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Jerko Škifić
E-mail: skific@riteh.hr
Tibor Jaklin
E-mail: tjaklin@riteh.hr
Tehnički fakultet Sveučilišta u Rijeci, Vukovarska 58, 51000 Rijeka, Croatia

Weather Downtime Assesment for Complex Offshore Projects

Abstract

Analysis of the expected downtime in complex offshore operations is performed with metocean analysis of the area of interest which is then compared to the operative limits defined by installation analyses. The metocean conditions are commonly represented by seastate hindcast time series. On the other end, the operative limits can be defined as maximum allowable sea state, as well as the maximum allowable vessel motion. This paper presents the methodology to evaluate the operative weather downtime based on classical operative sea state limit.

Keywords: downtime analysis, offshore operations, operative limits

1. Introduction

Offshore operations and installations are exposed to harsh marine environment. Consequently, operations can be suspended which could put human safety or equipment at risk. This is particularly valid claim for many areas where adverse metocean conditions could be encountered even during statistically good season. In order to quantify expected downtime caused by environmental conditions, three classes of information need to be specified as accurately as possible:

- Precise sequence and duration of operations
- Operative limits for relevant operations and/or sequence of operations
- Metocean data

Furthermore, definition of realistic operation's sequence, suspension procedures and limiting criteria are crutial for reliable downtime estimate.

Operation characteristics and their precedence relationships should be meticulously specified during project planning phase.

Operative limits are commonly expressed in terms of maximal allowable wave height, but more detailed criteria have been developed in the last decade. This development was primarily driven by the task of reducing downtime by shifting the operative limit definition to vessel motion limiting criteria. That has proven to be effective in terms of more realistic downtime assesment compared to classical approach.

This paper presents the wheather downtime assesment methodology that uses metocean data defined either as long or synthetic hindcast time series. By comparing metocean data with operative limits, one can provide workability assessment for each step along the time series. Consequently, the downtime can be accumulated for any sequence of operations, and can be expressed with different occurrence probability.

2. Operative limits

Operative limit is defined as a combination of values of metocean parameters, that define the threshold below which the operation can safely advance.

Typically, they are expressed in terms of significant wave height H_s, frequently coupled with wave period T_p and direction. Furthermore, the limit can be defined as maximal allowable motion at relevant vessel's location e.g. stinger tip. Additionally, some operations may depend on additional limits, such as wind and ocean current limits, as well as the fog, ice coverage limits, to name a few. It is worth noting that in some cases, the operative limit can be expressed as a combination of multiple limits, vessel motion and wind limit, for example.

Most commonly, operative limit is defined as maximal allowable H_s values for predefined combination of peak period T_p and directions, obtained as result of:

- dynamic installation analyses performed for many different combination of significant wave height, peak period and direction relative to vessel's incomming direction
- dynamic analyses performed using regular wave theory with the maximum expected wave for a defined, spectral form [1], e.g. JONSWAP.

An example of those H_s limits that are results of the above analyses is given in Figure 1.

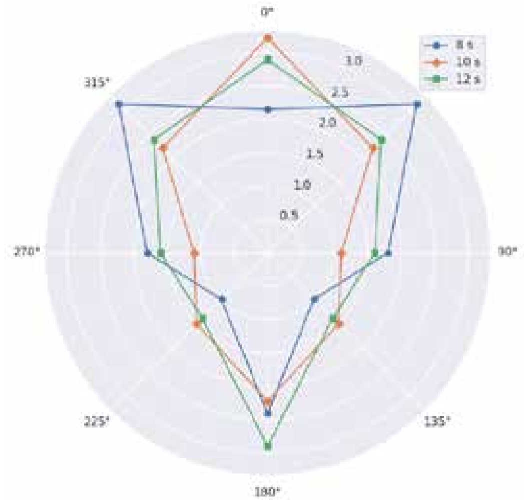

Figure 1 Limiting H_s for different peak period and incoming wave direction relative to the vessel

However, when crossed sea conditions are encountered, representative characterization of modeled environmental conditions cannot be obtained with above mentioned single collection of H_s, T_p and direction parameters [2]. In that case, a more appropriate approach requires the definition of a limiting motion for an operation, which then can be compared against a motion induced by an encountered sea state [2]. In this context, a limiting motion, lateral or vertical, refers to a relevant vessel location, and is defined as a single, or a combination of vessel motions: displacement, velocity, or acceleration.

Vessel's respond to the load of any possible sea state, can be calculated by using the Response Amplitude Operators (RAOs), which are usually provided to the vessel's Center of Gravity (CoG). They can be transferred to any vessel location P as

$$\begin{aligned} \hat{X}_P &= X_{CoG} + P_z\theta_y - P_y\theta_z \\ \hat{Y}_P &= Y_{CoG} - P_z\theta_x + P_x\theta_z \\ \hat{Z}_P &= Z_{CoG} - P_y\theta_x - P_x\theta_y \end{aligned} \tag{1}$$

where:

- X_{CoG}, Y_{CoG} and Z_{CoG} represent RAOs in complex notation for movements in X, Y and Z direction at the RAO center,
- P_x, P_y and P_z are the coordinates of the vessel location P relative to the CoG,
- θ_x, θ_y and θ_x are rotation angles around coordinate axes.

If the motion RAOs at the CoG is defined as

$$X_{CoG} = \bar{X}(\omega,\theta)\,e^{i(\omega t+\phi)} \tag{2}$$

where the $\bar{X}(\omega,\theta)$ denotes the vessel's motion amplitude due to a unit amplitude wave, i.e. magnitude of the response, ϕ stands for the phase shift relative to the wave, and ω represents the angular frequency, then it is easy to to calculate displacement, velocity and acceleration at any point *P*. For details, see [2].

3. Marine operations

As defined by Det Norske Veritas [3], marine operation is a *non-routine operation of a limited defined duration related to handling of object(s) and/or vessel(s) in the marine environment during temporary phases*. For the purposes of this article, the authors refer to an operation as an activity with prescribed net duration and a set of operational limits. It is worth noting that some types of operations require weather windows of a specific duration. Here, the term **weather window** [1] is defined as the time betweeen crossing of a threshold level for a metocean parameter or a set of metocean parameters and the next crossing of the same level. Complex offshore projects, depending on the scale and abstraction, can consist of hundreds of contiguous operations.

The operations can be considered *interruptible* and *non-interruptible*. That is, the execution of some an interruptible operation can be suspended at any time during its duration, if operative limits are not satisfied. The execution is then resumed when the environmental conditions allow are favorable (Figure 2). On the other hand, a non-interruptible operation must be carried out from start to finish without any delay (Figure 3).

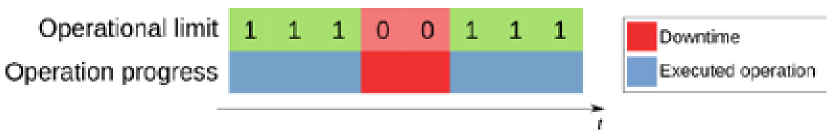

Figure 2 Example of an interruptible operation with downtime

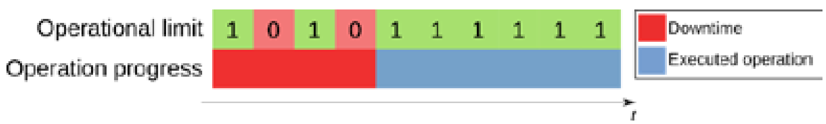

Figure 3 Example of a non-interruptible operation with downtime

Additionally, when dealing with complex projects, one has to take into an account precedence relationships, defined as a specific order in which the sequence of operations are to be executed. Most commonly, two types of relationships are used within such a project:

- **Finish-to-Start**. This is the most common relationship used between operations. An operation B cannot start before the previous operation A hasn't ended. Here, an operation A is often referred to as an **uncoupled operation**, since the start of an operation B does not have to coincide with the end of the operation A.
- **Fixed Finish-to-Start**. Here, an operation B can only start immediately and directly after its previous operation A has ended. There cannot be any delay between the end of operation A and the start of an operation B. Not surprisingly, operation A is referred to as a **coupled operation**. More generally, one can view the sequence of operations A and B as a single operation with two different operative limits.

Figure 4 shows an example of marine project consisting of three operations, where three distinct operational limits assigned to each operation. Operations 1 and 2 are non-interruptible operations and Operation 3 is interruptible. Precedence relationship for Operation 1 and 2 is defined as Fixed Finish-to-Start, while relationship for Operation 2 and 3 is defined as Finish-to-Start.

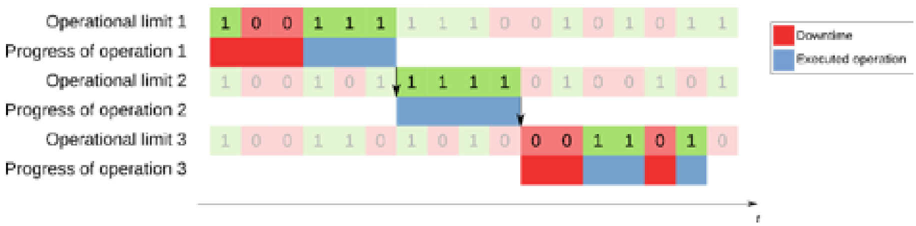

Figure 4 Example of sequence of marine operations with weather downtime. Operations 1 and 2 are non-interruptible operations, and Operation 3 is interruptible operation. Considering the precedence relationships, Operation 1 is a coupled operation, while Operation 2 is an uncoupled operation

Finally, when operation weather risk assessment is considered, the **Net Duration** (t_{ND}) of an operation is a deterministic measure defined as the time required for completion not taking into an account any delays.

Downtime (t_{DT}) is defined as a time during which an operation cannot proceed due to bad weather. **Total duration** is defined as a sum of **Net Duration** and **Downtime**, i.e:

$$t_{Total} = t_{ND} + t_{DT} \tag{3}$$

4. Hindcast time series

Nowadays, long hindcast metocean time series are available for any offshore area. Figure 5 shows an example of a significant wave height distribution per month while Figure 6 showns an example of a wave direction distribution for a specific month, both obtained for the same long hindcast time series. More precisely, Figure 5 displays distribution of significant wave heights for each month using density curves. It is worth noting that the width of each curve roughly corresponds with the frequency of data points in each month. Furthermorem the individual density curves are always built around center lines. As a consequence, density curves follow the exact same construction and interpretation. Additionally, the horizontal lines within each density curve correspond to quartiles.

Furthermore, hind cast time series typically include total sea states and their partitions. If such data can be considered representative of the metocean conditions, then the expected downtime calculations can be conducted by simulating operations' sequence for each metocean condition in hindcast time history.

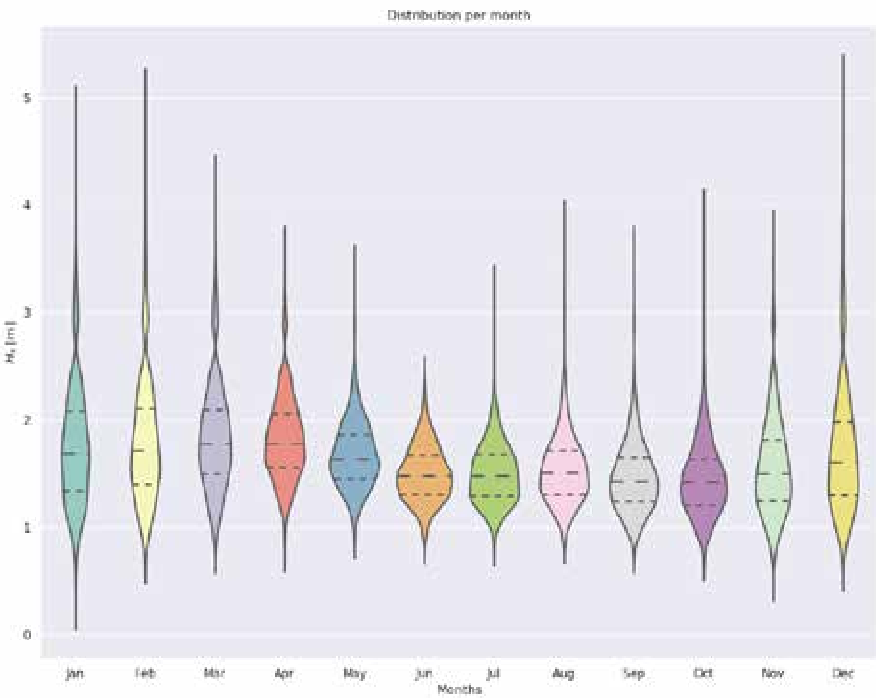

Figure 5 Example of a significant wave height distribution per month, obtained by a long hindcast time series

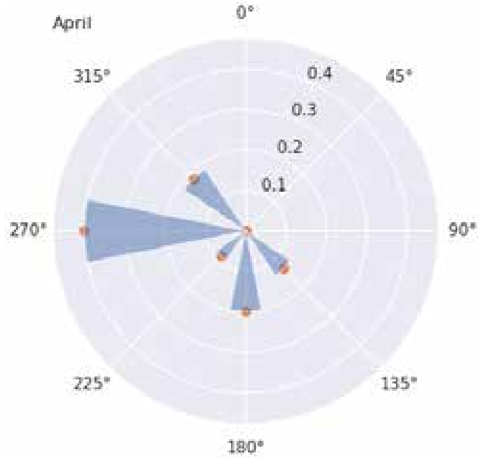

Figure 6 Example of a significant wave direction distribution for a specific month, obtained by a long hindcast time series

In some cases, recorded time series might not be long enough to guarantee statistically sane results. Or, the recorded time series doesn't contain sea states that have statistically significant occurence probability. Then, one needs to resort to generation of synthetic time series of metocean conditions with desired statistical properties. A number of models are developed, such as Box Jenkins model, Block resampling, Copula model, univariate and multivariate Markov chain models, to name a few.

Most models are designed to model up to two metocean parameters, which can be a decisive limiting factor, especially when dealing operative limits that need multiple parameters, e.g. motion limits in crossed sea conditions. However, those models provide a valuable tool for weather downtime analyses, especially in cases where operations strongly depend on temporal sequence of waves, e.g. heavy lift operations depend on the occurence of weather windows with very strict operative limits. In that case, it is common practice to generate synthetic time series at various temporal scales [4].

Usually, Markov chain models are applied to univariate metocean parameters, and are proven to properly reproduce main statistical properties, e.g. operative weather windows [10]. However, since the sea state conditions are inherently multivariate dependent phenomena, multivariate Markov models should be considered more appropriate [5]. Additionally, models using copulas are used to create realistic environmental time series by taking into an account abovementioned multivariate properties and the observed autocorrelation [6]. Copulas allow construction of model which avoid restriction imposed by models which describe pairwise families of bivariate distribution characterized by the same parametric family of univariate distributions. It is then possible to construct joint distribution requiring only marginal distributions of variables and their measures of dependence [6].

5. Weather downtime analysis

Although there exist a number of numerical methods dealing with weather downtime analysis [7], this paper will focus on an analysis by workability assessment for every time step of available hindcast time series. At this point it is of no significance if the defined hindcast time series is synthetic or not.

For this kind of analyses, compared to the synthetic time series', the long hindcast time series' are preferred. They can provide information for as many metocean parameters, and, in principle, can provide a more realistic assessment of real operative conditions, e.g. delays caused by pipe lowering and recovery.

Namely, for each time step of the time series and for each operation, one needs to establish if the sea state condition exceeds or not the operative limit. And at this point, it makes no difference if the operative limit is defined as a motion limit, limiting wave height, wind speed, or any combination of different limits, e.g. vertical displacement at the stinger tip and wind speed.

The algorithm creates a matrix of boolean values for every step of time series and for every operation, as it is shown in Table 1.

Table 1 Computed workability for each time step and each operation.

Time step	Operation 1	Operation 2	Operation 3	…	Operation N
Step 0	1	0	1	…	1
Step 1	1	0	1	…	0
Step 2	0	0	1	…	0
Step 3	0	1	0	…	0
…	…	…	…	…	…
Step N-1	1	1	0	…	0

When dealing with simple operative limits, such as wind speed coupled with or without direction, or maximal allowable wave height coupled with wave period and direction, the computational cost to determine the workability is small. One only needs to compare metocean parameters given in each time step with parameters defined in operative limit, taking into an account direction relative to vessel's heading.

On the other hand, motion limits require quite a bit of computational effort. First off, the motion estimate can be calculated by using:

- Total sea state (H_s, T_p),
- Sea state components (H_{si}, T_{pi}), where the index i denotes the i-th sea state component, and,
- Full 2D spectrum

Hindcast time series always provides the total sea state. However, its use is equivalent to that of an H_s limiting criterion. On the other hand, sea state partitions, if available, provide more accurate description of the observed sea state conditions. Finally, the full 2D spectrum, if available, currently provides the most accurate information about the sea state condition. However, the use of this information comes at the significant computational cost [2], compared to previous levels of information available in the hindcast time series.

From the computational point of view, the approach that uses sea state partitions is considered as an optimal choice.

When operative motion limits are considered, it is necessary to presume a spectral form for an observed time series. Then, the resulting moments for any sea state spectrum described by the sum of wave partitions can be represented as the sum of the moments of the spectrum for each partition [2].

Since the moments are proportional to the square of the H_s, spectral moments can be calculated for sea states with H_s =1 m for all directions and suitable range of wave periods T_p and peak enhancement factors of the spectrum. Here, the JONSWAP spectrum is a reasonable choice, since, according to its formulation, a [8], its peak enhancement factors are a function of H_s and T_p. The result is the spectral moment expressed as a a function of wave period T_p and direction for different peak enhancement factors and moment orders. More conveniently, spectral moments are calculated for preselected periods T_p, directions and peak enhancement factors and saved as series of tables. For any possible combination of wave partitions appearing in the hindcast time series, the algorithm needs to select the appropriate table for each component and multiply the selected moment value with the square of the partition's Hs and sum the moments, which results in the moments of the resulting spectrum. For details, see [2]. Finally, the workability can be calculated by comparing the obtained result with the defined operative limit.

Large projects can consist of hundreds of operations, and, for long hindcast time series with typical time step, the workability matrix can be quite large. However, since the matrix consists of boolean values only, the actual computer memory size is quite small.

When the workability matrix has been populated, and the start of the project has been selected, all it takes is to step through time steps of the workability matrix and sum downtimes for each operation. This procedure is then repeated for each year in the workability matrix (Table 2). This approach provides, besides an average downtime, possible spread around the average which can be expressed on percentiles or as a standard deviation [9], as shown in Figure 7.

The algorithm needs to properly take into an account each operation's characteristics. For example, the sum of downtime values for non-interruptible operation include time steps where the workability is satisfied if the number of favorable consecutive time steps does not exceed the nominal duration of that operation. Additionally, Fixed Finish-to-Start precedence relationship can have a significant impact on the downtime. Finally, when dealing with pipe laying operations, one needs to take into an account the time necessary for pipe abandonment and recovery in order to properly assess downtime.

Table 2 Duration and standby for a specific project start date

Year	Total Duration (days)	Standby (Days)
1990	59.515	7.895
1991	52.355	0.735
1992	77.57	25.95
1993	52.615	0.995
1994	53.96	2.34
1995	58.705	7.085
1997	59.495	7.875
1998	59.24	7.62
1999	59.785	8.165
2000	60.91	9.29
2001	55.66	4.04
2002	63.11	11.49
2003	56.275	4.655
2004	59.83	8.21
2005	54.995	3.375
2006	56.4	4.78
2007	64.075	12.455
2008	63.995	12.375
2009	58.21	6.59
Mean	**59.3**	**7.68**

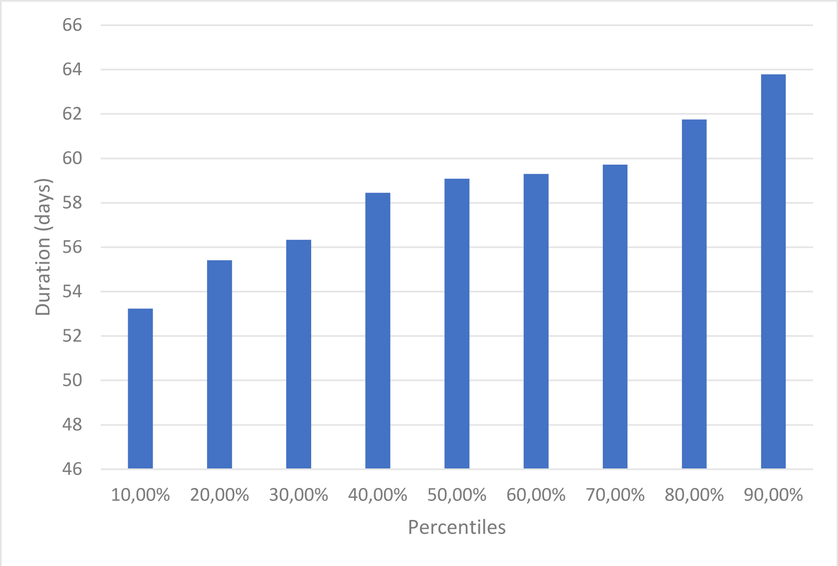

Figure 7 Calculated total duration percentiles for a specific project start date

Finally, the above procedure can be repeated for different project start dates (Figure 8), which can potentially reduce potential costs of installation project.

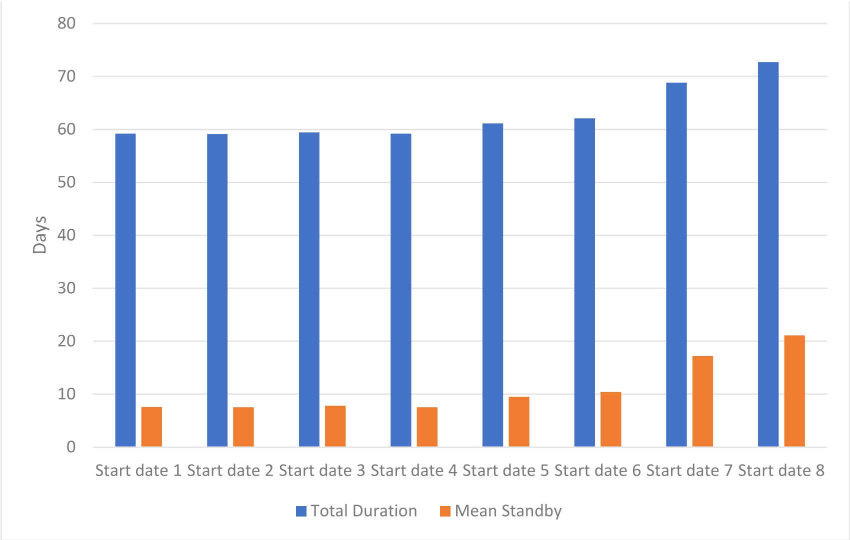

Figure 8 Calculated mean total duration and standby for preselected project start dates

6. Conclusion

Complex offshore projects require careful wheather downtime assesment, especially during early engineering phase. Wheather downtime estimated by stepping for each step of long hindcast time series has been described. The results obtained with such an algorithm have been proven to produce reallistic downtime values in real projects. In order to efficiently and reliably use this algorithm, precise operation's characteristics, along with operative limits should be defined. One has to take into an account that, if available, operative limits expressed as motion limits used in conjuction with wave partitions should produce more realistic results compared to simpler, classical representation of operative limits.

7. References

1. Det Norske Veritas, Modelling and Analysis of Marine Operations, Det Norske Veritas, 2013.
2. M. Drago, A. del Guzzo, L. Vitali i R. Bruschi, Weather Stand-by Assessment in Offshore Operations Using Motion Limit Criteria, *The 27th International Ocean and Polar Engineering Conference* , San Francisco, 2017.
3. Det Norske Veritas, Marine Operations, general, DNV-OS-H101,« Det Norske Veritas, 2011.
4. G. de Masi, R. Bruschi i M. Drago, Synthetic metocean time series generation for offshore operability and design based on multivariate Markov model, *OCEANS*, Genova, 2015.
5. B. Hagena, I. Simonsena, H. M. i b. M. Muskulus, A multivariate Markov Weather Model for O&M Simulation of Offshore Wind Parks, *Energy Procedia,* svez. 35, pp. 137-147, 2013.
6. G. Leontaris, O. Morales-Nápoles i A. Wolfert, Probabilistic scheduling of offshore operations using copula based environmental time series, *Ocean Engineering,* pp. 328-341, 2016.
7. Bruijn W. E. L. et al., Probabilistic downtime estimation for sequential marine operations, *Applied Ocean Research*, 86:257-267, 2019.
8. Det Norske Veritas, Environmental Conditions and Environmental Loads, RP-C205_2014-04, Det Norske Veritas, 2014.
9. M. Drago i M. Venturi, Probabilistic evaluation of performance and weather stand-by in offshore pipeline laying, *Proc. IMCA annual seminar*, New Orleans, Louisiana, 2011.
10. K. Anastasiou, C. Tsekos, Operability analysis of marine projects based on Markov theory*, Applied Ocean Research* 01/1996; 18(6):329-352, 1996.