-deep	Severe	

Table B6. Rule base for the mooring decision component.

Host system	Well arrangement	Well count	Mooring
Barge, Spar, Jackup or SS	Satellite or Clustered	Few, Low, Medium or High	Conventional
FPSO	Satellite	Few, Low, Medium or High	
FPSO	Clustered	High	
FPSO	Clustered	Low or Medium	Turret
TLP	Clustered	Low or Medium	Tethered
Compliant tower	Satellite or Clustered	Few, Low, Medium or High	Lead Cable
Jacket or GBS	Satellite or Clustered	Few, Low, Medium or High	Nothing
TLP	Satellite	Few, Low, Medium or High	Impossible
TLP	Clustered	High	

Table B7. Rule base for the offloading decision component.

Infrastructure near	Distance to coast	Well count	Oil production rate per well	Offloading
Yes No	Small, Medium or Large Medium	Few, Low, Medium or High Medium or High	Low, Medium or High High	Pipeline
No No No	Small and Large Medium Medium and High	Few, Low, Medium or High Few and Low Medium or High	Low, Medium or High Low, Medium or High Low or Medium	Shuttle tanker

Table B8. Rule base for the offloading system decision component.

Offloading	Storage capacity	Well count	Oil production rate per well	Offloading system
Pipeline	Low, Medium or High	Few, Low, Medium or High	Low, Medium or High	Pipeline
Shuttle tanker	Medium Medium High	Few or Low Medium Few, Low, Medium or High	Low, Medium or High Low Low, Medium or High	Internal storage
Shuttle tanker	Low Medium Medium	Few, Low, Medium or High Medium or High High	Low, Medium or High Medium or High Low	Offloading tank

Table B9. Rule base for the decommissioning decision component.

Water depth	Host system	Distance to coast	Decommissioning
Very shallow Moderately shallow Shallow Shallow and Medium Deep Ultra-deep	Barge Jackup, SS, FPSO Jacket, GBS TLP, SS and FPSO Spar, TLP, SS and FPSO Spar, SS and FPSO	Small, Medium or Large Small, Medium or Large Small, Medium Small, Medium or Large Small, Medium or Large Small, Medium or Large	Complete removal
Shallow Shallow	Jacket or GBS Compliant tower	Large Small, Medium or Large	Partial removal