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DECISION-MAKING OF SPARE SUBSEA TREES WITH MULTI-RESTRICTIVE FACTORS IN DEEPWATER DEVELOPMENT

PODEJMOWANIE DECYZJI DOTYCZĄCYCH WYKORZYSTANIA ZAPASOWYCH PODMORSKICH GŁOWIC EKSPLOATACYJNYCH W PROCESIE ZAGOSPODAROWYWANIA OBSZARÓW PODMORSKICH. MODEL UWZGLĘDNIAJĄCY LICZNE CZYNNIKI OGRANICZAJĄCE

In order to quantify the influential factors of subsea trees' maintenance proactively, multiple restrictive factors first are elaborated, such as locale meteorological conditions (i.e. weather), transport resources, heavy intervention vessels, maintenance technicians, spare trees and so on. Then, the focus is on three vital factors: weather, intervention vessel and spare trees. These restrictions dramatically impact the cost and accessibility of maintenance. For the inaccessible duration of significant wave height in weather model for computing non-feasibility days, we utilized the statistic data from the ERA Interim dataset. An analytical model is established to simplify the calculation of maintenance costs. As the predictive maintenances are seldom performed in subsea field, the built maintenance model only considers the corrective maintenance. Results show that hostile weather as well as the shortage of adequate spare subsea trees can induce severe downtime cost. The comparison of two contractual alternatives indicates that the better way to reduce the maintenance cost is to make the intervention vessel available enough. It is significant to provide quantitative views of subsea maintenance and to supply a method for the decision-making of spare subsea trees with multiple restrictive factors from the proposed model.

Keywords: *intervention vessel, maintenance model, restrictive factors, spare demand, subsea tree, weather prediction.*

Aby móc dokonać aktywnej oceny ilościowej liczących się czynników utrzymania podmorskich głowic eksploatacyjnych, najpierw zbadano wiele czynników ograniczających, takich jak lokalne warunki pogodowe oraz dostępność środków transportu, statków interwencyjnych o dużym tonażu, techników utrzymania ruchu, zapasowych głowic eksploatacyjnych, itd. Następnie skupiono uwagę na trzech kluczowych czynnikach: pogodzie oraz dostępności statku interwencyjnego oraz dostępności zapasowych głowic eksploatacyjnych. Ograniczenia związane z tymi czynnikami znacząco wpływają na koszty i możliwości konserwacji. Do obliczenia okresów,w których wysokie fale uniemożliwiają prace konserwacyjne wykorzystano dane statystyczne pochodzące z bazy danych ERA Interim. Stworzono model analityczny pozwalający na uproszczenie obliczeń kosztów utrzymania ruchu. Ponieważ na podmorskich polach naftowych rzadko wykonuje się zabiegi predykcyjnego utrzymania ruchu, skonstruowany przez nas model utrzymania ruchu uwzględnia jedynie utrzymanie naprawcze. Wyniki pokazują, że niekorzystne warunki pogodowe, jak również brak odpowiednich zapasowych głowic eksploatacyjnych mogą generować wysokie koszty związane z przestojami. Porównanie dwóch alternatyw pokazuje, że najlepszym sposobem na zmniejszenie kosztów utrzymania ruchu jest zapewnienie dostatecznej dostępności statku interwencyjnego. Proponowany model umożliwia ilościowy ogląd utrzymania ruchu w warunkach podmorskich i może być wykorzystany w procesie podejmowania decyzji dotyczących wykorzystania zapasowych podmorskich głowic eksploatacyjnych uwzględniającym wiele czynników ograniczających.

Słowa kluczowe*: Statek interwencyjny, model konserwacji, czynniki ograniczające, zapotrzebowanie na części zapasowe, podmorska głowica eksploatacyjna, prognozowanie pogody.*

1. Introduction

Subsea production system has become more and more popular in the process of deepwater development, since it is considered as the most suitable mode for deepwater production. Subsea tree is an important production package in subsea production system as seen in Fig. 1. It offers a number of functionalities, such as production regulation, chemical injection, especially safety control. Well fluid can be stopped by subsea tree once the unexpected events happened in downhole. Therefore, once the tree failed, it leads to a big trouble. Besides the huge downtime cost, the maintenance cost is also enormous because of maintenance difficulties. Even though it's a long history over a half of century to develop and utilize of subsea tree, coupled with a variety of reliability improvement measures so as to achieve high reliability, it is still hard to satisfy higher and higher availability requirements of offshore operators.

The inherent reliability of subsea tree has been determined after it's installed on the seafloor. Therefore, in order to gain high availability, the maintainability must be enhanced. Planning and scheduling of subsea tree maintenance can be considered as one of the most difficult tasks in offshore activities. Multi-restrictive factors such as weather, transport resource, heavy intervention vessel, technicians, repair time, and spare parts have significant impacts on maintainability [10]. These factors are usually inter-related. To maximize the availability of subsea tree, how to quantitatively evaluate these factors influencing the maintainability is needed to be settled. For many years, most of the major companies had made great efforts to address the related issues of subsea maintenance [2, 4, 15]. Many factors had been investigated, such as the important weather and the characteristics of subsea repair work. However, the problem of spare strategy was seldom debated deeply. A spare tree is of importance for maintenance since replacement of the tree is the most effective maintenance mode to reduce the repair time. The optimum number of spare trees is precisely operators' desire. Literature review indicates that there is no previously well-formed model aiming at subsea tree with considering the restriction of spare strategy. In addition, most of these researches were based on the view of overall offshore field utilizing simulation methods such as Monte Carlo simulation which are too complicated to put to use conveniently.

In this contribution, all the restrictive factors are investigated comprehensively with regard to the subsea tree. Based on an analytical method, a quantitative model for spare parts supply is presented to provide optimal demand strategy of spare parts. A case is offered to validate the model and to make the optimized decision of subsea tree maintenance.

The reminder in this paper is divided into four parts. In section 2, it expands these multiple factors restricting maintenance activities of subsea tree. In section 3, models built for weather prediction, failure analysis and spare parts demand are introduced. In section 4, a case study is performed to demonstrate the performance of the proposed models and discussions of parameter correlation are made. Last section is conclusion.

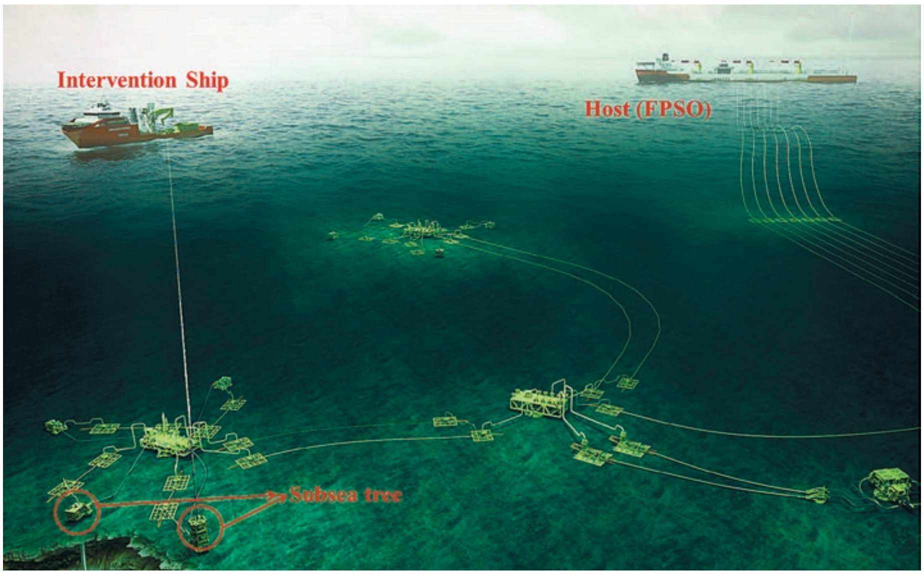


Fig. 1. Typical deepwater subsea production system (Courtesy by Aker Solutions & Baker Hughes)

2. The maintenance of subsea tree

2.1. Description of research object

Subsea tree usually is called subsea Christmas tree, equipped with valves, pipes, and connectors etc. According to the principal structures, subsea trees are mainly divided into two types, horizontal tree and vertical tree (i.e. conventional tree). The architectural differences of two types result in different activities prior to retrieving the tree from wellhead. For the vertical tree, the process is comparatively simple because it just needs installing a plug in the tubing head which is located in the wellhead. Consequently, the maintenance of vertical tree is not arranged in this paper. On the contrary, after undertaking the activities to secure the well, the tubing hanger has to be retrieved before pulling up the horizontal tree. The retrieval of horizontal tree must be performed by a heavy intervention vessel or a drill rig, which makes the maintenance task more complex. Hence, disposing of the complexity of horizontal tree's maintenance is just the research object.

In addition, subsea trees usually comprise miscellaneous configurations for diverse development requirements. Besides basic components such as wellhead connector, various valves, SCM (subsea control modular), injection system, tubing hanger, debris cap, there are some dispensable packages, such as choke, multiphase booster and multiphase flow meter. Because of high failure rates of SCM and these dispensable packages, to reduce the number of retrieval of subsea tree, they are designed to independent modular as a rule that can be individually retrieved. In this paper, the maintenances of these independent packages are neglected in the light of simplicity of maintenance process.

2.2. Maintenance strategy and concept in subsea field

The maintenance philosophy should be decided during the design phase in order to plan the strategy to procure and to contract the vessels, tools and equipment [11]. In principle, there are two primary types of maintenance strategies, preventive maintenance (PM) and corrective maintenance (CM). Besides, many scholars proposed various balanced maneuvers, such as RCM (Reliability Centered Maintenance) [12], CBM (Condition Based Maintenance) [20]. However, in practice, corrective maintenance is exclusive for operators, even though others are more reasonable theoretically. The directly leading cause is the cost for which maintenance activities in subsea industry are quite different with actions on land. Subsea maintenance, especially the subsea tree, has been restricted by water depth. The maintenance expenditures increase as water depth goes deeper. Operators may not take any PM activity even some latent failure was identified during operation. The reason is that PM cost in subsea industry is too high, sometimes is equal the cost of CM. Actually, owing to multilevel safety barriers such as quite a few fail-safe subsea gate valves, the consequence induced by a failure from subsea tree would not be catastrophic [17]. Based on the above, only CM strategy is considered in this paper.

The location and layout of subsea field have an influence on the employment of intervention vessel. Literature [6] introduced three types of maintenance concepts. Here, only remote maintenance of subsea equipment will be discussed. Remote maintenance contains all subsea work, including inspection, which cannot be conducted or controlled from the production facility. Remote maintenance must be carried out by a separate vessel, such as a heavy intervention vessel or drilling ship, as seen in Fig. 1.

2.3. Restriction of maintenance accessibility

The main challenges appear in consequence of different uncertainties related to the necessity of the maintenance activity, mainly determined by the probability of failure and its potential consequences and the feasibility of the maintenance activity, which is reliant on different restrictive factors, such as meteorological surrounding conditions and the access to required maintenance resources [19]. Then these influential factors are expounded.

1) Weather restriction

Weather conditions influencing maintenance activities are the sea state, in particular the significant wave height and wind conditions. Among restrictive factors, spare parts determine the transport resources for example. Small parts and maintenance technicians can be carried by helicopter that is not influenced by wave height, but by visibility conditions. The weight of a subsea tree is about 50~100t and the size is over 4m×4m×4m, which is regarded as large-scale equipment that has to be carried out by a ship which is impacted remarkably by the weather. The required intervention vessel for horizontal tree as mentioned is also influenced by the weather. Moreover, hostile environments could prohibit the implementation of retrieval and reinstallation of subsea tree for large fluctuation.

2) Maintenance resources

Maintenance resources usually involve vessels, tools, equipment and manpower required to perform the repair or maintenance actions. The equipment is specified by its characteristic properties: assumed transport time from harbor to field, its maximum capacity, repair operation duration, and its operational constraints with respect to maximum wind speed and wave height.

Theoretically, the transportation of subsea tree may be carried out by the intervention vessel. However, the intervention vessel may not berth in harbor when necessary since intervention vessels are occupied with high utilization rate. In an effort to reduce the set-up time, it is assumed that the transport of subsea tree is executed by a barge which is always available in harbor.

The availability of the intervention vessel has a great challenge ahead of offshore oilfield operators. The mobilization of the intervention vessel varies with the location and the diversity of contracts. The issue of contract with intervention vessel is generally decided in the initial stage of the field development. Literature [4] showed eight kinds of alternative intervention vessel contracts to all cases of subsea developments. Here three primitive intervention vessel alternatives for subsea tree's replacements are introduced:

a) Buy or construct an intervention vessel.
b) Contract vessel upon need.
c) Contract vessel(s) for a period of time.

Varieties of influential factors play important role in decision-making of intervention vessel contract. If there are dozens of subsea wells in the field, or the frequency of subsea intervention is high, the first contract is advisable even though the construction cost may be up to hundreds of millions of dollars. In this condition, it is considered that the intervention vessel for maintenance is always available. If weather permits, the vessel will be mobilized.

In the second case, once the production tree is failed, the process of contracting with an intervention vessel in spot market starts. It often takes a long time that may be up to 3 months [7], and the day rates are much higher than first case. What's more, the worst condition is to encounter the long non-feasible weather after the contract made, which leads to tremendous breakdown cost.

The last one is relatively flexible. Operators can select contract periods of 3 months to be especially used for the summer shutdown. Some operators might select contract periods of 2 years or more for preliminary stage of field development due to earlier failures as well as concentrated downhole workover after a few years. In practice, the main function of the intervention vessel is to workover the wells and thus the frequency of intervention applied to oil field is higher than the gas field. So the last contract is mostly used in crude oil production field [6]. To concern the effect of intervention vessel on subsea tree maintenance, the vessel is supposed to be applied to a gas field and the last contract is not considered in this study.

Here are other assumptions regarding maintenance resources:

- The replacement tools of subsea tree are available when required since they are easy to access and have less impacts on the feasible of maintenance and cost extension.
- ROV as an auxiliary tool can be offered by the intervention vessel.
- Professional subsea technicians are also available when required.

2.4. Demand spare parts for subsea tree

The plan of demand spare trees will be supported by tree's supplier in accordance with performance of the provided equipment when the procurement contracts are made. The purchasing strategy of subsea trees usually is one-off, i.e. the production trees and demand spare trees will be all in. Although the purchase (several to ten million dollars for one tree) and storage of subsea tree would be costly, the breakdown cost incurred by inadequate spare trees might be even larger. Consequently, the number of spare trees should be optimized.

Here are some assumptions related to spare trees:

- The retrieved tree will be a new spare part via being repaired for 3 months by original tree supplier.
- All spare parts are stored in the land base, which is usually close to the harbor.
- The degradation in the store is negligible, i.e. the spare tree is taken as a new one when the spare is available.

3. Modelling

3.1. Weather model

Whether it is possible to perform offshore operations is mainly determined by weather conditions. Amongst all parameters, significant wave height (SWH) is the most important limiting factor, in magnitude, as well as in persistence [12]. To assess the persistence of accessible sea state for the marine operation, many researchers have contributed to the study of dealing with persistence statistics. The accessible persistence is important, but the inaccessible persistence is also very more crucial in the process of assessing the feasibility of maintenance in section 3.4. The maximum of inaccessible persistence in one year is needed in section 3.4. Unfortunately, the research works in this respect are seldom. Literature [8, 9] proposed the waiting time for an accessible sea state acquired by the geometric law. The premise of using the geometric law is that all the wave height included in the waiting time is higher than the threshold level of SWH (h_{ac}). The concept of waiting time in that paper looks the same with the inaccessible persistence, but they are different in details. To explain the concepts, we show a fraction of wave in the Fig. 2. The 2.6m is supposed as h_{ac} , while 10 days is assumed as the threshold duration accessible persistence, i.e. the minimum duration required for the offshore complete operation at a time. $\boldsymbol{b_1}$ and $\boldsymbol{b_2}$ are the accessible durations that are higher than 10 days respectively, while $\boldsymbol{a}$ is the inaccessible persistence. The inaccessible persistence $\boldsymbol{a}$ might contain some duration of accessible persistence whose length are less 10 days. Accordingly, the duration of the inaccessible persistence may be equal to or much larger than the waiting time. There might be many pieces of inaccessible duration in one year, whereas the maximum of them is needed in section 3.4.

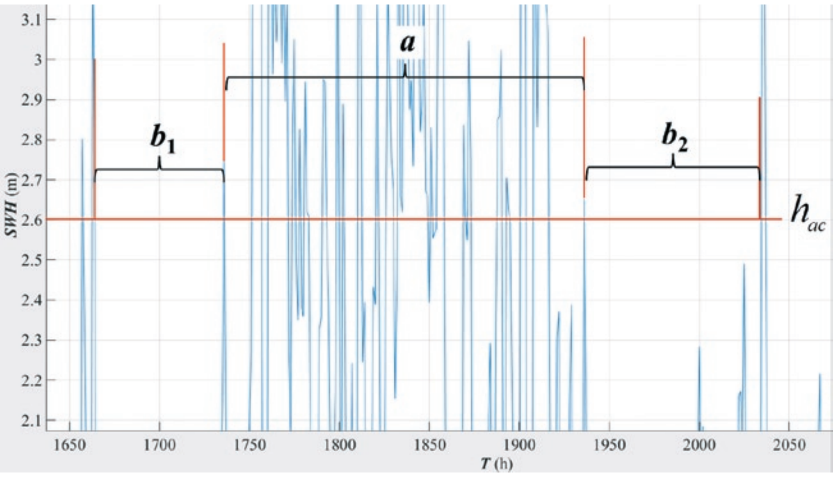


Fig. 2. The accessible persistence and the inaccessible persistence

To obtain it, we decide to apply the direct method. i.e. through the statistics. In the past, many methods had to be put forward to deal with the insufficient sample of wave height. Literature [1] provides that in order to apply this direct approach, considerably long records, typically of the order of 5-10 years, or even longer, are required. The available data we can obtain are collected for the past 37 years (1979-2015) from the ERA Interim dataset of the European Centre for Medium-Range Weather Forecasts in 6 h resolution [5]. The data are considered as enough for the accuracy in our study. For the selected field in section 4, here we give the description of how to obtain the maximum inaccessible persistence. From the website of ERA Interim, we selected the rectangle area between the subsea field (113.6ºE, 21.4ºN) and land base (115.6ºE, 19.6ºN), and the grid resolution was $0.25° \times 0.25°$, and consequently total 8×8 sites. MATLAB as a practical tool was utilized to perform the statistics by a small arithmetic we made. We could take the averages of each site in the history annually maximum inaccessible duration. Then we obtained the expected value of all sites. The computed value is 400.96 that is about 100 days.

3.2. Failure prediction of demand

As the basis, annual failure rates and mean time to restoration (MTTR) is of importance. As to subsea industry, the most common used failure database is OREDA (Offshore Reliability Data Handbook) [13] published by DNV and provided by several oil companies. The main parts of failure events in the OREDA database come from the useful life phase, where the failure rate is close to constant. All the failure rate estimates presented in this handbook are based on the assumption that the failure rate function is constant and time-independent, in which case $Z(t) = \lambda$ i.e. the failure rates are assumed to be exponential distributed with the parameter, λ. An important implication of the constant failure rate assumption is that an item is considered to be "as good as new" as long as it is functioning. All failures are purely chance failures and independent of the age of the item. The exponential distribution is expressed as follow:

- Probability distribution function:

$$f(t) = \lambda e^{-\lambda t},\ t \ge 0 \tag{1}$$

- Cumulative distribution function:

$$P(t) = 1 - e^{-\lambda t},\ t \ge 0 \tag{2}$$

3.3. Modelling for demand of spare trees

The program of spare trees is based on the amount of demand during a period of time. The period of time is defined by the lead time of a spare tree because it represents the time needed for replenishment of subsea tree. Due to the fact that all spare trees are purchased one-off, the period of time for demand estimation is replaced by the time of non-feasibility in this paper. The probability of failure in Equation (2) is implemented into a Bernoulli process. Executing Bernoulli processes is expressed with the help of the Binomial distribution in Equation (3). Its probability mass function represents the probability of getting exactly events after experiments [3]:

$$p(k; n, p) = \binom{n}{k} p^k (1-p)^{n-k} \tag{3}$$

Equation (3) is used to estimate the probability of appearance of a specific amount of demand k in an offshore field that consists of n subsea trees. The probability of 0 or less than k demands can be estimated with the cumulative distribution function in Equation (4):

$$P(k; n, p) = \sum_{k=0}^{k} \binom{n}{k} p^k (1-p)^{n-k} \tag{4}$$

The stock quantity can be obtained from the addition of the amount of demand k in Equation (4) with one, i.e. $S_q = k + 1$, as $P(k; n, p)$ is the service level of the inventory. What's more, the failure times occurred in one year may be predicted by the combination of Equation (2) and Equation (4).

3.4. The model of cost function

If the sum of all costs expensed during the life time of subsea tree is minimized, the result acquired with the integrated spare trees model is desired. Maintenance costs generally comprise several costs which are elaborated thoroughly as below.

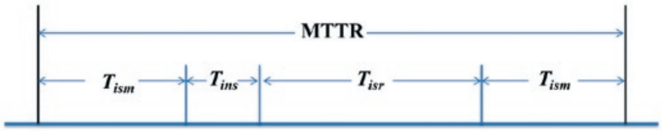
A loss of earnings incurs during downtime of subsea tree. The higher the throughput of the subsea tree, the higher will be the loss of earnings of a malfunctioned subsea tree. The downtime of a machine heavily depends on the feasibility of maintenance tasks. Obviously, the feasibility is a function of all the restrictive factors, i.e.:

$$F_{fn}(t) = f\left(A_{sta}, A_{tr}, A_{mt}, A_{is}, A_{sp}\right) \tag{5}$$

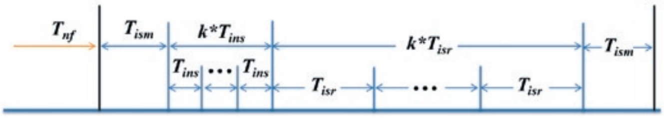
Where

$F_{fn}(t)$ – Feasibility of maintenance tasks at the time of t;
A_{sta} – Subsea tree accessibility, i.e. the availability of weather;
A_{tr} – Availability of transport resources;
A_{mt} – Availability of maintenance technicians;
A_{is} – Availability of intervention vessel;
A_{sp} – Availability of spare parts.

The specific formation of F_{fn} is usually difficult to be determined. For simplication, a concise formula recommended by literature [18] would be applied to judging the feasibility of subsea tree's maintenance, as seen Equation (6). Non-feasibility due to restrictive factors is implemented in the framework by means of binary vari-



(a) Relationship of various times in MTTR



(b) After non-feasibility times

Fig. 3. the costs variation with two contracts of intervention ships

ables. The variable changes its value regarding weather conditions and availability of resources. As a relaxation every variable in Equation (6) can be 0 or 1. Hence, feasibility is either given 1 or not 0. This assumption could be replaced with steady values between 0 and 1.

$$F_{fn}(t) = A_{sta} * A_{tr} * A_{mt} * A_{is} * A_{sp} \tag{6}$$

Here it is supposed that repair operation cannot be carried out within a period of time in which any binary variable equals zero. A restrained maintenance task results in downtimes until the next period without restrictions in accessibility. Consequently, vast lost earnings could be induced during a subsea tree failure if restrictive factors are present. After a period of non-feasibility, subsea trees are replaced in sequence. As a consequence, downtime after non-feasibility equals k times of repair time plus the time of intervention vessel mobilization as shown in Fig. 3.

Normally, as shown in Fig. 3(a)., if only one subsea tree failed, MTTR consists of the mobilization of intervention ship T_{ism}, the inspection time T_{ins} before performing repair and the replacement time T_{isr}. Here it is supposed that the work of the inspection is performed by the intervention ship. However, if the failed trees are more than one, the various times of repaire process are displayed in the Fig. 3(b). For the case of repaire, it only needs one round trip of the intervention ship. The parameters T_{ism} and T_{ins} usually are given by the operators based on the location of subsea field and the capacity of mobilizaiton of the intervention ship.

In one year, there are many pieces of non-feasibility time, but it always exists the maximum one, such as the 100 days acquired in the section 3.1. If the non-feasibility days are shorter, the other factors may contribute to the feasibility of maintenance. But when the non-feasibility is the maximum, actually the other factors could be overlooked because in the so long non-feasibility duration, the operators generally could deal with these factors before the feasibility days come. As a consequence, we take the maximum of inaccessible persistence as the non-feasibility days.

If feasibility is given during a breakdown of the system (see Equation (7)), downtime of the subsea tree is shorter than the non-feasibility (see Equation (8)). All the meanings of parameters using in the following equations are listed in Table 1.

$$T_d(F_{fn} = 1) = T_{mttr} \tag{7}$$

$$T_d(F_{fn} = 0) = (T_{nf} + T_{isr} * k) \tag{8}$$

$$C_{tdt1} = [(k_1 - k) * T_{mttr} + T_{tnf} + 2 * T_{ism} + (T_{ins} + T_{isr}) * k] * Q * P \tag{9}$$

Annual inventory cost usually includes spare part costs and the stock keeping costs which consist of direct cost and overhead cost. In this model, all the capital commitment costs are not considered. The annual inventory cost can be calculated by:

$$C_i = C_{so} + C_{sdr} * S_q * C_{sp} + C_{sp} * S_q / T \tag{10}$$

In feasibility duration, if a failure of subsea tree happens, the replacement process starts at once. Under this condition, the corrective maintenance is constituted by restoration cost of spare part, cost for maintenance technicians, cost of transport resources and cost of intervention vessel. Hence, corrective maintenance cost is expressed where at a time only one tree is replaced:

Table 1. Parameter values of the scenario

Items	**Representation**	**Acquisition**	**Results**
C	Sum of all operation costs	(14)	114.95×10^6 \$
C_{acis}	Annual construction cost of intervention vessel	Input	20×10^6 \$
C_{cm}	Corrective maintenance costs	(13)	27.2×10^6 \$
C_{cmn}	Corrective maintenance cost, after non-feasibility	(12)	6.52×10^6 \$
C_{cmo}	Corrective maintenance cost, one at a time	(11)	2.23×10^6 \$
C_i	Inventory costs	(10)	1.75×10^6 \$
C_{mt}	Cost for maintenance technicians	Input	1×10^4 \$/d
C_{sdr}	Stock keeping direct cost ratio	Input	0.005 /y
C_{so}	Stock keeping overhead cost	Input	1×10^5 \$/y
C_{sp}	Spare part costs	Input	6×10^6 \$
C_{sr}	Cost spare part restoration	Input	5×10^5 \$
C_{tdt}	Total downtime	(9)	66×10^6 \$
C_{tr}	Cost of transport resources	Input	2×10^5 \$/d
k	Amount of predicted failures	(2)+(4)	4
k_1	Amount of predicted failures in one year	(2)+(4)	10
Ls	Expected service level	Input	0.97
n	Number of experiments or subsea trees	Input	50
P	Price of production fluid	Input	80 \$/bbl
Q	Nominal capacity of subsea tree	Input	5×10^3 bbl
S_q	Stock quantity	(4)+1	5
T	Lifetime of subsea tree	Input	20 y
R_{is}	Rate of intervention ship	Input	1×10^5 \$/d
T_{ins}	Inspection time of the failed subsea tree	Input	1 d
T_{ism}	Time interval of intervention ship mobilization	Input	2 d
T_{isr}	Time interval of spare replacement	Input	3 d
T_{mttr}	Mean time to restoration	Input	8 d
T_{nf}	Time of non-feasibility	Weather	100 d
λ	Failure rate of subsea tree	Input	12.81×10^{-6}/h

$$C_{cmo} = C_{sr} + C_{mt} * \left(T_{ins} + T_{isr}\right) + C_{tr} + R_{is} * \left(2 * T_{ism} + T_{ins} + T_{isr}\right) \quad (11)$$

After non-feasibility, all failed trees would be replaced in sequence. Hence, the maintenance cost is computed by:

$$C_{cmn} = C_{sr} * k + C_{mt} * \left(T_{ins} + T_{isr}\right) * k + C_{tr} + R_{is} * \left[2 * T_{ism} + \left(T_{ins} + T_{isr}\right) * k\right] \quad (12)$$

Combining Equation (11) and Equation (12), the annual corrective maintenance cost is acquired by:

$$C_{cm} = \left(k_1 - k\right) * C_{cmo} + C_{cmn} \quad (13)$$

Eventually, the acquisition of the annual total maintenance cost is expressed by:

$$C = C_i + C_{tdt} + C_{cm} + C_{acis} \quad (14)$$

4. Model Validation

4.1. Scenario description

The verification of the model has been conducted with a single item, single echelon scenario. It involves an offshore field with 50 subsea trees in the water depth of 1500m. In the scenario the relaxation of constant production throughout one year is assumed. All parameters used within the scenario are defined in Table 1. Parameter values are either estimated or taken from expert interviews that were multiplied with a factor to warp real values.

Since the transport resources and technicians are easy to obtain comparatively, for simplifying the calculation and focusing on the more important factors, they are regarded as to be always available, that is $A_{tr} = 1$ and $A_{mt} = 1$. The transport time is set to 24h.

With the aim of analyzing the influence of restrictive factors, feasibility of maintenance activities can be controlled for ten days. The spare trees can only be replaced, if maintenance feasibility is allowed. If there are no restrictions, the decision of instant of subsea tree replacement only depends on the cost of corrective maintenance.

In the event of non-feasibility, the number of failure during that period increases with its duration. In the worst situation, some subsea trees cannot be operated during the whole time span of non-accessibility. Hence, loss of earnings is maximum. The demanded inventory level at the beginning of non-feasibility is calculated with the help of Equation (4), which estimates the number of expected spare part demands during the period of non-feasibility. For fulfilling 97% of all demands during non-feasibility, the number of spare parts in stock is computed.

4.2. Discussions of restricted accessibility scenario

The relationship of costs and spare trees is discussed with these factors in four aspects.

1) The discussion of two alternative contracts of intervention vessel

In the condition of the non-feasibility duration up to 50 days plus 50 subsea production trees, make a survey to figure out which contract of intervention vessel is more reasonable. Table 2 shows the comparison of two types of contracts. The annual rate of second contract is less than the first, but the caused cost of downtime is too high to make the total cost of second contract of intervention vessel higher. Thereby, the first contract is more reasonable.

The curves for two types of contracts are plotted. Fig. 4(a) supports the argument of previous paragraph. In addition, it is discovered that the curve of total cost that is cost of annual intervention vessel rate plus the caused downtime cost for the of second contract grows more slowly than the first contract, which means in a certain value, the total cost of first contract is not always lower than the second. A great many samples are calculated in Fig. 4(b), and it shows when the number of subsea production approximates 600, the costs of both types of contracts are equal. However, the number of production tree in offshore field is less than 150 at large and the value of 600 is impossible in reality. It means that the result shows the first

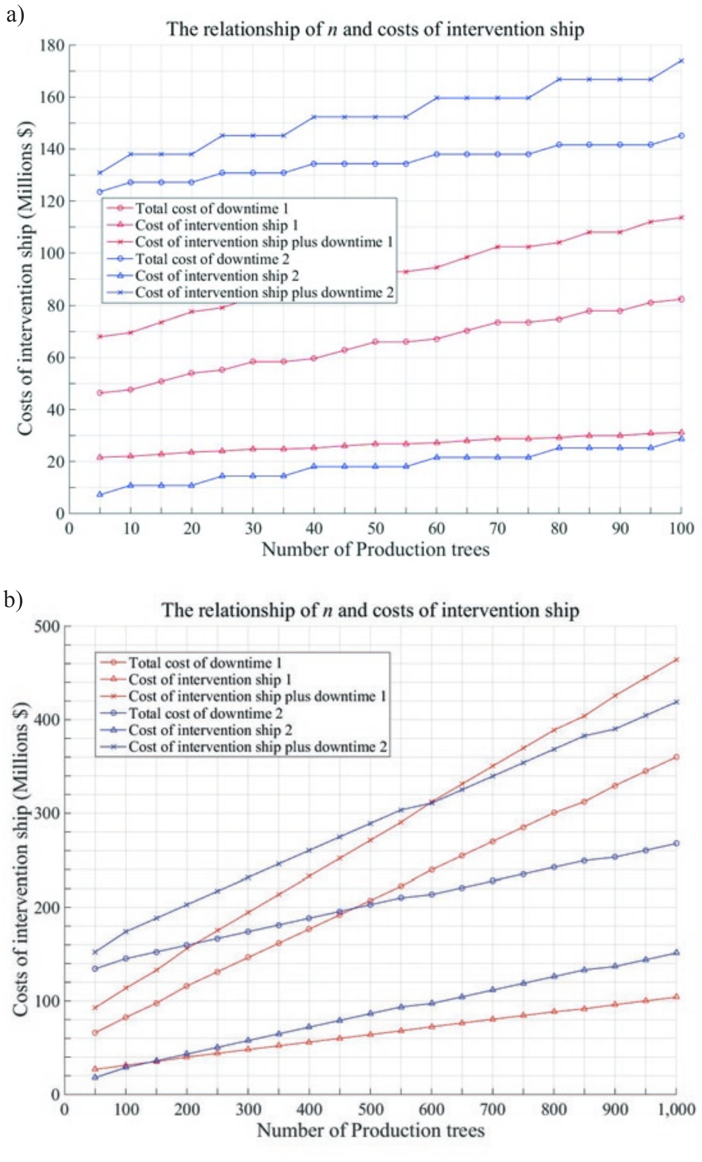


Fig. 4. the costs variation with two contracts of intervention ships

Table 2. The comparison of two types of contracts

No.	Contract strategies	Rate specifications	Annual rate (M $)	Downtime cost (M $)	Total cost (M $)
1	Buy or build	Construction cost=3×10^8 $, lifetime=20y, rate=1×$10^5$ $	26.8	66	92.8
2	Upon need	Rate=3×10^5 $, delivery time≈3 months	18	134.4	152.4

Note: Values of cost and rate may not be the latest. Here is just for calculation example.

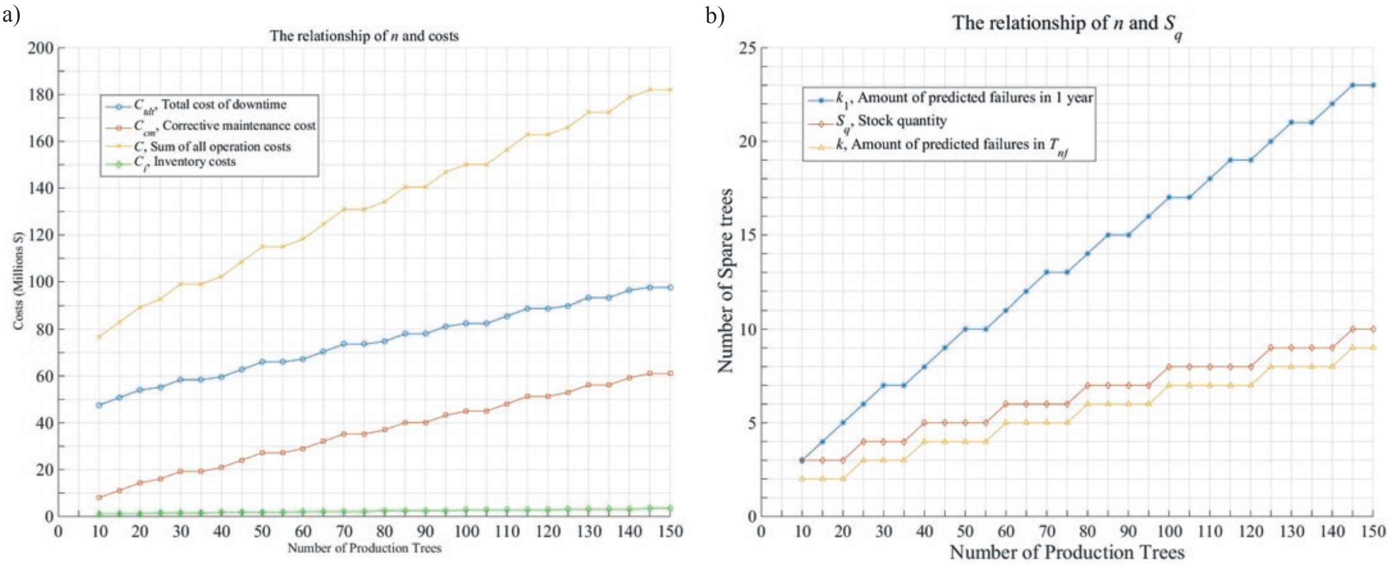


Fig. 5. The number of subsea production trees with intervention ship and the number of spare trees

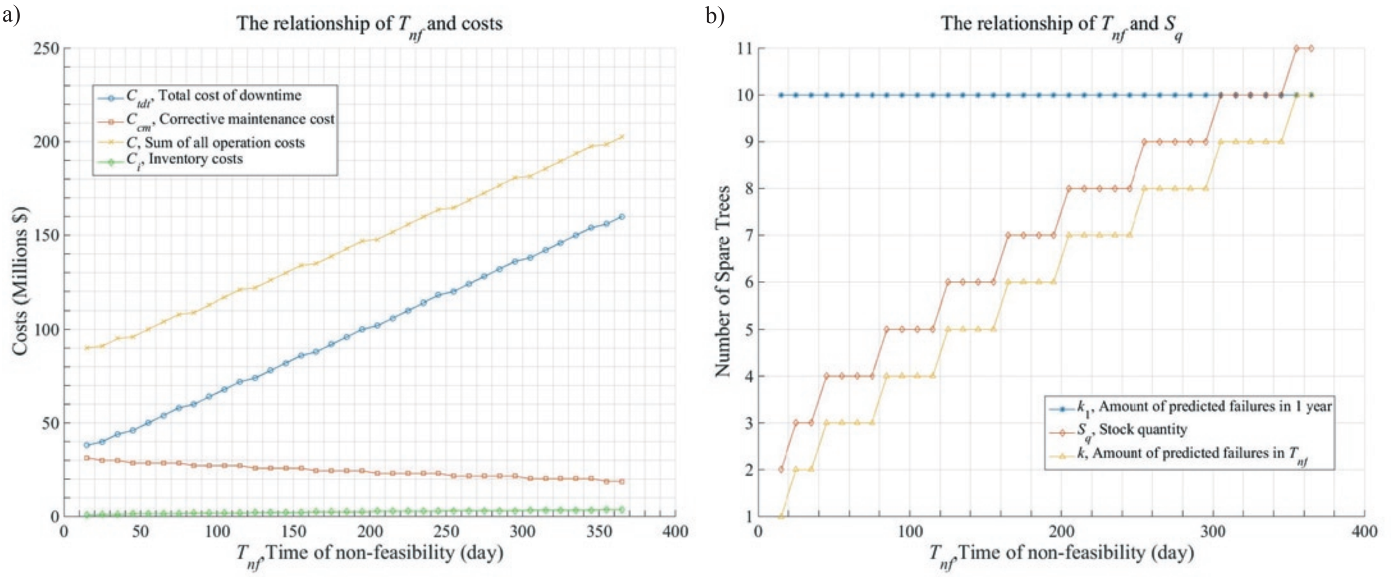


Fig. 6. The non-feasibility with intervention ship and the number of spare trees

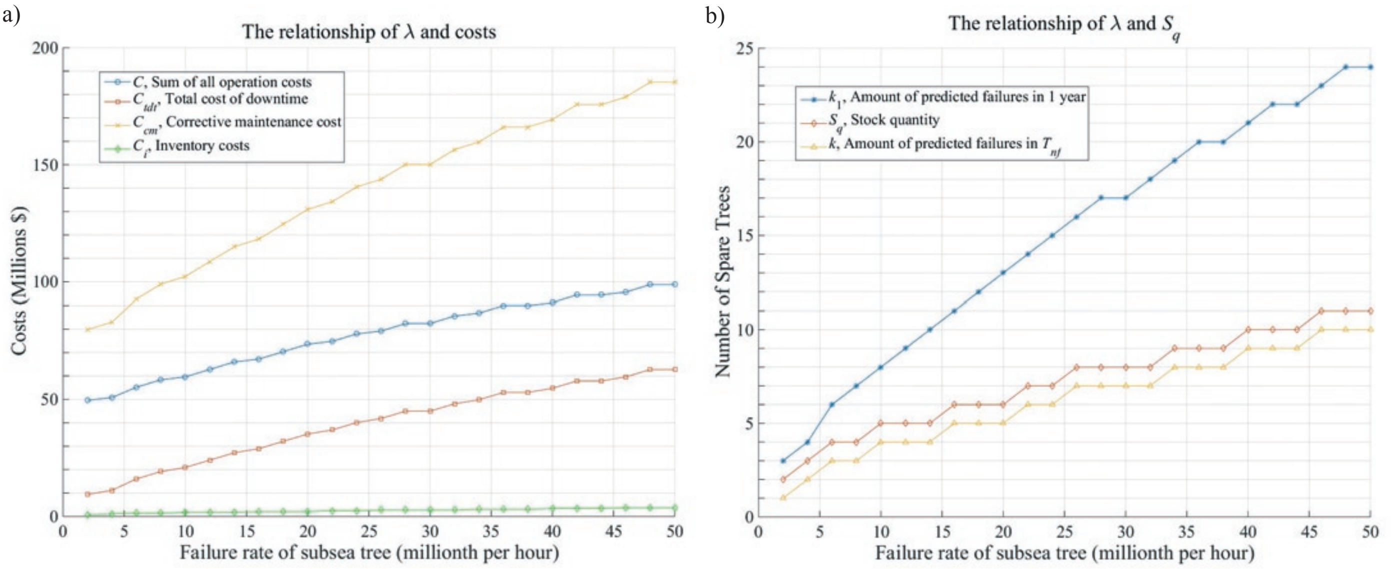


Fig. 7. The failure rate with intervention ship and the number of spare trees

contract of intervention is always optimum. The conclusion indicates that operators should make the intervention vessel available as far as possible no matter what they do.

2) The discussion of the amount of subsea production trees

Evidently, all the costs are amplifying with the increase of the number of subsea production trees from Fig. 5(a). Among of these costs, the proportion of inventory cost is low and increasing slowly. That means the operators maybe store adequate quantity of spare trees that might not result in higher inventory cost. The required spare trees go up absolutely with the growth of the number of subsea production trees as shown Fig. 5(b).

3) The discussion of the variation of the non-feasibility time

As the given value of the number subsea production trees is 50, the response of non-feasibility duration to kinds of costs as well as the quantity of spare trees is investigated. Apparently in Fig. 6(a), the curves of downtime cost and total costs increase in proportion to the non-feasibility duration. It is funny that on the contrary, the cost of corrective maintenance decreases with the augment of the non-feasibility duration which implies that the corrective maintenance cost can be declined when the failed tree are not repaired. However, the cost of corrective maintenance accounts for a rather small proportion of costs while the caused downtime cost is sizable. Therefore, once the subsea production failed, it must be repaired as soon as possible. The number of required spare trees rises absolutely with the growth of the number of subsea production trees showed Fig. 6(b).

4) The discussion of the variation of failure rate

Failure rate is one of important indicators reflecting the feature of reliability. It is quite clear that the larger the failure rate is, more prohibitive various costs are, as well as more spare trees are needed. Fig. 7(a) and Fig. 7(b) mirror this feature of relationship between failure rate and costs.

5. Conclusion

The results show the occurrence of enormous downtime cost can be increased in case that these restrictive factors in the subsea tree maintenance model are not taken into account thoughtfully, especially the intervention vessel and spare trees. Apart from the number of subsea production trees, the duration of non-feasibility has a significant effect on the decision of the demand quantity of spare trees. The demand of spare trees is grown with the enlargement of non-feasibility time. To purchase adequate number of spare trees one-off, the time of non-feasibility should be deliberated to avoid unnecessary downtime and to optimize inventory cost. When the failure rate ascends, obviously the amount of failure is increased, which leads to huge maintenance cost as well as colossal downtime cost.

Based on several simplifications and assumptions, the presented model for subsea tree maintenance has the capability to offer the opportunity of regulating of subsea tree maintenance as well as making sound decision of spare trees demand. Likewise, operators enable to make the applicable selection on the contract of intervention vessel according to the calculated costs. However, it is too simple to make the decision of contract with respect to intervention vessel entirely as no consideration of frequency of workover in offshore field, especially in the oil-produced field. Hence, the decision-making of contract of intervention vessel needs further study that more factors should be added.

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