Universitetet i Stavanger

FACULTY OF SCIENCE AND TECHNOLOGY

MASTER'S THESIS

Study program/specialization: Offshore Technology/ Subsea and Marine Technology	Spring semester, 2018 Open
Writer: Mikhail Chumikov	……………………………… (Writer's signature)
Faculty supervisor: Professor Ove Tobias Gudmestad External supervisor: Professor Anatoly Borisovich Zolotukhin	
Title of thesis: Subsea Template Lifting Operations in the Sea of Okhotsk	
Credits (ECTS): 30	
Key words: marine operations, weather window, icing	Pages: 51 Enclosure: 6 Stavanger, June 14th, 2018

Abstract

Sea of Okhotsk is characterized by harsh environmental conditions. The navigation period lasts approximately 5 months (June – October). Sea ice starts to form in November with 0.8-1.1 m thickness. Vessel icing is possible from October. Note that there are many oil and gas fields in the Sakhalin offshore which means that marine installation operations should be performed.

The area with possible subsea field developments will be considered in this project (Yuzhno-Kirinskoye field). The focus is on environmental conditions analysis (icing and sea description) as these are the most important for marine operations. We are not expected to carry out such operations when there is drifting sea ice.

Kirinskoye field subsea manifold installation example will be introduced to define some parameters for subsea manifold (mass, dimensions). Basing on manifold parameters a vessel for lifting operations will be chosen. Calculations and analysis are based on the parameters of a particular typical vessel.

Some discussions about lifting operations and environmental conditions standards (DNV) will be added.

The weather window estimation process will be shown in this report.

A probabilistic approach with Monte Carlo simulation will be used in calculations. It is important to know the probability of exceeding the operational limiting criteria value of wave height and icing rate. In the report relevant theory is included to perform calculations.

Acknowledgement

I would like to thank Professor Ove Tobias Gudmestad, Professor Anatoly Borisovich Zolotukhin and Professor Mirzoev Dilizhan Allakhverdievich for their consultation, support and valuable advices.

I appreciate that Stanislav Duplensky, Evgeny Pribytkov and Elena Skokova have found the time to give me useful information, which was included in the Master's Thesis.

Valuable consultation during the meeting in MRTS JSC office was given by Mikhail Balyka and Stanislav Nesterenko. The meeting was organised with the help of Anatoly Zolotukhin and Ekaterina Poelueva.

Table of Contents

List of Abbreviations

CDF – Cumulative Distribution Function

COG – Centre of Gravity

EDF – Exceedance Distribution Function

ITS – Integrated Template Structure

LRFD – Load and Resistance Factor Design

OCV – Offshore Construction Vessel

O&G – Oil and Gas

PDF – Probability Density Function

SWL – Safe Working Load

VMO – Veritas Marine Operations

List of Figures

List of Tables

1. Introduction

Several discoveries have been made on Sakhalin Island Shelf which attract the O&G companies. Some of the fields require subsea development due to deep waters and sea ice drifting. Kirinskoye field which is tied-back to shore is operating today (Figure 1).

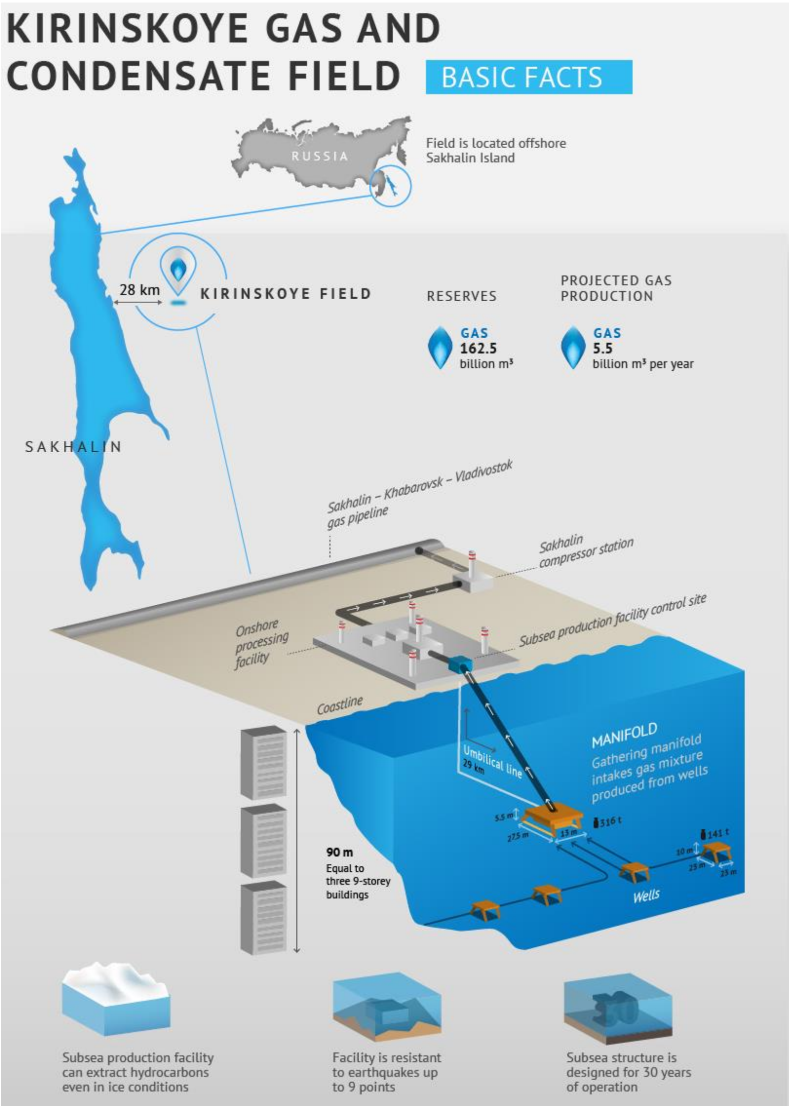


Figure 1 – Kirinskoye Field [1]

Future marine operations will be performed on another field in “Sakhalin 3” project as Gazprom is planning to develop Yuzhno-Kirinskoye field [2]. (Figure 2).

Figure 2 - Sakhalin Shelf Projects [3]

It is complex task to analyse all types of marine operations in Yuzhno-Kirinskoye field development project that is why only subsea template lifting operation is considered in this report. Initial data for lifting operation analysis and calculations is based on parameters of the Offshore Construction Vessel (OCV) “Normand Oceanic” as it has already performed marine operations in Kirinskoye project. Template parameters are close to Kirinskoye subsea manifold parameters. A company that needs to install subsea templates should be doing this in a safe way and with minimum risk. For instance, in Kirinskoye development project the analysis of manifold installation was based on DNV “VMO Standard” Part 2-5 [4], [5]. However, general information about requirements and recommendations for planning, preparations and performance of marine operations was given in DNV-OS-H101 [6]. Currently, DNVGL-ST-N001 [7] replaces the legacy DNV-OS-H-series.

Sea of Okhotsk is characterized by harsh environmental conditions. Estimation of exceeding the operational limits is carried out in this report as it is essential to define the risk of appearance of undesirable conditions. There are some important natural phenomena that have an impact on marine operations such as [6], [7]:

- wind;
- waves;
- current;
- tides.

Some environmental conditions also should be considered in marine operations design:

- sea ice;
- icing;
- temperature;
- fog etc.

The navigation period in the Sea of Okhotsk lasts approximately 5 months (June – October). Sea ice starts to form in November. Vessel icing is possible from October. In case of large scope of work installation vessels could be on site during icing period. This natural phenomenon does not lead to extremely dangerous conditions, especially on large vessels, but could decrease a safety level on board. According to [7], vessel icing should be considered in planning and execution of marine operations. This report includes explanation of icing mechanism and icing rate calculation procedure.

Subsea template installation is not a difficult operation which requires a very small significant wave height. Usually after onshore preparations the installation vessel goes to the installation area. The weather window should be longer than required time for installation to perform the lifting operation. The weather window estimation process will be shown in this report. Following LRFD calibrated alpha factor will be estimated.

2. Lifting Operation Area

The subsea template lifting operation which is considered in this report is referring to the Sakhalin Island Shelf. Sufficient depth and optimal conditions for subsea development are available for the development of the Yuzhno-Kirinskoye field, which is 6 km from the Kirinskoye field to the Southeast.

2.1. The Sakhalin Shelf and the Sea of Okhotsk

Harsh environmental conditions are the main feature of Sakhalin Island and the Sea of Okhotsk. Sea ice drifting, low temperature, winds and waves, seismic activity, tsunami are typical phenomena for this region [8].

Sakhalin is the largest island in Russia with the area of 78 000 km^2. On the west coast the Tatar Strait separates the island from the continental part. The east coast is washed by the Sea of Okhotsk. Sakhalin Shelf is the important fishing area where a lot of biological marine resources could be produced. Moreover, quite big amount of hydrocarbon resources have been explored and some of the oil and gas fields are under development (Table 1, Figures 1, 2, 3 and 4) [8].

Table 1 – Sakhalin Oil and Gas Industry Overview

Project name	Companies	Oil and Gas fields	Reserves	Water Depth	Distance to Shore	Main Facilities
Sakhalin - 1	Exxon Neftegas Limited	Chayvo	Oil: 26 mln m^3 Gas: 173 bln m^3 Condensate: 13 mln m^3	20-25 m	10-13 km	Offshore Orlan platform Onshore Yastreb rig Chayvo onshore processing facility De-Kastri Terminal
		Odoptu	Oil: 42 mln m^3 Gas: 198 bln m^3 Condensate: 11 mln m^3	25-30 m	6-10 km	Onshore Yastreb rig Chayvo onshore processing facility
		Arkutun-Dagi	Oil: 113 mln m^3 Gas: 292 bln m^3 Condensate: 16 mln m^3	35-50 m	23-33 km	Berkut platform Chayvo onshore processing facility
Sakhalin - 2	Sakhalin Energy	Piltun-Astokhskoye	Oil: 8 mln m^3 Gas: 140 bln m^3 Condensate: 10 mln m^3	30 m	16 km	Piltun-Astokhskoye-A platform (Molikpaq) Piltun-Astokhskoye-B
		Lunskoye	Oil: 8 mln m^3 Gas: 400 bln m^3 Condensate: 32 mln m^3	50 m	13 km	Lunskaya-A platform
Sakhalin - 3	Gazprom	Kirinskoye	Gas: 162 bln m^3 Condensate: 19 mln tons	90 m	28 km	Subsea production facility Onshore processing facility

Ref: [3], [8], [9].

Figure 3 – Sakhalin-1 Project [10]

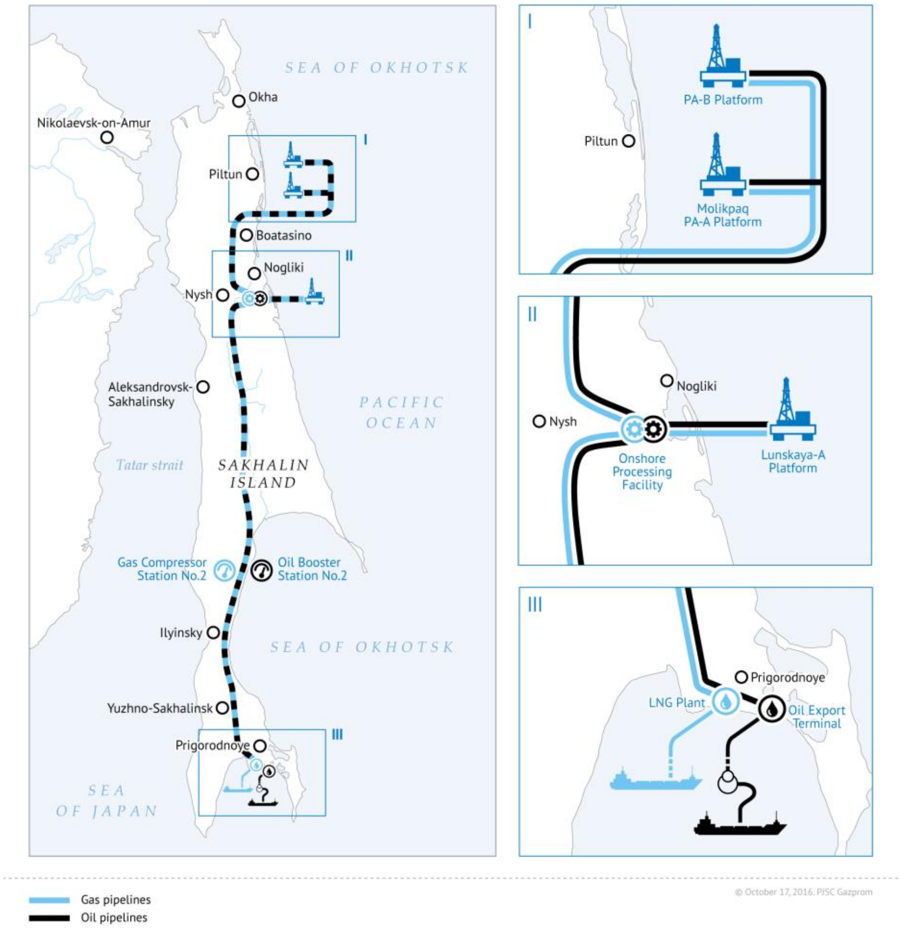


Figure 4 – Sakhalin-2 Project [11]

Gazprom is planning to develop Yuzhno-Kirinskoye field. Several subsea development concepts have been introduced. Two options are presented in Figures 5 and 6.

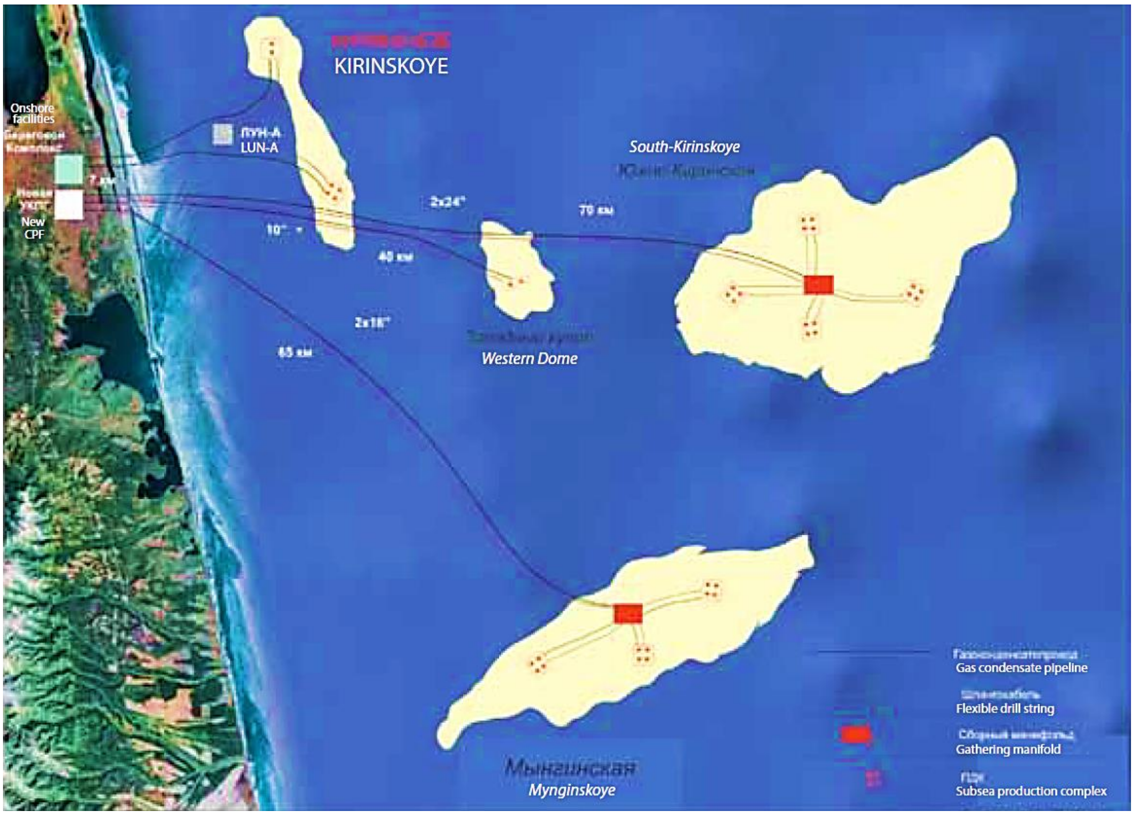


Figure 5 – Facilities Layout in Kirinskoye Block, Option 1 [12]

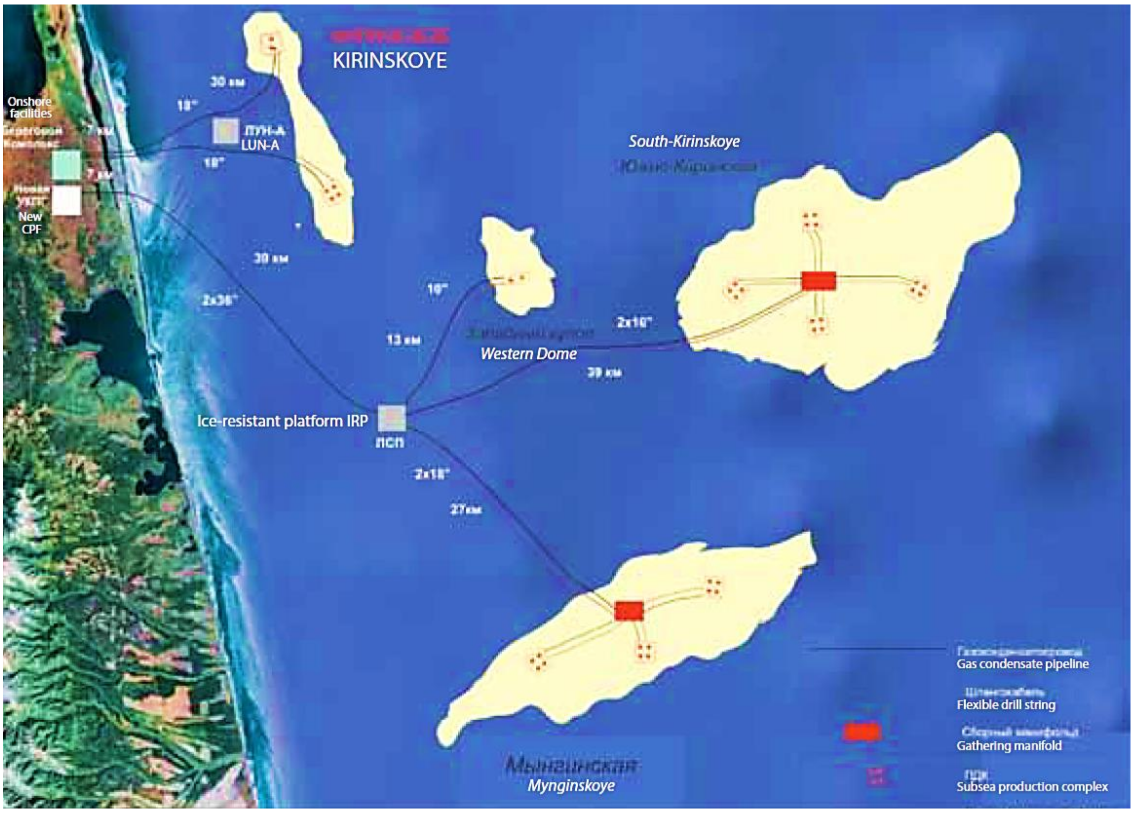


Figure 6 – Facilities Layout in Kirinskoye Block, Option 2 [12]

Yuzhno-Kirinskoye C1+C2 reserves (Russian system of reserves classification) amount is 711.2 bln m^3 of gas, 111.5 mln tons of gas condensate (recoverable) and 4.1 mln tons of oil (recoverable). The water depth changes from 110 m to 320 m. [3]

2.2. Meteorological Conditions

Sea of Okhotsk is considered as Sub-Arctic sea. Close location to the cold of the Siberian pole and development of the Siberian High results in harsh winters. However, small effect of tropical cyclones and Soya current contribute to mild summer climate. [13]

Temperature, wind speed and wave height distributions near Yuzhno-Kirinskoye field location (Figure 7) are shown on Figures 8, 9 and 10.

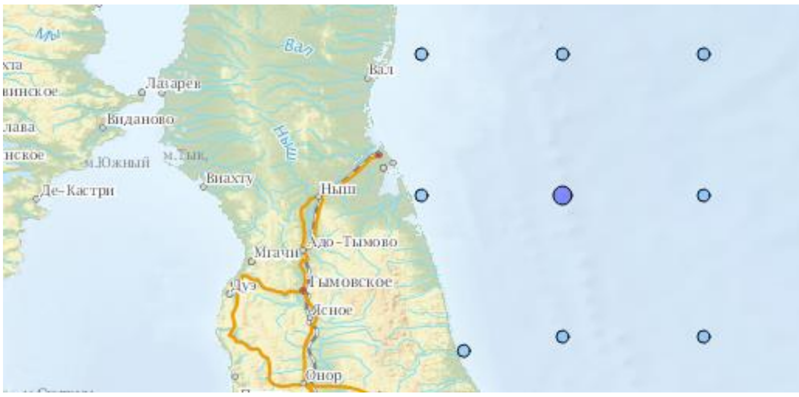


Figure 7 – Marked Point for Meteorological Data Extraction [14]

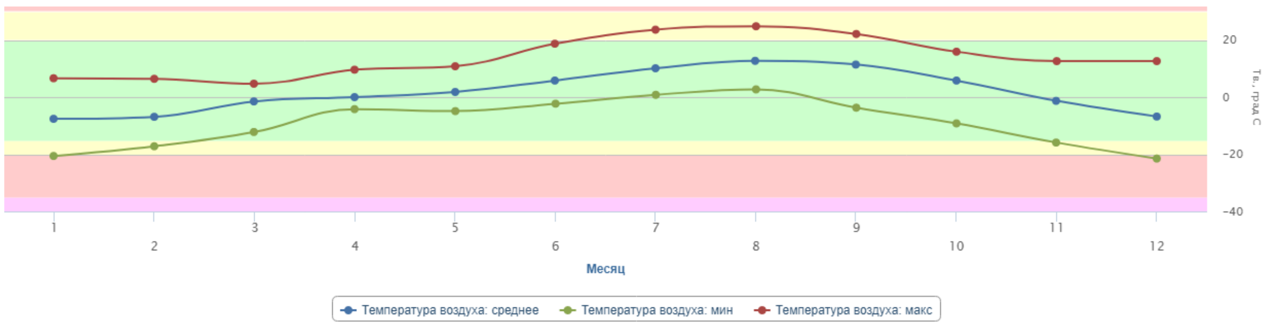


Figure 8 – Minimum (green), Maximum (red) and Mean (blue) Temperature (^{0}C) during a Year [14]

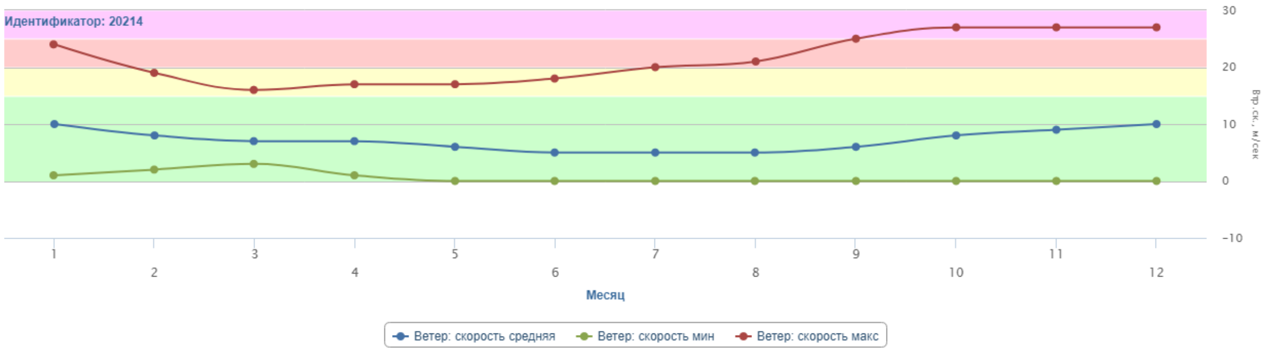


Figure 9 - Minimum (green), Maximum (red) and Mean (blue) Wind Speed (m/s) during a Year [14]

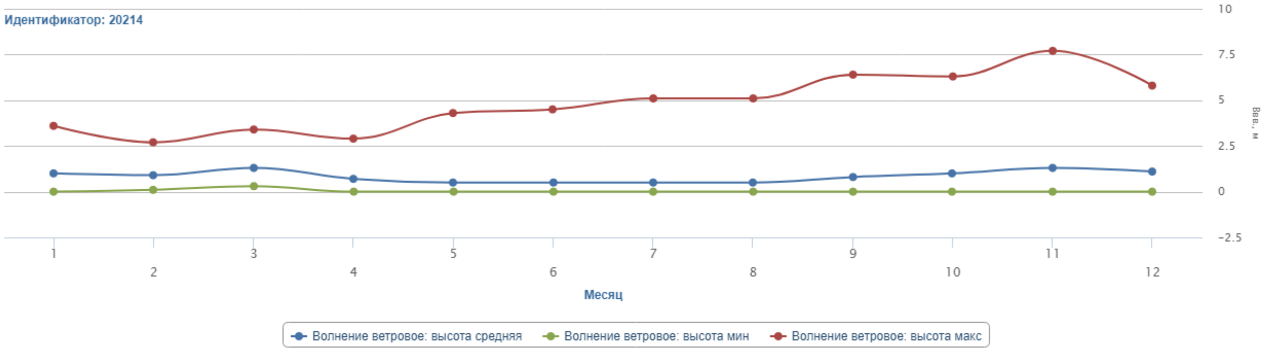


Figure 10 - Minimum (green), Maximum (red) and Mean (blue) Wave Height (m) during a Year [14]

3. Template and Vessel Selection

Selection principals are based on [4], [15]. The main objective is to perform marine operation. Initial parameters such as COG, mass, slings connection points etc. are presented in subsea equipment manufacturer's documents. A company which is responsible for marine operation performance should prepare installation procedure and lift analysis utilizing special software (e.g. OrcaFlex) and following relevant standards (e.g. [7]).

3.1. Template Structure

Due to lack of information about possible subsea development concepts of Yuzhno-Kirinskoye field it is hard to select exact type of subsea structure which could be installed in this location. Many different factors will influence on selecting optimal subsea development concept. Comparison between Kirinskoye and Yuzhno-Kirinskoye fields is presented below (Table 2, Figure 11).

Table 2 – Comparison of Kirinskoye and Yuzhno-Kirinskoye Fields

Parameters	Kirinskoye	Yuzhno-Kirinskoye
Reserves	Gas: 162.5 bln m^3 Condensate: 19.1 mln tons	Gas: 711.2 bln m^3 Condensate: 111.5 mln tons
Peak production rate	5.5 bln m^3/year	21 bln m^3/year (planned)
Subsea facility	6 satellite wells 1 manifold Etc. (Figure 11)	N/A

Ref: [3]

Assumption: 6 wells provide 5.5 bln m^3/year production rate, therefore 21 bln m^3/year production rate could provide $\frac{21*6}{5.5} \approx 23$ wells.

According to [16] it is risky to drill complex wells because of short navigation period. One semi-submersible drilling rig could compete only one well per year.

Consequently, to reduce complexity it is better to use satellite wells or 4-slots Integrated Template Structure (ITS).

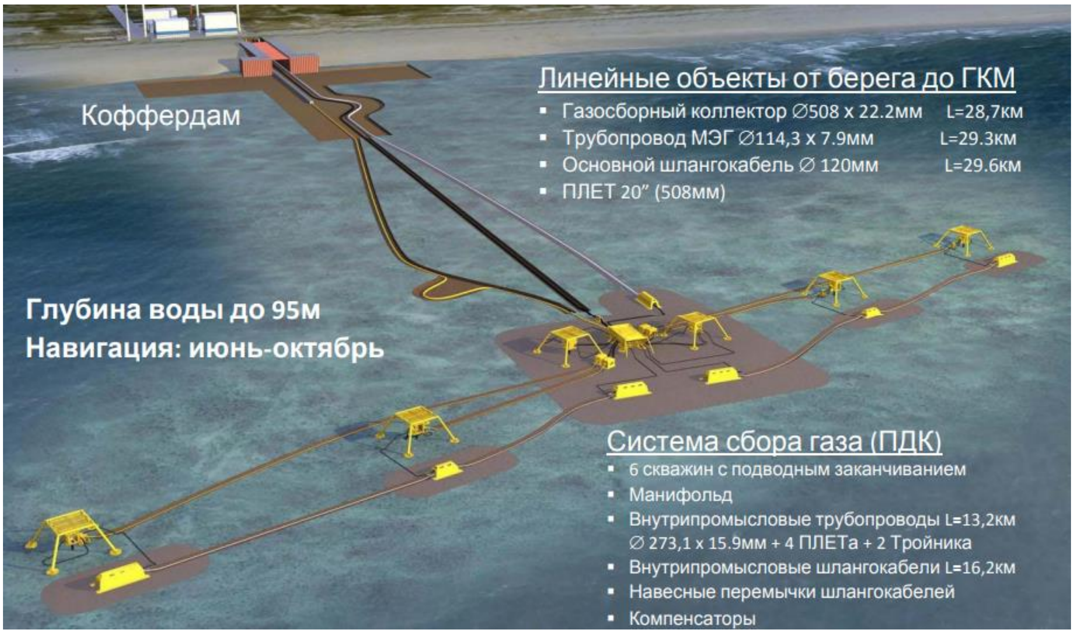


Figure 11 – Kirinskoye Field Layout [17]

Such parameters as mass, length, width and height of ITS, piles’ length etc. depend on specific field data. As an example, template structure with pre-installed manifold having the same mass and dimensions as Kirinskoye subsea manifold is taken (Figure 12, 13).

Figure 12 – Kirinskoye Subsea Manifold [17]

Figure 13 – Kirinskoye Subsea Manifold Lift off [4]

Manifold parameters:

- mass 300 tons [4];
- dimensions 27.5×13.1×4.9 m

3.2. Offshore Construction Vessel

300 tons manifold lifting operation considered in this report. “Normand Oceanic” vessel (the owner is Subsea 7) could perform this operation as the main crane Safe Working Load (SWL) is 400 tons and in addition active heave compensation system make it possible to operate in higher values of significant wave height H_s (Figure 14 and 15).

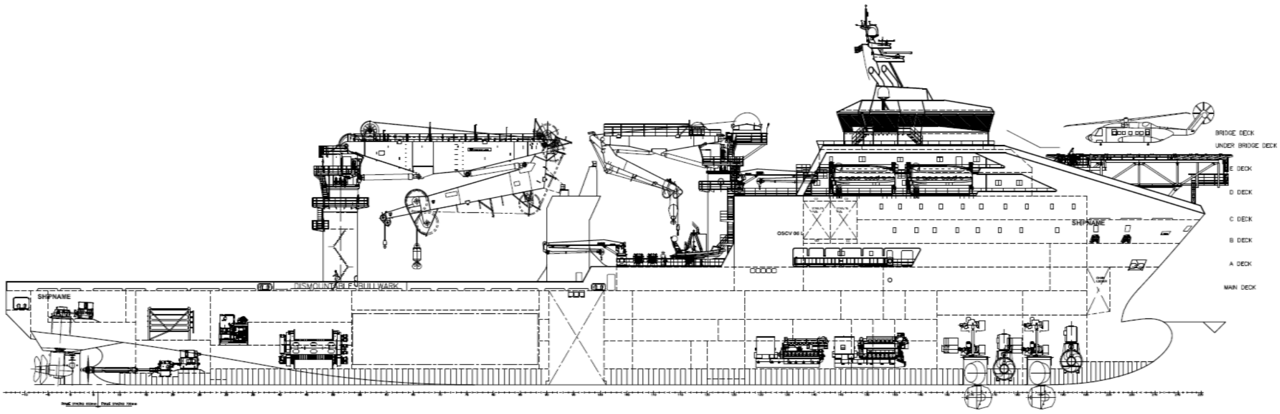


Figure 14 – OCV “Normand Oceanic” [18]

Normand Oceanic

Vessel main Particulars

- Vessel design: STX OSCV 06 L
- Class definition: 1A1, E0,DYNPOS AUTRO, DK(+), VIBR, TMON, HELDK-SH, ICE C, SF, CLEAN DESIGN, NAUT-AW, COMF-V(3),C3

Principal dimensions

- Vessel built: 2011
- Yard: STX Brattvåg
- LOA: 156,9 m
- Breadth mld: 27,0 m
- Summer draft: 8,5 m
- Deadweight: 11986 t
- Lighstship: 10805 t
- Gross tonnage: 16511 t

Power

- Total: 19 200 kW
- Main propulsion: 10 000 kW
- Max speed: 17,6 kn
- Economical speed: 12 kn

Propulsion

- Thusters: 2x 3000 kW
- Stern propeller: 1 x 4000 kW

Thrusters

- Bow thruster: 2x1900 kW
- Azimuth thruster: 2X 1500 kW

Cargo deck

- Deck space: 2 100 m²
- Deck strength: 10 t/m²
- Deck lenth x bredadth: 88,5 x 25,5 m

Cargo capacity summary

- Fuel oil: 2199,3 m³
- Ballast water: 8864,1 m³
- Fresh water: 1641,9 m³

Deck equipment

- Starboard crane: 2 x 3 t@15m
- Tugger winches: 4x10t

Offshore crane I

- Type: National Oilwell Varco
- SWL: 400 t@15 m
- Wire capacity: 3000 m

Aux winch

- SWL: 20 t single / 40 t double
- Wire capacity: 2600 m single / 1300 m double

Offshore crane II

- Type: National Oilwell Varco
- SWL: 100 t@15 m
- Wire capacity: 2000 m

Aux winch

- SWL: 10 t
- Wire capacity: 150 m

Dynamic Position system

- Class definition: DNV DYNPOS AUTRo, (DP3)
- Type: Kongsberg K-POS DP 21
- DGPS: Kongsberg DPS 200, K. 132, K. 116, 2 x SEAPATH
- HIPAP: 2x HIPAP 500
- Fanbeam: 1xMK 4,2
- Joystick: Kongsberg KPOS DP-11 BU, Kongsberg cJoy

Accomodation

- Total number of bunks: 140
- 1 man cabins: 58
- 2 man cabins: 41
- Mess room/Rec rooms: 1/4

Helicopter deck

- Type: Marine Aluminium
- CAP 437: Offshore helicopter, BSL D5-1, HCA
- Helideck monitoring system: Kongsberg HMS 100
- Diameter: 22.9 m

ROV equipment

- ROV hangar: 1 with launch for moonpool and recovery system for ROV

Moonpool

- 1 work moonpool w/hydraulic hatches and vertical guide beams
- Size: 7,2 x 7,2 m, 5,5 x 3,5 m

Carousel room

- Prepared for installation of carousel with 3000 t capacity

Figure 15 – “Normand Oceanic” vessel specification [18]

Lift analysis should be carried out before performing marine operation. Companies should follow required standards to perform safe marine operations. For example, in 2011 when subsea manifold was installed in Kirinskoye field location companies followed DNV-OS-H205 [5]. DNVGL-ST-N001 [7] has replaced legacy DNV-OS-H-series standards.

4. Short Term Sea Description

Important theory of sea description is based on [19].

Solution of linearized governing equations (i.e. boundary equations are applied at the mean free surface and first order terms are considered):

$$\xi(x,t) = \xi_0 \sin(\omega t - kx)$$

It is a sinusoidal wave but real waves do not look like this (except swell). They are less regular.

Assume that sea surface repeats after time T. Applying Fourier analysis the sea surface could be described as the sum of sinusoidal waves:

$$\xi(t) = \sum_{n=1}^{\infty}\left(a_n \cos\frac{2\pi n}{T} t + b_n \sin\frac{2\pi n}{T} t\right)$$

If $\xi_n = \sqrt{a_n^2 + b_n^2}$ and $\theta_n = arctan\left(\frac{b_n}{a_n}\right)$ sum transformed to:

$\xi(t) = \sum_{n=1}^{\infty} \xi_n \cos(\omega_n t - \theta_n)$.

Assume phase as a random variable uniformly distributed between 0 and 2π:

$\varXi(t) = \sum_{n=1}^{\infty} \xi_n \cos(\omega_n t - \varTheta_n)$

In order to obtain one realization of Ξ(t), N different phases could be generated, Θ_n, n=1, …, N.

Ξ(t) is a sum of a lot of independent random components. None of the components dominate hence according to the central limit theorem:

$f_{\varXi}(\xi,t) = \frac{1}{\sqrt{2\pi}\sigma_{\varXi}(t)} e^{-\frac{1}{2}\left(\frac{\xi}{\sigma_{\varXi}(t)}\right)^2}$ – Ξ_t is Gaussian (normal) probability distribution.

Description of a short term sea state:

- Wave spectrum, $S_{\Xi\Xi}(f)$.
- Spectral moments: $m_{\varXi,n} = \int_0^{\infty} f^n S_{\varXi\varXi}(f) df$
- Variance of surface process: $\sigma_{\varXi}^2 = m_{\varXi,0} = \int_0^{\infty} S_{\varXi\varXi}(f) df$

- Expected frequency between zero-up-crossing $\bar{f}_{02} = \sqrt{\frac{m_{\Xi,2}}{m_{\Xi,0}}}$ and average period between zero-up-crossing $\bar{t}_{02} = \frac{1}{\bar{f}_{02}}$
- Expected number of global waves in time T: $n_T = T\bar{f}_{02}$

5. Duration of Marine Operation

According to [7], the duration of marine operations could be defined by an operation reference period, T_R (see Figure 6): $T_R = T_{POP} + T_C$

where

T_R = Operation reference period;

T_{POP} = Planned operation period;

T_C = Estimated maximum contingency time.

The planned operation period (T_{POP}) should normally be based on a detailed schedule for the operation.

Typical subsea template (ITS) lifting operation times are as follows [15]:

- Launch ROV and survey location - 2 h

- Connect lift rigging to template and remove sea fastening - 1h

- Overboard and deploy template - 4 h

- Orientate template by ROV or flying clump weight - 1 hr

- Land template, confirm position - 3 h

- Complete and confirm suction penetration of the structure - 24 h

- Overboard and install guide posts - 6 h

- Install template hatches - 8 h

- Overboard manifold - 1 h

- Deploy and land manifold on template - 2 h

- Recover rigging and ROVs - 2h

Planned operation period on Kirinskoye field was 24 h. Scope of work [4]:

- Set-up over installation location;
- ROV preparation and deployment;
- Survey of location, preparation of ROV tools;

- Rigging installation, remove sea fastening;
- Overboard and deploy manifold;
- Orientate template by ROV, land the manifold, confirm position;
- Recover rigging and ROV.

Contingency time, T_C, is added to cover:

- General uncertainty in the planned operation time, T_{POP}.

- Possible contingency situations which may occur during marine operation consuming extra time to finish the installation.

DNVGL [7] requires more than 6 hours contingency time. Six hours value of contingency time is taken.

Reference time for manifold installation is 30 h (24+6).

6. Weather Restricted and Weather Unrestricted Operations

Marine operations with a reference period (T_R) less than 96 hours and a planned operation time (T_{POP}) less than 72 hours are considered to be weather restricted (Figure 17). In case of larger values of T_R and T_{POP} if marine operation can be halted it is still considered as weather restricted. Otherwise, marine operation should be designed as weather unrestricted. [7]

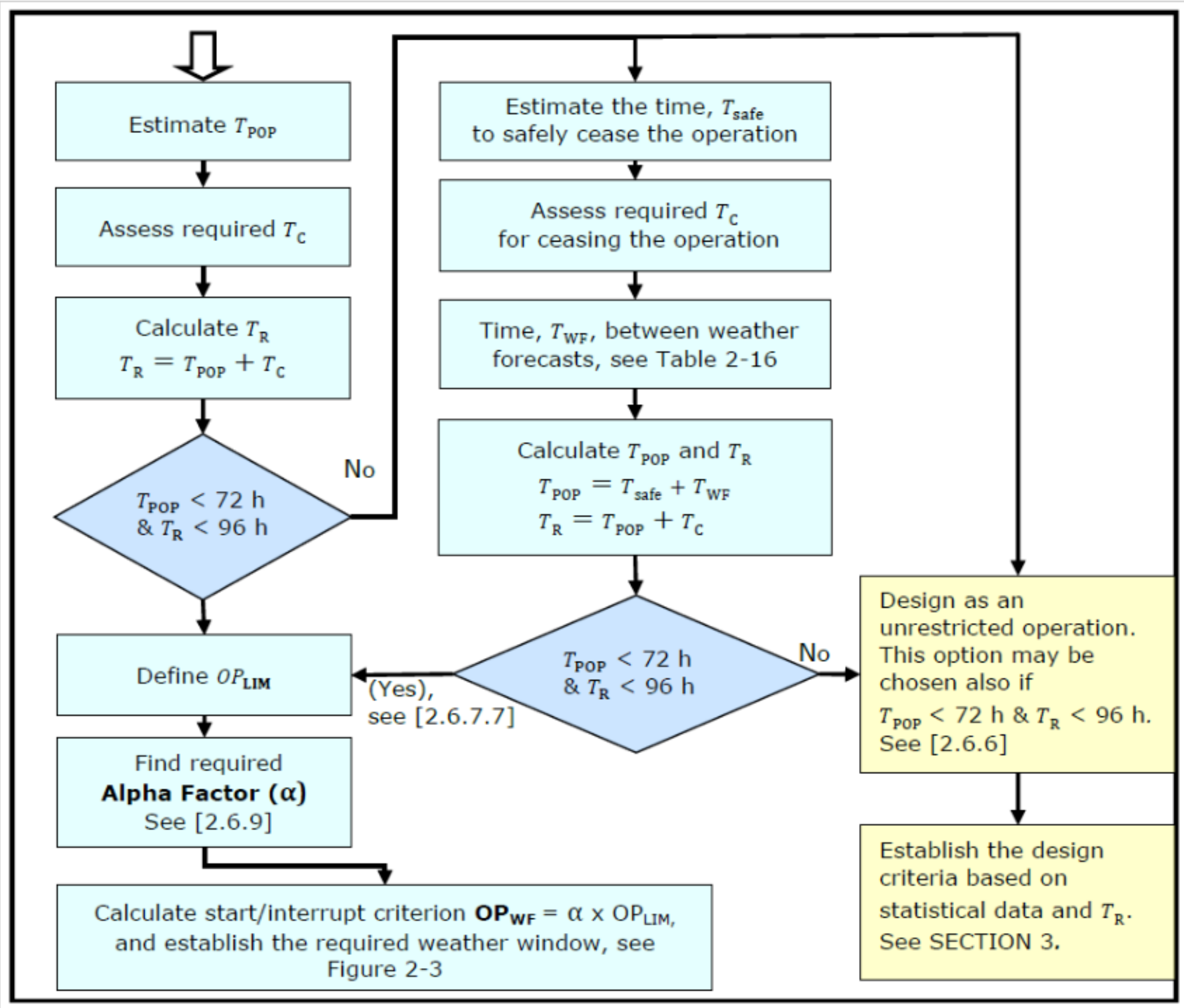


Figure 16 – Determination Procedure of Weather Restricted and Weather Unrestricted Operations [7]

As reference time for manifold installation is 30 h and planned operation period is 24 h this marine operation is considered as weather restricted. The next step is to define operational limiting environmental criteria (OP_{LIM}).

7. Operational Limiting Environmental Criteria

Environmental loads for weather restricted operations are selected independent of statistical data. For weather unrestricted marine operations the design criteria is based on extreme value statistics.

The OP_{LIM} depend on: [7]

- The environmental design criteria.
- Maximum wind and waves for safe working or personnel transfer.
- Weather restrictions determined for equipment.
- Limiting weather conditions of diving system (if any).
- Limiting conditions for position keeping systems.
- Any limitations identified, e.g. in HAZID/HAZOP, based on operational experience with involved vessel(s), equipment, etc.
- Limiting weather conditions for carrying out identified contingency plans.

DNV GL Standard [7] defines some equipment limitations for subsea lifting operation. That is why analysis should be performed to not exceed these restrictions. Than simulations are carried out to define which value of environmental parameters leads to exceeding equipment limitations. It is easy to check which values of Hs and Tp correspond to extreme tension, for instance, in slings or crane fall utilizing special software (e.g. OrcaFlex).

As an example, key points of Kirinskoye manifold lift analysis are introduced bellow: [4]

1. Acceptance criteria for operations:
    - The minimum clearance between the lifting equipment or the crane boom and any other object/structure should normally not be less than 3m.
    - The manifold should not tilt more than 2 degrees in any direction.
    - The crane includes a Dynamic Amplification Factor (DAF) of 1.3.
    - The slings are designed for a DAF of 2.0.

- Utilization Factor (UF) should always be greater than zero.

2. Analyzed environmental conditions:
   - Hs = 0.75-2.5 m (changed values).
   - Tp = 6-10 s (changed values).
   - Pierson-Moskowitz wave spectrum.
   - Different angles wave headings.
3. Main crane load chart:

   Example of load chart is presented on Figure 18.

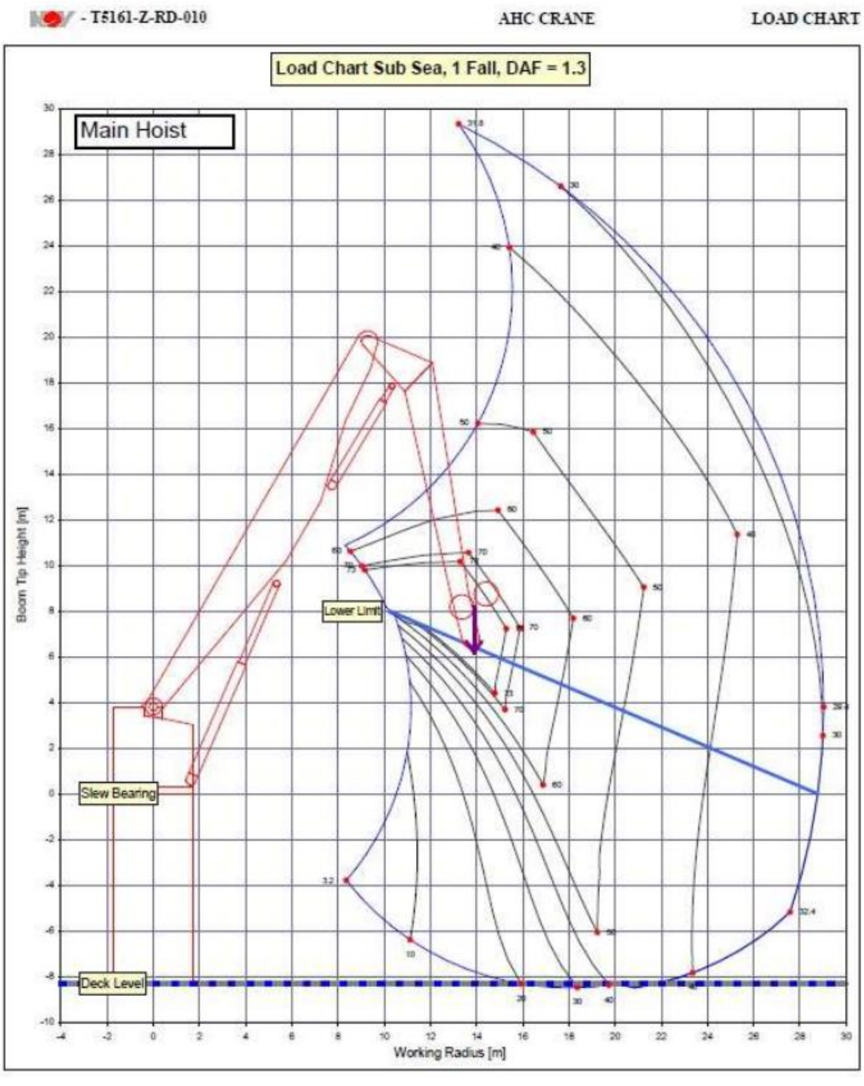


Figure 17 – Load Chart Example [22]

4. OrcaFlex simulations. The highest values are compared with criteria written above. The procedure (see Table 3):

Table 3 – Simulations Procedure [4]

Input	Hs_1	Hs_2	Hs_N
	Tp_1, Tp_2...Tp_N	Tp_1, Tp_2...Tp_N	Tp_1, Tp_2...Tp_N
	Several simulations for each Hs_1 Tp combination	Several simulations for each Hs_2 Tp combination	Several simulations for each Hs_N Tp combination
Important values calculated after simulations	Vessel pitch, roll Crane tip surge, heave Crane cross fall Manifold surge, sway, roll, pitch, yaw Crane fall and slings tension, DAF, UF		

The governing criterion is the crane cross-fall angle.

5. Operable sea states can be chosen after simulations analysis maximum. These sea states (Table 4) are used as operational limiting environmental criteria for weather window selection.

Table 4 – Example of maximum Hs and Tp

Tp, [s]	Hs, [m]
6	2.5
7	2
8	1.5
9	1
10	0.75

8. Weather Window

According to DNV GL [7], for subsea manifold lifting operation with 24 h planned operation period and 30 h reference period alpha factor shall be adjusted to defined operational limits. The alpha factor depends on the Weather Forecast (WF) levels which are described in standard [7] (Table 5).

Table 5 – Weather Forecast Levels [7]

Weather Forecast Level	A1	A2	B	C
Operation Sensitivity	High		Moderate	Low
Examples	• mating operations • offshore float over • multi barge towing • major (e.g. GBS) tow out operations • offshore installation operations • jack-up rig moves • sensitive laying operations		• tow-out operations • weather routed sea transports • offshore lifting • subsea installation • semi-submersible rig moves • standard laying operations.	• onshore/inshore lifting • load-out operations • short tows in sheltered waters/harbour tows • standard sea transports without any specified wave restrictions.
Meteorologist on site	Yes	No	No	
Dedicated Meteorologist	Yes	Yes	No	No
Minimum independent WF sources	2		2	1
Maximum WF interval	12 hours		12 hours	12 hours

"B" Weather Forecast level is chosen.

It is hard to forecast the weather with a hundred percent confidence. According to [7], uncertainty in forecasting of the environmental conditions could be taken into account by implementing the alpha factor. By multiplying alpha factor and values of operational limiting environmental criteria operational criteria - OP_{WF} can be defined ($OP_{WF} = \alpha \times OP_{LIM}$).

Without environmental monitoring applying Load and Resistance Factor Design (LRFD) method and “B” WF level alpha factor can be chosen from Table 6 [7].

Table 6 - LRFD Alpha Factor for waves, Level A2 or B – No Environmental Monitoring [7]

Planned Operation Period [h]	Operational limiting (OP_{LIM}) significant wave height [m]						
	$H_s = 1$	$1 < H_s < 2$	$H_s = 2$	$2 < H_s < 4$	$H_s = 4$	$4 < H_s < 6$	$H_s \geq 6$
$T_{POP} \leq 12$	0.68	Linear Interpolation	0.80	Linear Interpolation	0.83	Linear Interpolation	0.84
$T_{POP} \leq 24$	0.66		0.77		0.80		0.82
$T_{POP} \leq 36$	0.65		0.75		0.77		0.80
$T_{POP} \leq 48$	0.63		0.71		0.75		0.78
$T_{POP} \leq 72$	0.58		0.66		0.71		0.76

Defined OP_{WF} are in Table 7.

Table 7 - Operational Criteria (OP_{WF}) Estimation

Tp, [s]	OP_{LIM} = Hs, [m]	Interpolation equation	OP_{WF}, [m]
6	2.5	α = 0.015 Hs + 0.74 = 0.7775	1.94
7	2	α = 0.77	1.54
8	1.5	α = 0.11 Hs + 0.55 = 0.715	1.07
9	1	α = 0.66	0.66
10	0.75*	-	-

* According to DNVGL-ST-N001 [7] (Section 2.6.10.3) design wave heights less than one meter are normally not applicable for offshore operations.

Note that uncertainty in the forecasted wave periods should also be taken into account.

Finally, the weather window could be defined.

Required weather window could be estimated by searching a time interval when the operation will be completed. The operation is considered completed when the object is in a safe condition. For manifold lifting operation this condition will be the end of all scope of work.

Following DNV GL Standard [7], planned operation period start point is at the moment of the last weather forecast. See Figure 20.

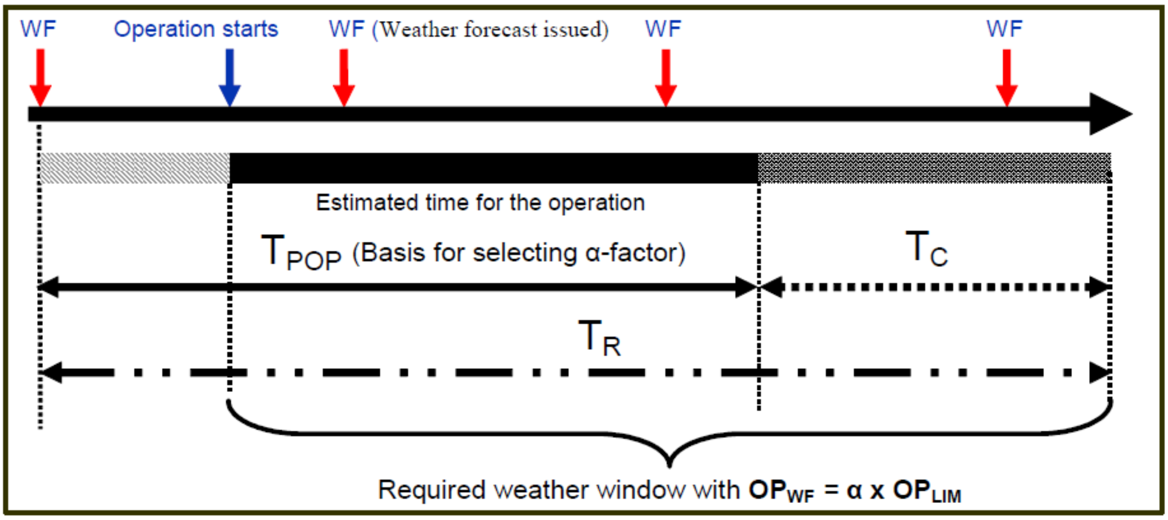


Figure 18 - Operation Periods [6]

Hence, required weather window could be estimated (see Figure 19) by searching time interval when forecasted parameter (e.g. significant wave height) is lower than defined operational criteria (OP_{WF}).

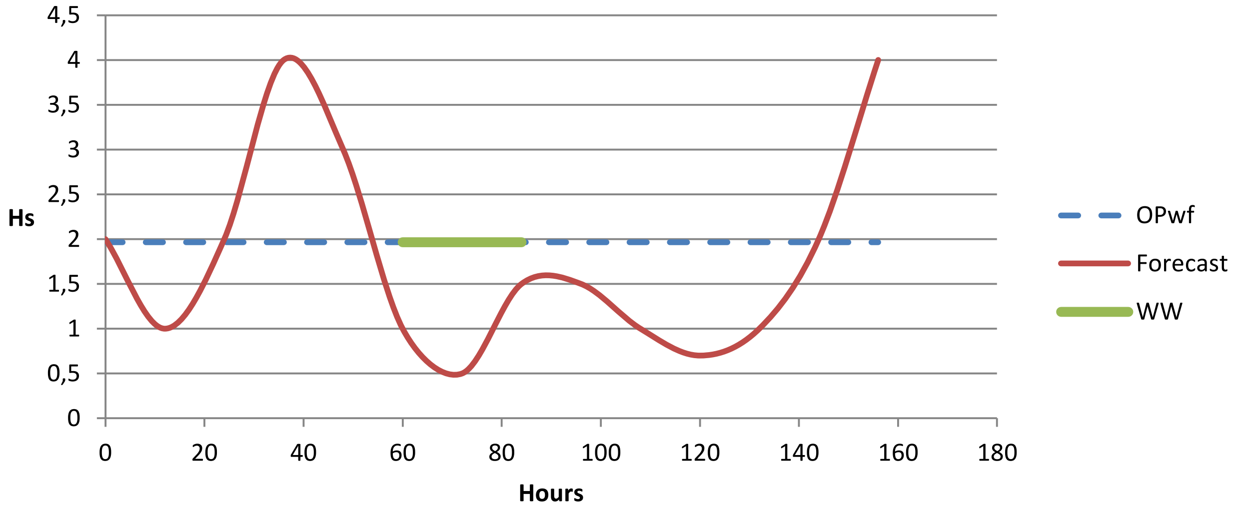


Figure 19 – The Weather Window Example for Manifold Lifting Operation

8.1. Weather Forecast

According to [7], the weather forecasts should be received at regular intervals before and during the manifold installation. Different providers should be the sources of independent weather forecasts (the most severe weather forecasts is preferred in case of difference between them). Public weather forecasts are not applicable for subsea lifting operations.

DNV GL [7] requires that the weather forecast should have general description of the weather situation and the predicted development and information about:

- wind speed and direction,

- waves and swell, significant and maximum height, mean or peak period and direction,

- rain, snow, lightning, ice etc.,

- tide variations and/or storm surge,

- visibility,

- temperature, and

- barometric pressure

- possibility for squalls and polar lows.

The weather forecasts should be issued for each 12 hours for minimum the T_R + 24 h. Also an outlook for at least the next 24 hours should be added. Standard [7] defines the levels of WF according to operational sensitivity to weather conditions and the operation reference period (see Table 5).

9. Probability of Exceeding the Operational Environmental Limiting Criteria

According to DNV GL Standard [7], the following should be checked to select appropriate alpha factor for waves:

> "The expected uncertainty in the weather forecast should be calculated based on statistical data for the actual site and the operation schedule, i.e. T_{POP}. The Alpha Factor should be calibrated to ensure that the probability of exceeding the operational environmental limiting criteria (OP_{LIM}) by more than 50% in LRFD is less than 10^{-4}."

According to long term wave statistics ([23] , Table 8), the most frequently appeared wave heights and periods in the Sea of Okhotsk could be defined. Note: $H_{3\%}$ is the wave height with 3% probability of exceedance defined value.

Table 8 – Joint Distribution of $H_{3\%}$ and Wave Period for ice-free period [23]

$H_{3\%}$, [m]	Wave period, [s]				
	2-4	4-6	6-8	8-10	10-12
0-2	3.1	35.5	8.9	0.8	0.07
2-4	1.4	22.4	10.6	0.9	0.06
4-6	0.14	5.0	6.3	0.9	0.02
6-8		0.4	1.8.	0.8	0.02
8-10			0.2	0.4	0.03
10-12			0.01	0.11	0.02

Wave period Probability Density Functions (PDF) for $H_{3\%}$ 0-2 m and $H_{3\%}$ 2-4 m are shown in Figure 20.

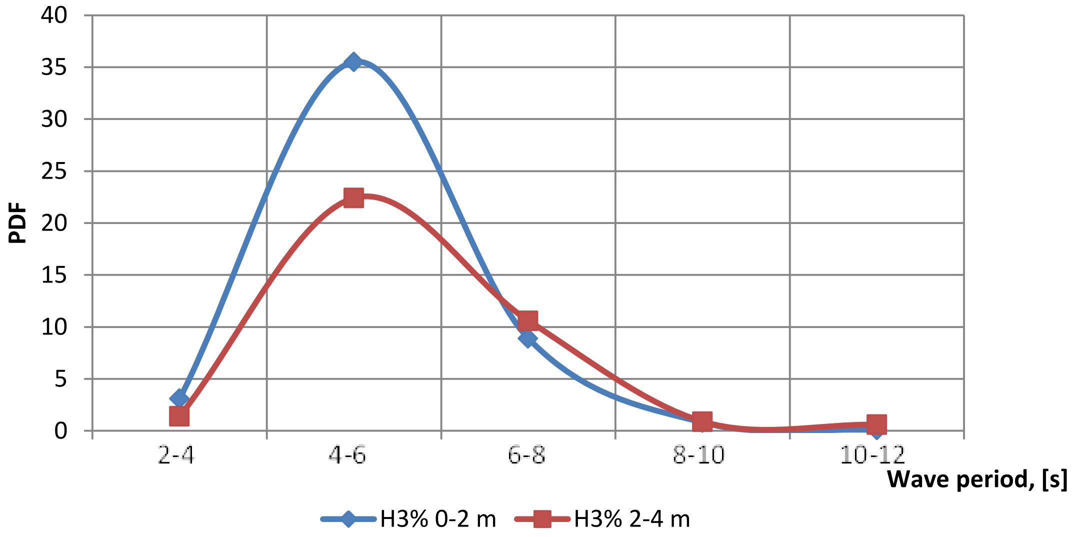


Figure 20 – Wave Period PDF for H3% 0-2 m and H3% 2-4 m

Analysing Figure 20, it could be said that waves with 4-6 seconds periods are the most frequently appeared when wave heights do not exceed 4 m. Larger wave periods are common for larger wave heights.

According to [22], JONSWAP spectrum at $\gamma = 2 \pm 1$ for $Hs/Tp^2 < 0.03$ and $\gamma = 1.4 \pm 0.4$ for $Hs/Tp^2 \geq 0.03$ is adopted for the assessment of spectra in the Sea of Okhotsk. Significant wave height, Hs (100 year return period) = 9.3 m. Wave spectrum peak period (100 year return period) = 14.6 s.

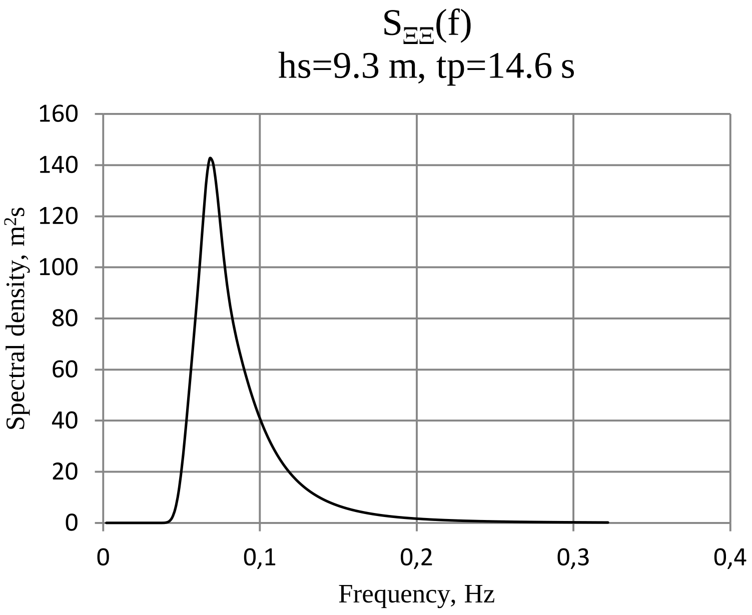


Figure 21 – JONSWAP Spectrum (based on [22])

However, for the purpose of designing marine operations simulations should be performed for the sea states assumed to be the limiting sea states for the operations [23]. For Kirinskoye field lifting analysis Pierson-Moskowitz wave spectrum was chosen. [23]: "If extreme loads are established, it is important to repeat the simulations with different random seed in order to reflect in inherent randomness of loads/responses that can be experienced during the operation. The number of simulations depends on the selected probability level for the characteristic design loads. This means that the design process must be established before the program for the simulations can be determined. A good rule of thumb is that one should select the number of repetitions so high that one can expect to see some few realizations above this level."

For the first pair of Hs and Tp values (see Table 4) the wave height with 10^{-4} probability of exceedance is defined. After that, for fixed Tp another Hs value is estimated such that the 50% increased value of this wave height will correspond to 10^{-4} probability of exceedance. Estimated Hs value is compared with OP_{LIM} and, finally, alpha factor could be defined.

Acceptable exceedance for whole operation is $F_{h_s}(h_{s,\ 24h}) = 10^{-4}$. In order to be successful during operation we must be successful for all 3 hour periods in 24 hour T_{POP}:

$$1 - F_{h_s}(h_{s,\ 24h}) = \left(1 - F_{h_s}(h_{s,\ 3h})\right)^{\frac{24}{3}}$$

$$P = F_{h_s}(h_{s,\ 3h}) = 1 - \left(1 - F_{h_s}(h_{s,\ 24h})\right)^{\frac{1}{8}}$$

For Gaussian surface elevation process distribution of global maxima (global crest height) is Rayleigh distribution [19]:

$$\text{CDF:}\ \ F_{c_G}(c) = 1 - e^{\left(-\frac{1}{2}\left(\frac{c}{\sigma_{\Xi}}\right)^2\right)}$$

Distribution of 3 hours maximum crest height:

$$P = F_{c_{3h}}(c) = \left(1 - e^{\left(-\frac{1}{2}\left(\frac{c}{\sigma_{\Xi}}\right)^2\right)}\right)^{n_{3h}}$$

The zero-up-crossing wave period t_{02} may be related to the peak period by the following approximate relations ($1 \leq \gamma \leq 7$) [23] (note: $\gamma = const = 1$ for PM wave spectrum):

$$\frac{t_{02}}{Tp} = 0.6673 + 0.05037\gamma - 0.006230\gamma^2 + 0.0003341\gamma^3$$

Number of waves in 3 hour: $n_{3h} = \frac{T}{t_{02}} = \frac{3 \times 3600}{0.726 \times T_p}$

Assume that variance is equal to [23]: ${\sigma_{\Xi}}^2 = \frac{1}{16} H_s^2$

As a result of calculations (see Appendix A) new Hs value is estimated such that the 50% increased value of OP_{LIM} wave height corresponds to 10^{-4} probability of exceedance.

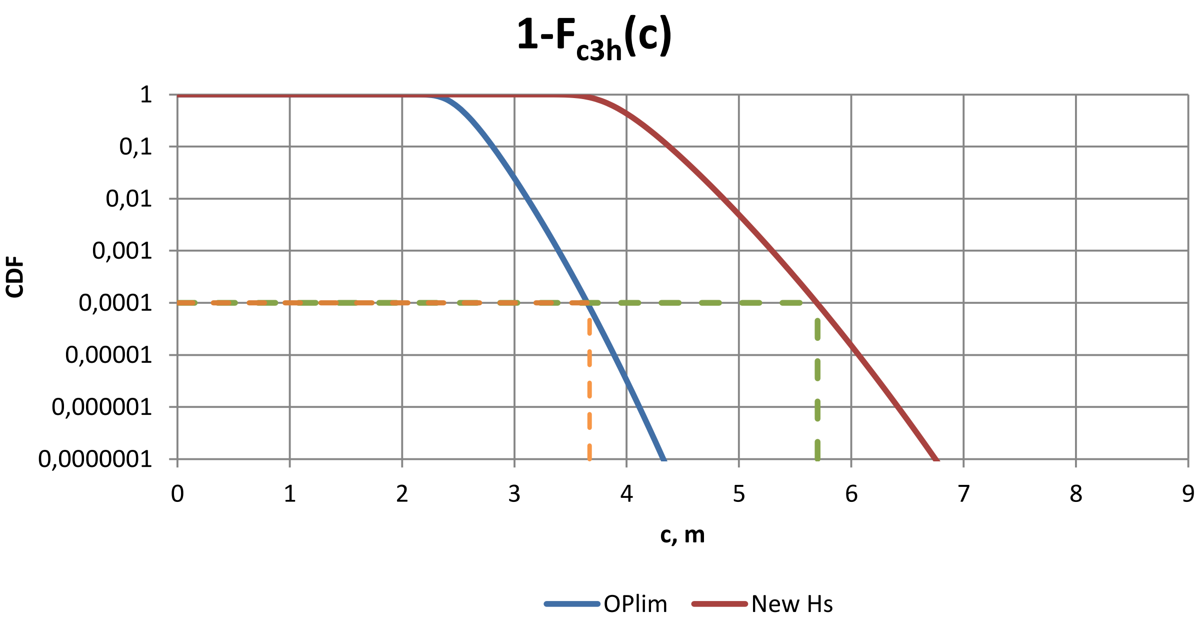


Figure 22 – Cumulative Distribution Functions Calculated for Different Hs

Calibrated alpha factor is 0.641. In case of 56% higher value of forecasted Hs than OP_{LIM} value, the probability of exceeding the operational environmental limiting criteria (OP_{LIM}) by more than 50% in LRFD is less than 10^{-4}.

10. Icing

Strong wind, big wave height and low air temperature are common conditions for the Sea of Okhotsk which could be observed since autumn. Such conditions are contributes to vessel icing. This phenomenon should be taken into account as big amount of ice causes some problems to perform marine operation such as slippery deck, blocked exits and equipment as well as vessel instability. Icing is very dangerous for fishing boat. There are some examples when fishing boats are capsized because of severe icing on the deck which was the reason of vessel reduced stability. As for big vessels with high free board, icing could lead to safety level decreasing. However, if possible icing conditions are forecasted and icing rate is defined, marine operation can be planned with special precautions to perform risk reduction activities.

Icing phenomenon has been studied for a long period. Some icing prediction models was introduced, however, today researchers are still trying to improve their models to make more accurate predictions.

According to [24], the reason of icing is mostly because of sea spray. Spray is generated when the vessel hits the sea waves. In the air the spray is moving and cooling and finally freezing. Required conditions for icing are open water, strong wind, waves and air temperature below freezing point of water. Icing mechanism is shown on Figure 23.

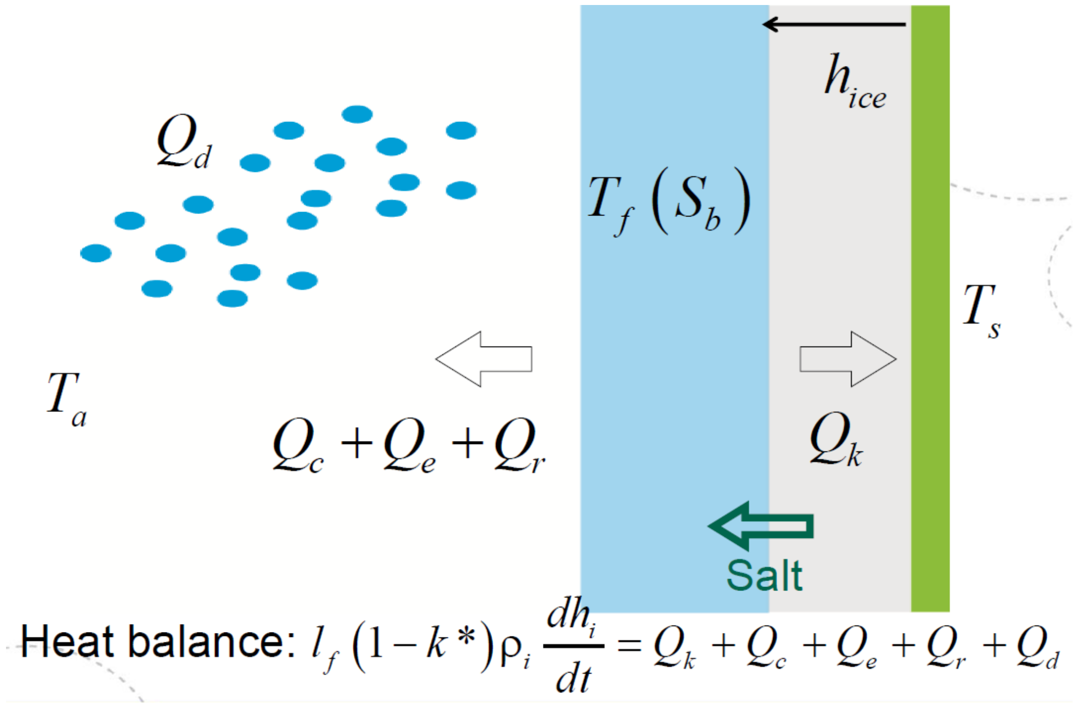


Figure 23 – Wet Icing. Heat Fluxes (continuous spray) [24]

The terms in Figure 23 are defined as follows:

Q_r – radiation. This term could be neglected due to no sun during storm.

$Q_d = Rc_w(T_f - T_d)$ – spray cooling due to freezing temperature.

R – spray flux during spraying, c_w – specific heat capacity of water, T_d – droplet temperature, $T_f = -\frac{S_b}{0.0182}$ – freezing temperature which depends on water salinity.

$Q_c = h(T_f - T_a)$ – convective heat flux.

T_a – air temperature, h - heat transfer coefficient.

$h = \frac{Nuk_a}{L}$, $Nu = 0.03Re^{0.8}$ – for turbulent flow, $Re = \frac{VL}{\nu}$, k_a – thermal conductivity of air, L – characteristic size.

$Q_e = 0.017h\left(e_v(T_f) - r_H e_v(T_a)\right)$ – evaporative heat flux.

$e_v(T) = 611.2e^{\frac{17.67T}{T+243.5}}$ – saturated vapour pressure for given temperature, r_H – relative humidity of air.

$Q_k = k_{ice}\frac{dT}{db}$ – conduction heat flux (this term is neglected in calculations).

k_{ice} – heat conductivity of ice, b – ice thickness.

For periodic spray the heat equation becomes:

$$l_f(1-k^*)I = Q_c + Q_e + \frac{t_{dur}}{t_{per}} Q_d$$

l_f – latent heat of fusion of water, I – ice accretion rate, $k^* \approx 0.3$ – the interfacial distribution coefficient.

Assume the freezing temperature (due to different salinity content) and droplets temperature to be random variables with normal distributions. Monte Carlo simulations (see Appendix B) will be used to estimate the probability distribution function of ice growth.

Samuelsen E. [25] collected icing-rate severity categories from different literature sources in one table (see Table 9). Upper boundary icing-rate value of light icing in Overland classification is considered in this report. Minimum ice on the deck gives the smallest safety risk.

Table 9 – Icing-rate Severity Categories [25]

Category/Source	Mertins (1968)	LU[a]	WMO[b]	WC[c]	BR[d]	Overland[e]
Trace	-	-	-	0.25-0.64 cm $(3\ h)^{-1}$	<0.20 cm h^{-1}	-
Light	1-3 cm $(24\ h)^{-1}$	0.5-2 cm $(12\ h)^{-1}$	1 cm $(3\ h)^{-1}$	0.64-1.27 cm $(3\ h)^{-1}$	0.20-0.40 cm h^{-1}	<0.70 cm h^{-1}
Moderate	4-6 cm $(24\ h)^{-1}$	1-3 cm $(4\ h)^{-1}$	1-5 cm $(3\ h)^{-1}$	1.27-1.91 cm $(3\ h)^{-1}$	0.40-0.96 cm h^{-1}	0.7-2.0 cm h^{-1}
Severe	7-14 cm $(24\ h)^{-1}$	>4 cm $(4\ h)^{-1}$	6-12 cm $(3\ h)^{-1}$	1.91-3.18 cm $(3\ h)^{-1}$	>0.96 cm h^{-1}	2.0-4.0 cm h^{-1}
Very severe	≥15 cm $(24\ h)^{-1}$	-	>12 cm $(3\ h)^{-1}$	>3.18 cm $(3\ h)^{-1}$	-	>4.0 cm h^{-1}
	Icing-rate unit (cm h^{-1})					
Light	≤0.17	≤0.25	≤0.33	≤0.42	≤0.40	≤0.70
Moderate	0.17-0.29	0.25-1.0	0.33-2.0	0.42-0.64	0.40-0.96	0.7-2.0
Severe	>0.29	>1.0	>2.0	>0.64	>0.96	>2.0

a Lundqvist and Udin (1977).
b WMO definition from 1975 according to Lundqvist and Udin (1977).
c Wise and Comiskey (1980).
d Brown and Roebber (1985)
e Overland *et al.* (1986) and very severe from Overland (1990).

For certain weather conditions the probability of exceedance 7 mm/hr ice growth value will be estimated.

11. Ice Growth Calculation

Ice growth distribution is shown on Figure 24. Matlab code is in Appendix C.

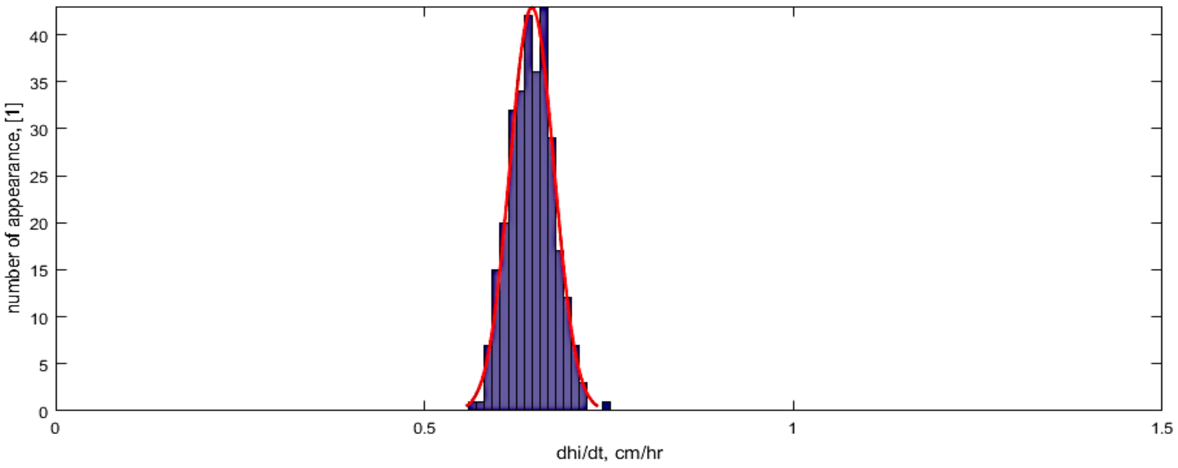


Figure 24 – Ice Growth Probability Density Function

A cumulative probability distribution is defined (see Figure 25) to calculate probability of exceeding the required value of ice growth.

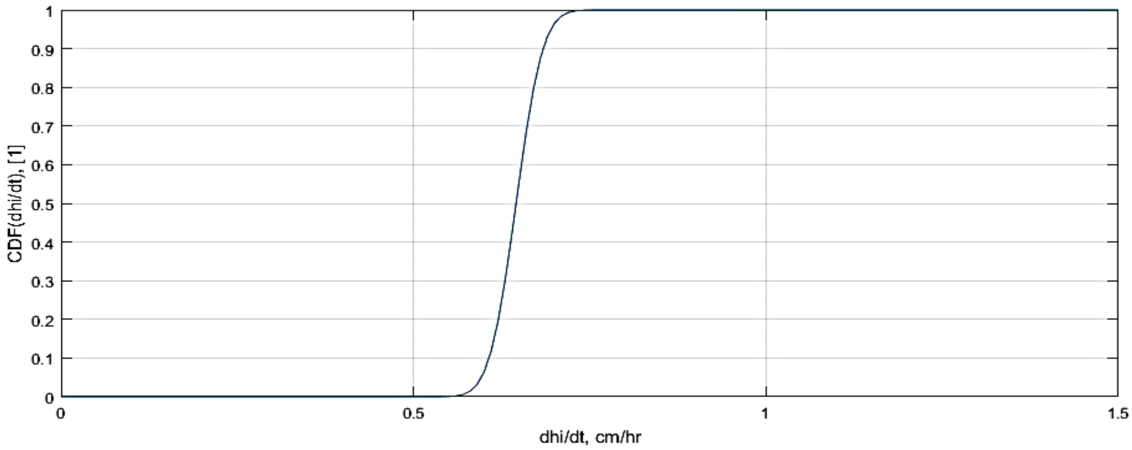


Figure 25 - CDF of Ice Growth

Probability of exceeding 7 mm/hr ice growth is $EDF = 1 - CDF = 0.034$ (see Figure 26).

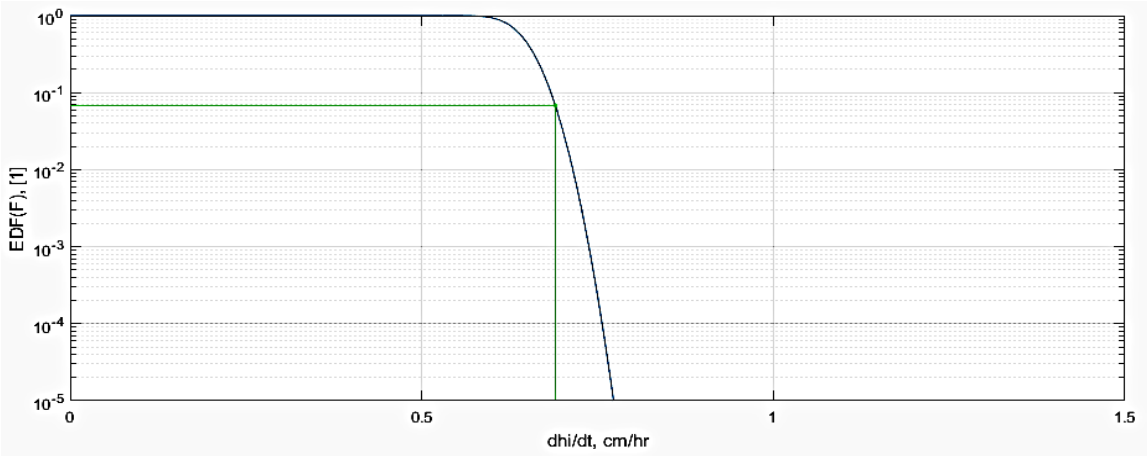


Figure 26 - Estimation of 7 mm/hr Probability of Exceedance

12. Discussions

12.1. Weather Window Estimation

A huge scope of work should be performed before subsea manifold installation. The manifold lift analysis should be carried out to satisfy safety requirements. The basic theory in such analysis is the stochastic approach of sea state description. When operational limiting criteria are established the weather window can be defined. Following LRFD approach, the probability of exceedance the operational limiting criteria by more than 50% should be less than 10^{-4}. According to this, calibrated alpha factor was defined.

12.2. Calculated Probability of Exceedance icing-rate value

Performed calculations give only rough estimation of exceedance probability. More accurate models are based on high quality data and specific vessel parameters. Moreover, computational fluid dynamics principals are applied in these models. More information about ship-icing prediction methods is available in [25].

However, general icing physics was applied with utilizing of two parameters as random variables with normal probability density functions. Monte Carlo simulation with three hundred iterations was used to define icing-rate PDF. Hence, CDF was defined to estimate the probability of exceedance 7 mm/h icing-rate. If in LRFD 10^{-4} probability of exceedance limiting value is established, the chosen weather conditions are not suitable for marine operation performing.

13. Conclusion

The procedure of weather window estimation which is based on DNVGL-ST-N001 Standard [7] was shown in this report. As the sea state could not be described by deterministic values of several parameters, limiting factors of marine operations are estimated by a probabilistic approach. It is important to operate in such conditions that probability of exceedance of limiting value will be very low.

The DNV GL Standard [7] procedure (for the wave limiting factor) was applied for Sea of Okhotsk conditions. It was shown how to describe the sea state. The weather window for a specific vessel and possible marine operation was estimated. And finally, the probability of exceedance the limiting values was calculated.

Due to short ice-free period in the Sea of Okhotsk companies will have less time to perform marine operations. Ship icing has to be analyzed to stay safe while working in autumn period. The basic analysis procedure is shown in this report.

References

[1] "PJSC Gazprom," [Online]. Available: http://www.gazprom.com/f/posts/62/971877/infographics-kirinskoye-en.jpg. [Accessed 4 April 2018].

[2] E. V. Petrenko, "Subsea Technology - The Key Solution for The Arctic and Far East fields development," in *13th International Conference and Exhibition for Oil and Gas Resources Development of the Russian Arctic and CIS Continental Shelf,* Saint-Petersburg, 2017.

[3] "PJSC Gazprom," [Online]. Available: http://www.gazprom.com/f/posts/19/374463/sakhalin3-map-01-en-2016-04.png. [Accessed 15 January 2018].

[4] S. Nesterenko, *Information regarding manifold installation during Kirinskoye field development,* 2018.

[5] DNV GL, *Lifting Operations (VMO Standard - Part 2 - 5), DNV-OS-H205,* 2014.

[6] DNV GL, *Marine Operations, General, DNV-OS-H101,* 2011.

[7] DNV GL, *Marine operations and marine warranty, DNVGL-ST-N001,* 2016.

[8] A. I. Ermakov and V. S. Vovk, "Meteorological and Hydrogeological Conditions of the North Eastern Coast of Sakhalin Island in the Okhotsk Sea," in *Basics of Offshore Petroleum Engineering and Development of Marine Facilities*, Stavanger, Moscow, St Petersburg, Trondheim, Oil and Gas, 1999, pp. 137-143.

[9] "Exxon Neftegas Limited," [Online]. Available: http://www.sakhalin-1.com/en-ru/company/about-us/phases-and-facilities. [Accessed 5 April 2018].

[10] "ITOCHU Group," [Online]. Available: http://www.itochuoil.co.jp/e/project/001_sakhalin.html. [Accessed 15 April 2018].

[11] "PJSC Gazprom," [Online]. Available: http://www.gazprom.com/about/production/projects/lng/sakhalin2/. [Accessed 15 April 2018].

[12] M. N. Mansurov and E. V. Zakharov, "Sakhalin 3: The Geological and Engineering Principles," *ROGTEC*, no. 30, pp. 48-57.

[13] Sapozhnikov et al., "Hydrochemical Atlas of the Sea of Okhotsk 2001," [Online]. Available: https://www.nodc.noaa.gov/OC5/okhotsk/ok_doc.html#1.. [Accessed 12 January 2018].

[14] "ESIMO," [Online]. Available: http://portal.esimo.ru/dataview/viewresource?resourceId=RU_RIHMI-WDC_929&parameter=tempair&sea=okhot. [Accessed 20 April 2018].

[15] S. Duplensky, *Information regarding typical time needed for Marine Operations,* Stavanger, 2017.

[16] D. A. Mirzoev, *Information regarding Yuzhno-Kirinskoye field development,* Moscow, 2018.

[17] V. A. Golubev, "Gazprom activities on Russian Shelf," in *International Conference and Exhibition for Oil and Gas Resources Development of the Russian Arctic and CIS Continental Shelf*, Saint Petersburg, 2013.

[18] "SolstadFarstad ASA," [Online]. Available: https://solstad.no/wp-content/uploads/2014/01/Oceanic_ok_Part1.pdf. [Accessed 10 November 2017].

[19] S. Haver, “Lecture notes. OFF600 Marine Operations course,” Stavanger, 2017.

[20] “offshore-crane.com,” [Online]. Available: https://www.offshore-crane.com/120-ton-nov-subsea-knuckleboom-crane-for-sale/. [Accessed 20 May 2018].

[21] Russian Maritime Register of Shipping (RS), “Wind and Waves Statistical Data in Barents Sea, Sea of Okhotsk and Caspian Sea,” Saint Petersburg, 2003.

[22] G. V. Zhukov and S. V. Karlinsky, “Production Platforms for Russian Offshore,” in *The Sixth ISOPE Pacific/Asia Offshore Mechanics Symposium*, 2004.

[23] S. Haver, “Metocean Modelling and Prediction of Extremes,” Stavanger, 2017.

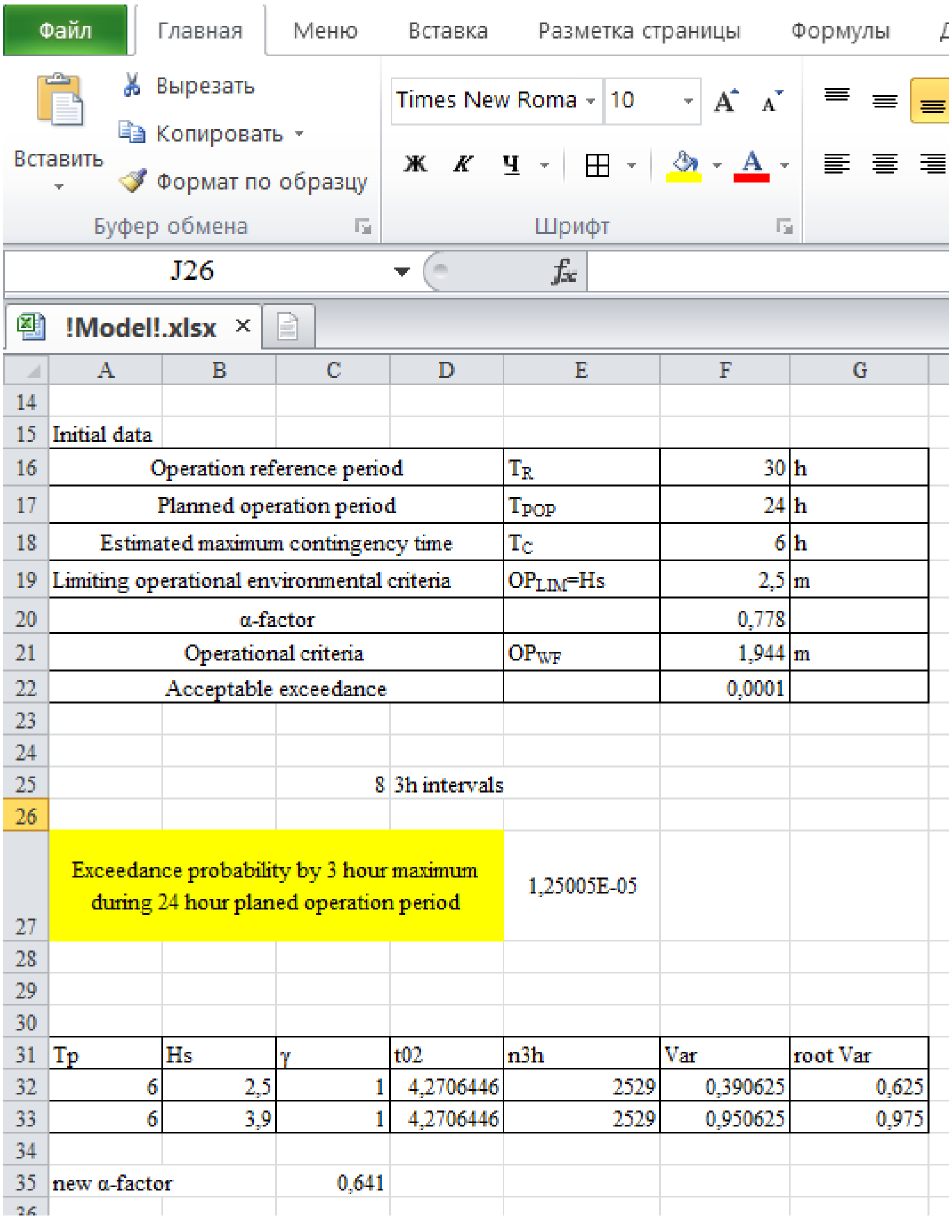
[24] DNV GL*, Environmental conditions and environmental loads, DNV-RP-C205.,* 2010.

[25] A. Kulyakhtin*, Icing, the course AT-327, UNIS,* 2017.

[26] E. M. Samuelsen, “Ship-icing Prediction Methods Applied in Operational Weather Forecasting,” *Quarterly Journal of the Royal Meteorological Society,* no. Volume 144, issue 710, 2017.

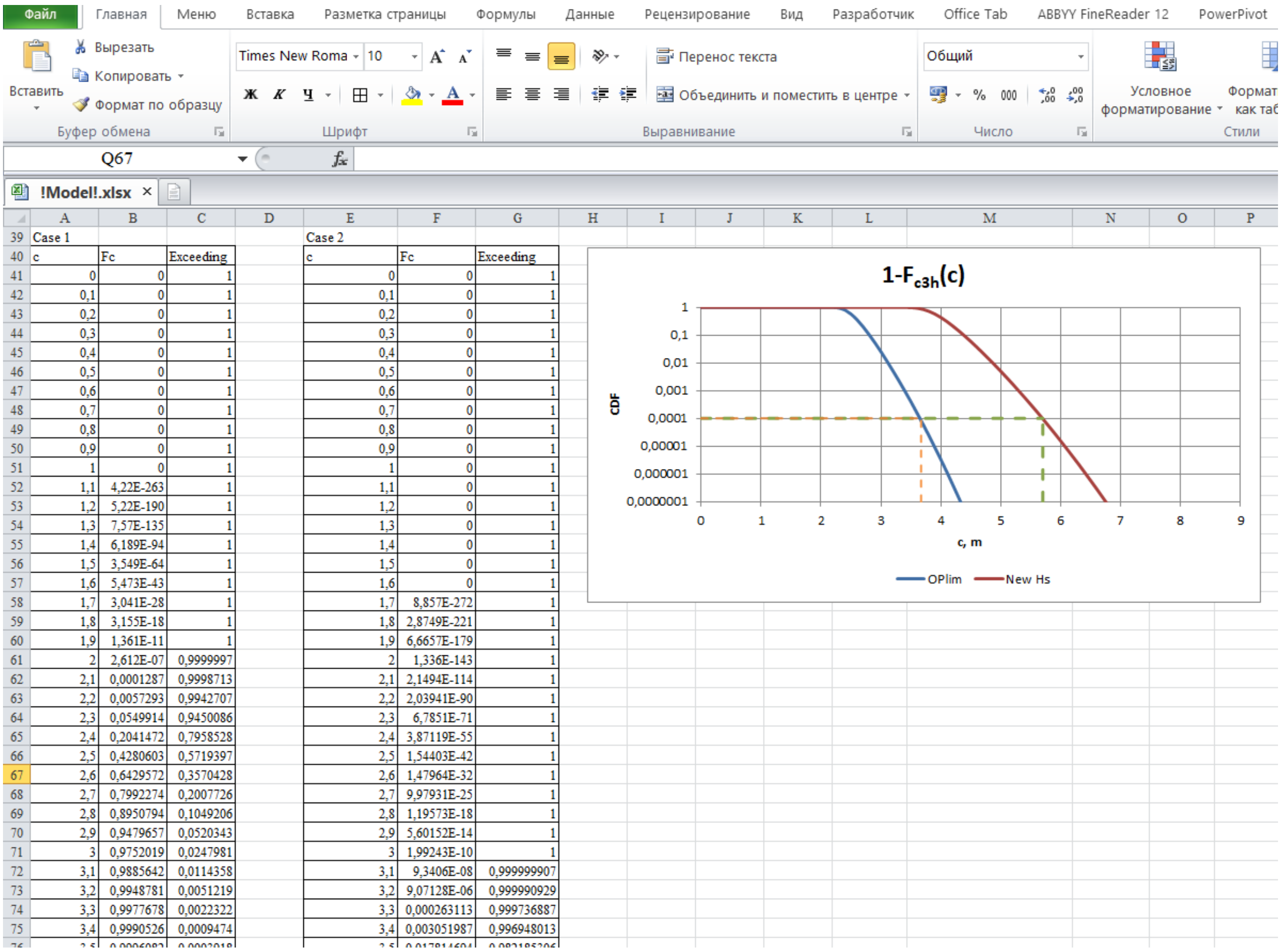
[27] A. Shestov*, Ice actions - Probabilistic approach (Monte Carlo Simulation), the course AT-327, UNIS,* 2017.

Appendix A



	A	B	C	D	E	F	G
14							
15	Initial data						
16	Operation reference period				T_R	30	h
17	Planned operation period				T_{POP}	24	h
18	Estimated maximum contingency time				T_C	6	h
19	Limiting operational environmental criteria				OP_{LIM}=Hs	2,5	m
20	α-factor					0,778	
21	Operational criteria				OP_{WF}	1,944	m
22	Acceptable exceedance					0,0001	
23							
24							
25			8	3h intervals			
26							
27	Exceedance probability by 3 hour maximum during 24 hour planed operation period				1,25005E-05		
28							
29							
30							
31	Tp	Hs	γ	t02	n3h	Var	root Var
32	6	2,5	1	4,2706446	2529	0,390625	0,625
33	6	3,9	1	4,2706446	2529	0,950625	0,975
34							
35	new α-factor		0,641				

Figure A 1 – Excel Sheet (part 1) for CDF Estimation



	A	B	C	E	F	G
39	Case 1			Case 2		
40	c	Fc	Exceeding	c	Fc	Exceeding
41	0	0	1	0	0	1
42	0,1	0	1	0,1	0	1
43	0,2	0	1	0,2	0	1
44	0,3	0	1	0,3	0	1
45	0,4	0	1	0,4	0	1
46	0,5	0	1	0,5	0	1
47	0,6	0	1	0,6	0	1
48	0,7	0	1	0,7	0	1
49	0,8	0	1	0,8	0	1
50	0,9	0	1	0,9	0	1
51	1	0	1	1	0	1
52	1,1	4,22E-263	1	1,1	0	1
53	1,2	5,22E-190	1	1,2	0	1
54	1,3	7,57E-135	1	1,3	0	1
55	1,4	6,189E-94	1	1,4	0	1
56	1,5	3,549E-64	1	1,5	0	1
57	1,6	5,473E-43	1	1,6	0	1
58	1,7	3,041E-28	1	1,7	8,857E-272	1
59	1,8	3,155E-18	1	1,8	2,8749E-221	1
60	1,9	1,361E-11	1	1,9	6,6657E-179	1
61	2	2,612E-07	0,9999997	2	1,336E-143	1
62	2,1	0,0001287	0,9998713	2,1	2,1494E-114	1
63	2,2	0,0057293	0,9942707	2,2	2,03941E-90	1
64	2,3	0,0549914	0,9450086	2,3	6,7851E-71	1
65	2,4	0,2041472	0,7958528	2,4	3,87119E-55	1
66	2,5	0,4280603	0,5719397	2,5	1,54403E-42	1
67	2,6	0,6429572	0,3570428	2,6	1,47964E-32	1
68	2,7	0,7992274	0,2007726	2,7	9,97931E-25	1
69	2,8	0,8950794	0,1049206	2,8	1,19573E-18	1
70	2,9	0,9479657	0,0520343	2,9	5,60152E-14	1
71	3	0,9752019	0,0247981	3	1,99243E-10	1
72	3,1	0,9885642	0,0114358	3,1	9,3406E-08	0,999999907
73	3,2	0,9948781	0,0051219	3,2	9,07128E-06	0,999990929
74	3,3	0,9977678	0,0022322	3,3	0,000263113	0,999736887
75	3,4	0,9990526	0,0009474	3,4	0,003051987	0,996948013

Figure A 2 - Excel Sheet (part 2) for CDF Estimation

Appendix B

The procedure of Monte Carlo simulation is represented in Figure B 1.

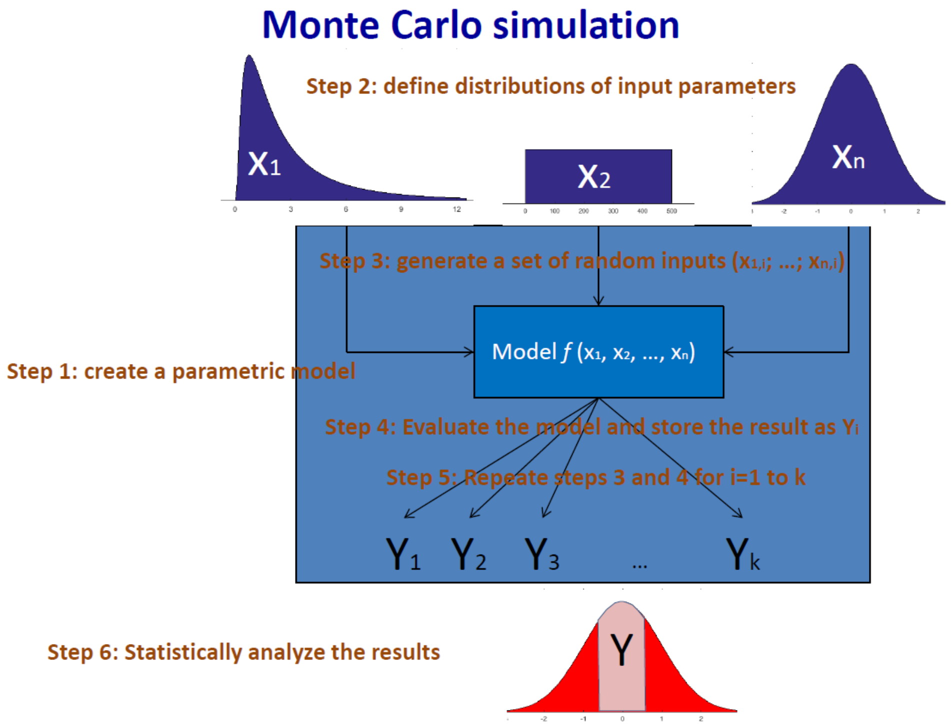


Figure B 1 – The Monte Carlo Simulation Procedure [25]

Appendix C

Matlab code for Monte Carlo simulations [7]:

```
clear all;
close all;
visc=13*10^(-6); %kinematic viscosity of air
cw=4000; %specific heat capacity of water
lf=3.4*10^5; %latent heat of fusion
pi=900; %ice density
k=0.3; %interfacial distribution coefficient
ki=2.3;  %heat conductivity of ice
ka=0.024; %thermal conductivity of air
D=27; %vessel width
V=15; %wind speed
rh=0.8; %relative humidity of air
R=0.1; %spray flux during spraying
tdur=2;
tper=60;
Tf=makedist('Normal','mu', -1.717, 'sigma', 0.03);
Td=makedist('Normal','mu', 6, 'sigma',1.33);
hFig = figure('units','normalized','outerposition',[0 0 1 1]);
iterations=300;
x=0:0.01:1.5;
Re=V*D/visc;
Nu=0.03*Re^0.8;
h=Nu*ka/D;
Qk=0; %neglected
Ta=262;
 for i=1:iterations
    T_f(i,1)=random(Tf)+273;
    T_d(i,1)=random(Td)+273;
    I_growth(i,1)=((h*(T_f(i)-Ta))+(0.017*h*(611.2*exp((17.67*(T_f(i)-
273))/((T_f(i)-273)+243.5))))+((tdur/tper)*R*cw*(T_f(i)-T_d(i))))/((1-
k)*lf*pi)*100*3600;
    pdf_freez=pdf(Tf,x);
    cdf_freez=cdf(Tf,x);
    pdf_dropl=pdf(Td,x);
    cdf_dropl=cdf(Td,x);

    if i>5
        subplot(2,2,1);
            histfit(I_growth);
```

```
        xlabel('dhi/dt, cm/hr');
        ylabel('number of appearance, [1]');
        axis([0 1.5 0 inf]);

subplot(2,2,2);
    f=0:0.01:1.5;
    pd_I=fitdist(I_growth,'Normal');
    pdf_I=pdf(pd_I,f);
    cdf_I=cdf(pd_I,f);
    plot(i,pd_I.sigma/pd_I.mu*100,'.r'); hold on;
        grid on;
        axis([0 iterations 0 inf] )
        xlabel('iteration number');
        ylabel('\sigma / \mu, %');

subplot(2,2,3);
plot(f, cdf_I);
    xlabel('dhi/dt, cm/hr');
    ylabel('CDF(dhi/dt), [1]');
    grid on;

subplot(2,2,4);
    if i>6
        set(h1,'Visible','off');
        set(h2,'Visible','off');
        set(h3,'Visible','off');

    end
    edf_I=1-cdf_I;
    h1=plot(f, edf_I);hold on;
    set(gca, 'YScale', 'log');
    axis([0 1.5 10^-5 1]);
    xlabel('dhi/dt, cm/hr');
    ylabel('EDF(F), [1]');
    grid on;

    SL=max(find(f<0.7));
    a=SL;
    h2=stem(f(a),edf_I(a),'.g');
    xx=[0 f(a)]; yy=[edf_I(a) edf_I(a)];
    h3=plot(xx,yy,'g');
```

```
    pause(0.001);
 end
end
```