Operability study of floating bulk transhipment opertion

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Thesis report

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Summary

Floating Bulk Transhipment Operation (FBTO), as a link in the whole bulk logistic chain, used to be performed only in well-sheltered water. Current operability assessment of FBTO is mainly based on experience and rules of thumbs, only taking into account environmental conditions such as significant wave height and wind speed. Corresponding to rocketing development of FBTO in more challenging environment, it becomes more and more important to develop a dedicated and reliable methodology which can assess the operability of FBTO properly.

Matching the features of FBTO, long duration and multiple operational phases, persistency analysis is introduced in the operability study. However, persistency analysis has still not been thoroughly studied and well-supported by literature. Moreover, among all existing operability techniques, persistency analysis as one of them has its capability and limitation. To be better adapted to FBTO and to further extend the methodology for other offshore operations, it is thus beneficial to decompose the operability assessment procedure and then categorize the available techniques, as well as to understand conditions of each.

This thesis report starts with a benchmark study of worldwide FBTO project. Among various FBTO configurations, the most representative scenario is chosen, which consists of 1 capesize vessel, 1 floating crane and1 feeder vessel. Operation procedure and criteria are described based on interviewing different floating bulk transhipment operator companies. After that, this thesis proposes an operability assessment methodology for FBTO and has the versatility in assessing any other offshore operation, if the three components of this methodology, operability assessment table, mechanism and switches, are used properly. The methodology concludes with an operability assessment scheme, in which useful operability study techniques, such as persistency analysis, scatter analysis, frequency-domain analysis etc., are categorized. Then, an in-depth study about persistency analysis is performed. Persistency analysis approaches more reality than scatter analysis because it accounts duration and chronological sequence of the operation, as well as change in weather conditions. Finer persistency data quality and proper selection of sampling interval will both lead to more accurate operability assessment. Last but not least, the case study illustrates how the proposed methodology works. The first case compares persistency analysis to scatter analysis, while the second one studies the influence due to persistency data of different resolution on operability assessment. The last case demonstrates using this methodology to predict expected duration of FBTO including possible suspension.

Preface

This thesis enlightened me and broadened my horizon.

I would like to thank my daily supervisor, Alex van Deyzen, who has always been supportive, for the knowledge and experience he shared and for guiding me through my graduation.

I would also like to thank Prof. Rene Huijsmans from TU Delft and Willemijn Pauw from Marin for their valuable feedback and suggestions. The most important one is from Prof. Huijsmans, which is "the more is not the better". This saying is now kept as my motto and enlightens me to always consider "why" ahead of "how" and "what".

Also, acknowledgment to the company, Royal HaskoningDHV, for providing me such a challenging thesis project and to everyone who has helped me during my graduation thesis.

Last and the most important, I would like to express my gratitude to my girl friend, Lei Chen, who always supports me and believes in me during my two-year master study. And also gratitude to my family, who paid a huge amount of tuition fee to support my study abroad.

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Contents

Nomenclature

FBTO	Floating Bulk Transhipment Operation
FD	Frequency Domain
MAD	Maximum Allowable Duration
MPM	Most Probable Maximum
OPS	Operational Phase Sequence
SSS	Sea State Sequence
TD	Time Domain

1. Introduction

1.1. Floating bulk transhipment operation

Floating Bulk Transhipment Operation (FBTO) makes use of side-by-side mooring normally between feeder vessel, transhipping vessel and sea-going vessel. A feeder vessel is a bulk transporting vessel with lighter displacement enabling it to enter the existing port, while a sea-going vessel often has deeper draft exceeding the limit of the port. Between them, there is a transhipping vessel generally comprising of two components: crane and cargo handling & delivery system (see e.g. [Mathur]). Bulk cargo is transferred (e.g. by floating crane) from sea-going vessel to feeder vessel via transhipping vessel during bulk import, or the other way around during export. Such operation is called a FBTO. In some cases, the transhipping vessel and the feeder vessel can be substituted by a custom-design vessel with both bulk handling & delivery ability and storage capacity. Another common practice is to utilize a converted or custom-designed vessel with combined function of both sea-going vessel and transhipping vessel. Both of the above FBTOs involve 2 vessels instead of 3.

The development and wide usage of FBTO corresponds to the situation that port developments have not been able to keep pace with rapid growth in vessel's size since the Second World War (see e.g. [Mathur]). Very large capacity bulk carriers are, in most case, favored from economic point of view but deep-depth sea port doesn't necessarily lead to more profits. This results in a rocketing market for FBTO. Such operation avoids usage of deep sea port. They can be located in various geographic settings and operate under various environmental conditions. In a word, FBTO is chosen when regarded as the best option economically.

An important development of FBTO is that it is performed in more and more exposed sea, instead of well-sheltered water such as inside port or behind breakwater. Facing severer environmental conditions, FBTO becomes a more critical link in the whole logistic chain. Current operability assessment method of FBTO is based on rules of thumbs, taking into account only environmental criteria such as Hs (significant wave height) and Uw (wind speed). Thus, a dedicated and reliable operability study becomes of great significance, in order to cope with rocketing development of FBTO and change in operation location.

1.2. Operability study

Conventional operability method is performed with a statistical model consisting of a short-term probability distribution of ship response and a long-term occurrence probability distribution of sea states in form of wave statistics table ([Naito et al. [2006]]). The fundamental method utilizing scatter diagram is proposed by Nordenstrom [1973] and hereby defined as, scatter analysis. Scatter analysis produces weather thresholds or downtime lines in a wave scatter diagram. To determine such thresholds, it is important to calculate vessel responses and then prepare them in form of most probable maximum (MPM) value, as proposed by Ochi [1981]. Vessel response for side-by-side mooring scenario, such as FBTO, can be calculated as described by Huijsmans et al. [2001]. However, Scatter analysis neglects duration and chronological sequence of the assessed operation, as well as influence of changing weather.

To account the influence of chronological sequence, Dallinga et al. [2004] and Grin and Van De Voorde [2004] propose scenario simulation technique and it was first adapted to assessment of vessel's voyage performance and seakeeping ability. GRIN et al. [2005] uses scenario simulation to assess the whole LNG transportation chain, including LNG offloading performance, by including diffraction analysis. To account the influence of changing weather, de Wilde et al. [2009] proposes a persistency analysis method based on a large statistics data-set of environment record. Accounting both of the above influence, Feikens et al. [2011] demonstrates adapting persistency analysis to an offshore operation with multiple operational phases and compare it to scatter analysis.

However, influence due to adapting persistency analysis is still not thoroughly studied. In addition, there exist various operability assessment methods, each with its merit and drawback. Persistency analysis, as one of them, takes into account chronological sequence of operation and persistency property of environmental condition. By approaching more reality, persistency analysis at the same time sacrifices calculation time. It is thus beneficial to decompose the operability assessment procedure and then categorize the available choices, as well as to understand conditions of each choice.

1.3. Objective

Problems stated in the above sections lead to the objective of this thesis.

- **Gain knowledge and insight of FBTO**
- **Develop a methodology to assess the operability of FBTO**
- **Study the influence of adapting persistency analysis**
- **Come up with an operability assessment scheme with systematically-categorized choices (mechanisms and switches) which can be used dependently on project input of an arbitrary offshore operation**

2. FBTO overview

2.1. Introduction

Commercially speaking, there are 2 processes which involve FBTOs:

1. Bulk import
2. Bulk export

During each commercial process, there exist 2 operation-wise concepts:

1. Loading
2. Unloading

The above concepts should not be mistaken with each others. Both of the operations, loading and unloading, take place during either bulk import or bulk export. Normally, if a transhipment approach can be used during bulk import, it can also be used the other way around during bulk export. But that's not always the case and more will be described in the later sections. If not specifically stated, the operation is assumed to be during bulk import in this report.

This chapter aims to present an overview of FBTO worldwide. In Section 2.2, floating bulk transhipment operation will be categorized. In Section 2.3, different types of transhipping vessel will be illustrated. In Section 2.4, typical mooring configurations will be described. In Section 2.5, equipment utilized in FBTO will be introduced. In Section 2.6, there will be a summary of worldwide FBTO project.

A small comment from the writer: categorization does help understand FBTO, but readers should always be careful because floating bulk transhipment is very flexible. More and more configurations are created and adapted. For example, a self-unloading vessel, which served originally for the purpose of bulk import, can now be used as the loader for another sea-going vessel during bulk export. Similar cases are frequently seen. Thus, it is no harm to state that the categorization done in this chapter is based on the current information (obtained through investigation of more than 80% of major floating transhipment companies worldwide). It is wise to keep the mind always open.

2.2. FBTO type

Table 2.1 lists types of operation in general . Please be aware that different FBTOs can take place together at the same location. A hybrid floating bulk transhipment operation is not rare to see.

No.	Type	Bulk Import	Bulk Export
1	Direct floating transhipment	✓	✓
2	Indirect floating transhipment	✓	✓
3	Moving floating transhipment	✓	×
4	Self-unloading transhipment	✓	✓

Table 2.1.: FBTO category

2.2.1. Direct floating transhipment

During import/export process, bulk cargo will be directly transferred from a sea-going vessel to a feeder vessel via a transhipping vessel or the other way around. Bulk cargo will not be (temporarily) stored in transhipping vessel. Figure 2.1 shows a typical direct floating transhipment.

Figure 2.1.: Typical direct floating transhipment

The main features of direct floating transhipment can be summarized as below:

- Normally 3 vessels or more involved:[1]

$$1 \times sea\,going + n \times transhipping + m \times feeder \quad n, m = 1, 2, 3 \qquad (2.1)$$

- No temporary storage of bulk in transhipping vessel

Table 2.2 discusses advantages and disadvantages of this method (see e.g. [van de Sande [2011]]).

[1]According to the investigation, $m \leqslant n \leqslant 3$. Number of transhipping vessels depends on size of feeder vessel and sea-going vessel.

Advantage	Flexible	Depending on size of sea-going vessel, 1-3 transhipping vessels can be deployed.
	Standard equipment	Shorter lead time and higher re-sale value.
Disadvantage	Inefficient barge logistics	A larger barge fleet is required.
	Inefficient transhipment	Transhipping will be stopped in case of changing barge and changing hatch
		Longer slewing moment

Table 2.2.: Advantage and disadvantage of direct floating transhipment

2.2.2. Indirect floating transhipment

The main features of indirect floating transhipment can be summarized as below:

- Normally 3 vessels or more involved:[2]

$$1 \times sea\,going + 1 \times transhipping + n \times feeder \quad n = 1, 2 \tag{2.2}$$

- Buffer (storage) in transhipping vessel
- Double handling

Figure 2.2.: Typical indirect floating transhipment

Buffer refers to the existing storage of the transhipping vessel (namely floating terminal). Take bulk import as an example, the bulk will first be unloaded from the sea-going vessel into the cargo holds of the transhipping vessel. As the second step, the transhipping vessel will then unload the bulk into the feeder vessel(s). Such process is called "Double Handling". Figure 2.2 is a typical indirect floating transhipment. One thing to be noticed is that the transhipping vessel shown in the figure also has the ability to adapt direct floating transhipment when needed (namely bulk is transferred directly from sea-going vessel to feeder vessels).

[2] According to the investigation, $n \leqslant 2$

Advantage and disadvantage of this method can be found in Table 2.3 (see e.g. [van de Sande [2011]]).

Advantage	Shorter slewing moment	Slewing angle of crane reduces to 90 degree from 180 degree
	Continuous (un)loading (due to existing buffer)	When there is no feeder vessel
		During hatch changeover of sea-going vessel
	Better logistics	Smooth load on hinterland chain
	Extra options	Due to more deck space, metal separators etc. can be equipped
Disadvantage	Less flexible	Only one sea-going vessel can be (un)loaded at the same time
	Custom built solution	More lead time and lower re-sale value

Table 2.3.: Advantage and disadvantage of indirect floating transhipment

2.2.3. Moving floating transhipment

Both sea-going vessel and transhipping vessel will go into port. Part of bulk will be reloaded to the transhipping vessel from the sea-going vessel to reduce the draft. As a result, both vessels will have the allowable draft to sail into inland shallow water. When the target location is reached, the sea-going vessel will be completely emptied. It will then be deberthed and depart. Figure 2.3 is a typical moving floating transhipment.

Figure 2.3.: Typical moving floating transhipment

The main features of moving floating transhipment can be summarized as below:

- Normally 2 vessels involved:

$$1 \times sea\,going + 1 \times transhipping\,(with\,storage) \quad (2.3)$$

- Both vessels go into port
- Used only during bulk import

Table 2.4 discusses advantages and disadvantages of this method (see e.g. [van de Sande [2011]]).

Advantage	Reduced number of terminals & feeder fleet
	Reduced amount of double handling
	Indirect or direct transshipment is used when it is most needed
Disadvantage	Throughput[a] time lost due to sailing between two unload locations
	More time lost due to extra berthing and deberthing
	Propelled terminal required
	Higher crane capacity required due to short unload time

[a] production over a period of time

Table 2.4.: Advantage and disadvantage of moving floating transhipment

2.2.4. Self-unloading transhipment

Another type of transhipment operation utilize a self-unloading vessel to unload bulk into:

- feeder vessel or hinterland facility during bulk import
- sea-going vessel during bulk export

Based on specially designed cargo hull (together with boom and belt conveyor) or on-board crane, bulk can be unloaded without help of a separate transhipping vessel. More about self-unloading vessel configuration can be found in Section 2.3.3. Figure 2.4 shows typical self-unloading vessels.

(a) Crane-based self-unloading vessel

(b) Gravity-based Self-unloading vessel

Figure 2.4.: Typical self-unloading transhipment

The main features of self-unloading floating transhipment can be summarized as below:

- Normally 2 vessels or more involved:[3]

[3] Normally, $n \leqslant 3$

$$\begin{cases} Bulk\,import: & 1 \times sea\,going\,(with\,unloading\,facility) + n \times feeder \quad n = 1, 2, 3 \\ Bulk\,export: & 1 \times sea\,going + n \times feeder\,(with\,unloading\,facility) \quad n = 1, 2, 3 \end{cases} \tag{2.4}$$

- No separate transhipping vessel needed
- Only unloading ability, not the other way around

Table 2.5 discusses advantages and disadvantages of this method (see e.g. van de Sande [2011]).

Advantage	Efficient transhipment	On-board facilities (especially gravity-based) unload bulk at relatively high efficiency
	More production time	Less time lost due to less complicated mooring system
	Less vessels involved	Such operation doesn't require a separate transhipping vessel
	No quay equipment required	Such operation doesn't require unloading facility on a normal quay
Disadvantage	Less flexible	Feeder fleet composition is highly restricted by type of unloading facility
	Custom design/conversion	Extra cost and more lead time
		Lower re-sale value
	Less cargo hold capacity	The cargo hold is specially shaped like hoppers, which compromises the capacity

Table 2.5.: Advantage and disadvantage of self-unloading transhipment

2.3. FBTO transhipping vessel

The transhipping job is mostly done by a transhipping vessel, while exception exists as mentioned in Section 2.1. Table 2.6 categorizes types of vessels equipped with transhipping facility.

No.	Type
1	Floating terminal
2	Floating crane
4	Self-unloading vessel (barge)

Table 2.6.: FBTO category

2.3.1. Floating terminal

Figure 2.5.shows a typical floating terminal.

The main features of floating terminal are listed below:

- Custom-designed
- Combined ability of bulk handling & delivery (often with bulk storage ability)
- Equipment on-board:
  - Grab crane
  - Hopper

Figure 2.5.: Floating terminal (Princess Chloe)

  - Belt conveyor
  - Loading boom
  - Cargo hold (optional)
  - Extra equipment, i.e. online weighing, mechanical samplers and metal separators (optional)

- Flexible working process
  - Bulk can be transferred directly to on-board delivery system and then loaded into feeder vessels.
  - Bulk can be temporarily stored in the terminal and then transferred into feeder vessels (double handling), which keeps both unloading processes continuous.

Table 2.7 is a list of important worldwide floating terminals.

2.3.2. Floating crane

Figure 2.6 shows a typical floating crane.

Figure 2.6.: Floating Crane (Atlas-4)

The main features of floating crane are listed below:

- Standard-designed (floating crane mounted on barge)
- Only floating crane on-board (low single production capability)
- Flexible usage (normally assisted by tug and winch)

Transhipping vessel	Bulk Wayuu	Bulk Gulf	Bulk Trieste	Bulk Prosperity	Bulk Irony
FBTO type	Indirect	Indirect	Indirect	Indirect	Moving
Owner	Coeclerici	Coeclerici	Coeclerici	Coeclerici	Coeclerici
DWT [ton] / Draft [m]	68800 / -	80000 / -	122000 / -	10500 / -	13579 / -
Storage	✓	✓	✓	✓	×
On-board equipment	4 × Cranes (40000 tpd[a])	4 × Cranes (30000 tpd)	4× Cavaletto (11000 tpd)	2 × Liebherr MPG (30000 tpd)	2 × Liebherr CBG 300 (25000 tpd)
	3 × Ship loaders	4 × Hoppers+ 1× Conveyor systems		1 × Ship loader+ 1× Belt conveyor	1 × Ship loader + 1× Belt conveyor
Designed capacity [tph[b]]	2000	1400	1100	1250	1500
Additional information	Old converted Panamax (1982)	Old converted Panamax (1986)	-	self-propelled	self-propelled

Transhipping vessel	Bulk Challenger	Bulk Pioneer	PT Indo Straits	OFT Zeus	Princess Chloe
FBTO type	Indirect	Indirect	Direct	Direct	Direct
Owner	Coeclerici	Coeclerici	Coeclerici	Scorpio Logistics	Swire
DWT [ton] / Draft [m]	10500 / -	10500 / -	- / -	11000 / -	- / 4
Storage	✓	✓	×	×	×
On-board equipment	2 × Liebherr MPG (2800 tph)	2 × Cranes (30000 tpd)	1× Gottwald G HPK 8200 B (1500 tph)	2× MacGregor 32 ton grab (30000 tpd)	Liebherr CBG 30(25) / 28(30)
	1 × Transfer boom	2 × Ship loaders	-	1 × Ship loader	1× Belt conveyor
Designed capacity [tph]	1200	1500	1500	1250	>2000
Additional information	self-propelled	-	-	self-propelled	-

Transhipping vessel	Kalimantan Floating Terminal	Oldendorff Isken	Pride of Marampa		
FBTO type	Indirect	Direct	Direct		
Owner	ASL Energy	Oldendorff	Oldendorff		
DWT [ton] / Draft [m]	- / -	- / -	- / -		
Storage	✓	×	×		
On-board equipment	4 × Liebherr CBG 300 (4000 tph)	3 × Liebherr MPG (40000 tpd)	Cranes		
	-	Hopper and chute	Belts		
Designed capacity [tph]	4000	1250	-		
Additional information	self-propelled	-	-		

[a] tpd stands for tonnes per day
[b] tph indicates tonnes per hour

Table 2.7.: Floating terminals worldwide

2.3.3. Self-unloading vessel

There are various configurations of self-unloading vessels. The three most common ones are:

1. Gravity-based self-unloading vessel (as shown in Figure 2.4b)
    a) Bulk unloading sequence: hoppered hold ⇒ gravity gate ⇒ belt conveyor ⇒ elevating system ⇒discharge boom
2. Crane-based self-unloading vessel (as shown in Figure 2.4a)
    a) Bulk unloading sequence: normal cargo hold ⇒ deck crane
3. Hybrid self-unloading vessel (as shown in Figure 2.7)
    a) With both deck cranes and belt conveyor on-board
    b) Bulk unloading sequence: normal cargo hold ⇒ deck crane ⇒ hopper ⇒ belt conveyor ⇒discharge boom

The main features of floating terminal are listed below:

- Custom-designed or converted
- Combined ability of bulk carrier & bulk transhipping
- Unloading ability only
- External facility required to get loaded

Figure 2.7.: Hybrid self-unloading vessel

2.3.4. Transhipping vessel utilized in various FBTO types

FBTO Type	Transhipping vessel type
Direct floating transhipment	Floating terminal
	Floating crane
Indirect floating transhipment	Floating terminal
Moving floating transhipment	Floating terminal
Self-unloading transhipment	Self-unloading vessel (barge)

Table 2.8.: Transhipping vessel utilized in various FBTO types

2.4. FBTO Mooring configuration

Mooring configurations of FBTOs vary a lot with different operation locations. This section won't attempt to categorize all existing mooring configurations, but to describe major mooring settings which can cover 80% cases. Floating crane is chosen here as transhipping vessel because a major part of FBTO is done by it, which will be further illustrated in Chapter 3.

2.4.1. Open sea

In most cases, single point mooring will be the first priority. As shown and illustrated in Figure 2.8, the sea-going vessel will be moored by anchor to enable weather-vane. If possible, the floating crane will be connected to the sea-going vessel while the feeder barge will be connected to the floating crane. Both the floating crane and the feeder barge can move relatively with the help of winches.

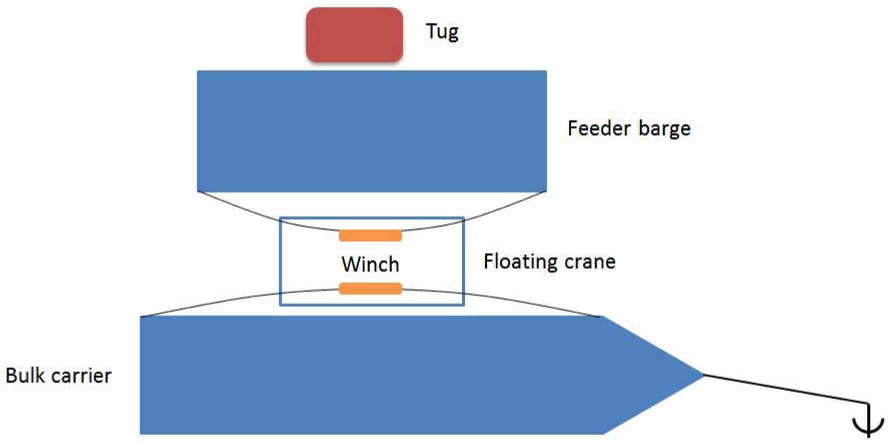


Figure 2.8.: Typical FBTO mooring in open sea

2.4.2. Sheltered sea

In sheltered sea, mostly in harbor, due to the space limit and relatively calm environmental condition, none-weather-vane mooring is adapted as the first option. There are two possible FBTOs during bulk import:

- Ship to ship
- Ship to quay

For ship-to-ship cases, sea-going vessel will be connected to dolphins in a none-weather-vane manner. Same as in open sea, floating crane will be connected to sea-going vessel while feeder barge will be connected to floating crane if possible.

For ship-to-quay, a typical arrangement is connecting sea-going vessel to dolphins by mooring lines and then place floating cranes in between sea-going vessel and quay, where they will be connected to quay. Figure 2.9 is a schematic drawing.

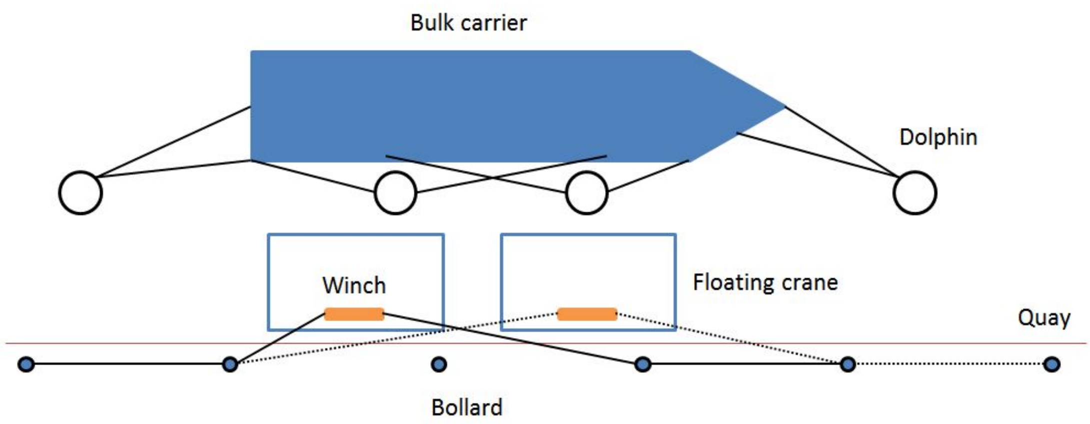


Figure 2.9.: Typical ship-to-quay FBTO mooring

2.5. Equipment on-board

This section will introduce several on-board equipment which are commonly used in FBTO. As mentioned in previous sections, floating crane, hopper, conveyor belt, boom and cargo hold are the most popular elements. Among them, cargo hold serves for the purpose of temporary storage of bulk. Hopper, belt conveyor and discharge boom, in cooperation with each others, are able to deliver bulk. Cargo handling ability in most cases is guaranteed by on-board crane which will be described below. Besides, some other widely used on-board equipment will be introduced in this section.

2.5.1. On-board crane

Floating crane is standard-designed to be used on-board. Table 2.9 introduces main manufacturers of floating crane.

No.	Company
1	Liebherr
2	Kenz-Figee
3	E-Crane
4	Gottwald
5	MacGregor
6	NKM Noell

Table 2.9.: Floating crane producer

Detailed floating crane data can be found mostly on website of those crane manufacturers. An average lifting capacity of floating crane is $35{\sim}45$ t with an operating radius around 30 m. Besides lifting capacity and operating radius, another important criterion is the slewing speed of the crane because the slewing moment is the most critical factor restricting the production rate. An average best-performance slewing speed is $1.0{\sim}1.2$ rpm.

2.5.2. Ship loader

A ship loader, commonly used in ports and jetties, is designed especially for loading dry bulk. It mainly consists of an extendable boom, a belt conveyor, a tripper to elevate and a mobile structure to support the boom. It is usually mounted on rails and sometimes on tyres, which enables it to reach the whole length of the vessel. Figure 2.10 is a typical ship loader.

Figure 2.10.: Ship loader

To be used on-board, special design has been adapted to guarantee the outreach of the discharge boom. It is widely utilized on floating terminal and self-unloading vessel.

2.5.3. Cavaletto system

The Cavaletto system is designed especially for on-board bulk transfer. It mainly consists of a grabber crane, a hopper, a belt conveyor and a discharging boom. As an example, it is currently utilized aboard the Bulk Trieste (Coeclerici). Figure 2.11 is a schematic drawing of a typical Cavaletto system.

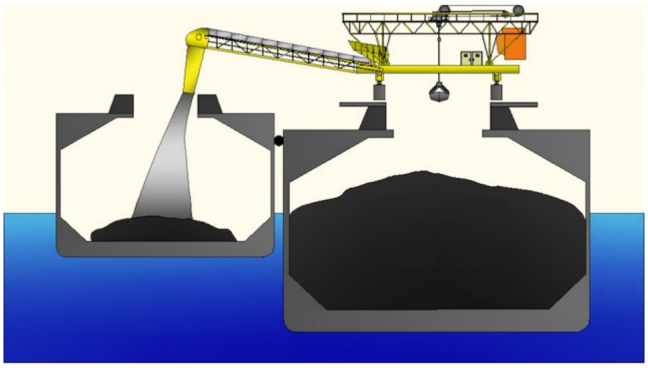


Figure 2.11.: Cavaletto system

2.6. Worldwide FBTO project

Nearly all important FBTO companies have been investigated during the first phase of the thesis. Although there must be FBTOs done in the locations not mentioned below, Table 2.10 has already included most important ones, which is able to present the readers a useful overview worldwide. All information below is gathered via internet investigation and literature reading. For floating bulk transhipment operator companies information, please refer to e.g. [ASL, Coeclerici, Oldendorff]. For floating crane producers, please check e.g. [Liebherr, Kenz-Figee & E-Crane].

Comments:

1. The capacity here refers to transhipping handling capacity. It is not the maximum capacity but an average value claimed by each company. Thus, the unit $mtpy \neq \frac{365 \times tpd}{1000000}$ because there won't be 365 active working days per year.
2. Self-unloading at this location takes place in 2 phases:
   a) A hybrid self-unloading vessel (E. Oldendorff) unloads bulk to 3 self-unloading barges (gravity-based).
   b) Self-unloading barges unload bulk to onshore receiving facilities.
3. The operation at this location takes place in 2 phases:
   a) Hybrid self-unloading vessels (Bulk Zambesi and Limpopo) are loaded by on-shore facilities.

   b) Bulk Zambesi & Limpopo sail to the deep-water anchorage and then self-unload bulk into sea-going vessel.

4. The operation there is quite unique:
   a) A sea-going vessel is unloaded via Oldendorff Isken to several gravity-based self-unloading vessels.
   b) Those self-unloading vessels go into the port and then feed the coal onto an on-shore belt conveyor.

5. Another important company, CSL, is not listed in the list below due to lack of detailed information. It is operating worldwide, including Canada, Australia, USA, China and so on.

Location			Owned by	Main transhipping vessel		FBTO type	Capacity* (check Comment 1)
Asia	Kalimantan, Indonesia	Open sea	Swire	Princess Abby	Floating crane	Direct	25000 tpd
Asia	Kalimantan, Indonesia	Open sea	Swire	Princess Chloe	Floating terminal	Direct	56500 tpd
Asia	Kalimantan, Indonesia	Open sea	Coeclerici	Bulk Pioneer	Floating terminal	Indirect	30000 tpd
Asia	Kalimantan, Indonesia	Open sea	Coeclerici	Bulk Celebes	Floating terminal	Direct	22000 tpd
Asia	Kalimantan, Indonesia	Open sea	Scorpio Logistics	OFT Zeus	Floating terminal	Direct	30000 tpd
Asia	Kalimantan, Indonesia	Open sea	ASL Energy	Kalimantan Floating Terminal	Floating terminal	Indirect	80000 tpd
Asia	Sumatra, Indonesia	Open sea	Coeclerici	PT Indo Straits	Floating terminal	Direct	30000 tpd
Asia	Abu Dhabi, United Arab Emirates	Open sea	Oldendorff	E. Oldendorff	Self-unloading vessel	Self-unloading* (check Comment 2)	4.8 mtpy[a]
Asia	Goa, India	Open sea	LDA	-	Floating crane	Direct	8.0 mtpy
Asia	Western India	-	Coeclerici	Bulk Prosperity	Floating terminal	Indirect	30000 tpd
Asia	Arabian Gulf	Half-open sea	Coeclerici	Bulk Gulf	Floating terminal	Indirect	30000 tpd
Oceania	Fly River, Papa New Guinea	Open sea	Swire	M.V. Erawan	Self-unloading vessel	Self-unloading	-
South America	Berbice River, Guyana	Half-open sea	Oldendorff	-	Floating crane	Direct	2.0-2.5 mtpy
South America	Gulf of Paria, Trinidad	Half-open sea	Oldendorff	-	Floating crane	Direct	6.0 mtpy
South America	Colombia	Open sea	LDA	-	Floating crane	Direct	15.0 mtpy
South America	Maracaibo Lake, Venezuela	Lake	Coeclerici	Bulk Wayuu	Floating terminal	Indirect	35000 tpd
North America	Evansville, Indiana, USA	Inland river	E-Crane	-	Floating crane	Direct	-
Africa	Beira, Mozambique	Half-open sea	Coeclerici	Bulk Zambesi	Self-unloading vessel	Self-unloading* (check Comment 3)	6.0 mtpy[b]
Africa	Beira, Mozambique	Half-open sea	Coeclerici	Bulk Limpopo	Self-unloading vessel	Self-unloading* (check Comment 3)	
Africa	Matadi, Congo	Inland river	E-Crane	-	Floating crane	Direct	-
Europe	Gulf of Iskenderun, Turkey	Half-open sea	Oldendorff	Oldendorff Isken	Floating terminal	Direct* (check Comment 4)	3.0 mtpy
Europe	Piombino, Italy	Open sea	Coeclerici	Bulk Irony	Floating terminal	Moving	18000 tpd
Europe	Trieste, Italy	Harbour	Coeclerici	Bulk Trieste	Floating terminal	Indirect	20000 tpd
Europe	Black Sea	Lake	Coeclerici	Bulk Kremi I	Floating terminal	Indirect	-
Europe	Amsterdam, Netherlands	Half-open sea	Rietlanden	-	Floating crane	Direct	-
Europe	Amsterdam, Netherlands	Harbour	Rietlanden	-	Floating crane	Direct	-
Europe	Rotterdam, Netherlands	Harbour	Marcor	-	Floating crane	Direct	-

[a] mtpy stands for million tonnes per year.

[b] 6.0 mtpy is the total capacity of the both

Table 2.10.: Worldwide FBTO project

3. Selected FBTO scenario

3.1. Introduction

Chapter 2 presents a basic overview of FBTO. As stated, FBTO is a highly flexible operation with different operation types, different transhipping vessels, different mooring configurations and different on-board equipment. Each FBTO scenario has difference in vessel particulars, mooring system, operational procedure, adapted criteria and etc. As a recap, the purpose of this thesis study is to develop a methodology which aims to deal with all possible FBTO scenarios and, one step further, has versatility in assessing operability of an arbitrary offshore operation besides FBTO. To accomplish that, a particular FBTO scenario is selected. Illustrations of the methodology in the following chapters will be based on this selected FBTO scenario. As the next step, how to extend this methodology for other FBTO scenarios, as well as other offshore operations, will be explained in the later chapters.

In this chapter, how the most interesting FBTO scenario is chosen will be explained in Section 3.2. Basic information about the selected FBTO scenario will be described in Section 3.3. In Section 3.4, general operational procedure of the scenario will be illustrated. In Section 3.5, criteria adapted for each operational phase will be discussed.

3.2. Most interesting FBTO scenario

Figure 3.1.: Worldwide FBTO

FBTO is going on worldwide as shown in Figure 3.1. Here, number in the circle indicates number of projects going on there while circle without number indicates there is FBTO at that location but number of projects is unclear.

Among all the FBTOs, taking place now or in the past, Figure 3.2 is a pie chart of different transhipping vessels used in the operation. The statistics here is obtained from interviewing various operator companies and crane manufacturing companies. The values of percentage should be considered as estimations.

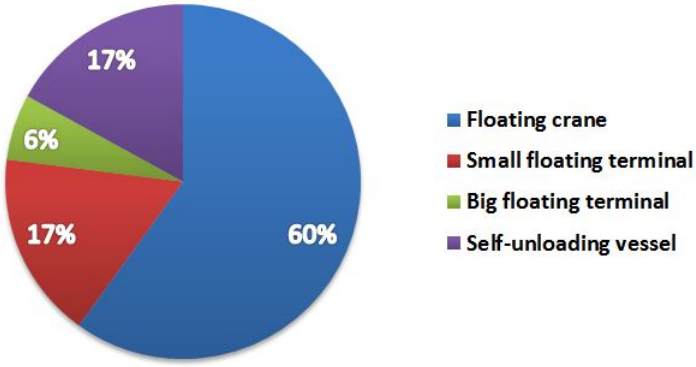


Figure 3.2.: Types of transhipping vessels used in FBTO

As the mostly used transhipping vessel, floating crane is therefore chosen. As mentioned in Chapter 2, there can be 1 or multiple floating cranes used in one FBTO and there will usually be 1 feeder barge alongside 1 floating crane. Serving the purpose of demonstrating this methodology, 1 floating crane with 1 bulk barge is selected for transhipping vessel and feeder vessel to avoid redundant complexity.

As stated, FBTO in open sea is more interesting for this thesis study because larger vessel response can be expected in more exposed water. Thus, 1 capesize vessel is chosen as the sea-going vessel because FBTO in open sea involves mostly capesize class bulk carriers.

Thus, the most interesting FBTO scenario is selected to be: **1 capesize vessel + 1 floating crane + 1 bulk barge in open sea**.

3.3. Scenario basics

Vessels

A capesize vessel is typically with more than 80000 DWT and a size of $300m \times 45m \times 19m$ for $L \times B \times D$.

Figure 3.3.: Example capesize vessel

Floating crane doesn't have a well-known classification and usually custom-designed. Figure 3.4 shows a floating crane with around $60m \times 25m \times 5m$ for $L \times B \times D$.

Figure 3.4.: Example floating crane

Bulk barge also has various size. A common type of bulk barge used in Indonesia for FBTO is a 10000-ton dumb barge as shown in Figure 3.5.

Figure 3.5.: Example dumb barge

Mooring

The mooring arrangement, as well as relative position information, can be found in the schematic drawing below:

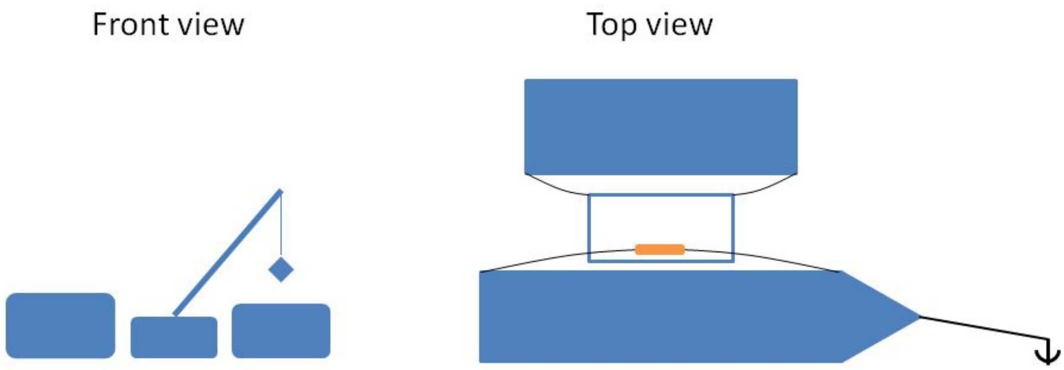


Figure 3.6.: Schematic drawing of mooring configuration

3.4. Operational procedure

Through interviews with various operator companies, a general operational procedure for the selected FBTO scenario is summarized below:

- $Phase\ 1, 2\&3$:
  - Capesize vessel arrives at the design location and gets berthed by its own anchor;

  - Floating crane is towed to the location by tug;
  - Bulk barge is towed to the location by tug;

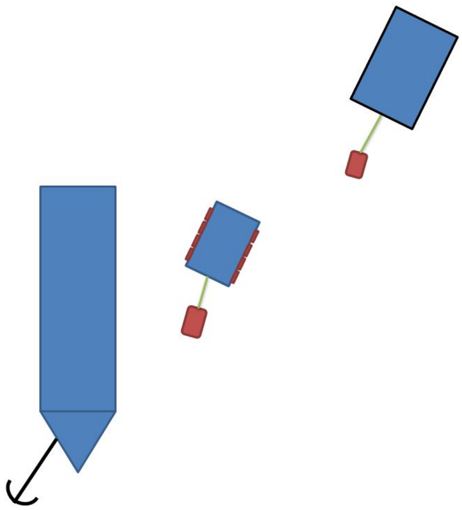


Figure 3.7.: schematic drawing of $Phase\,1, 2\&3$

- $Phase\,4$: Floating crane is moored to capesize vessel by mooring lines;

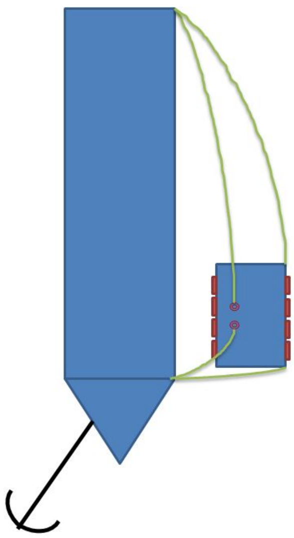


Figure 3.8.: Schematic drawing of $Phase\,4$

- $Phase\,5$: Bulk barge is moored to floating crane by mooring lines;

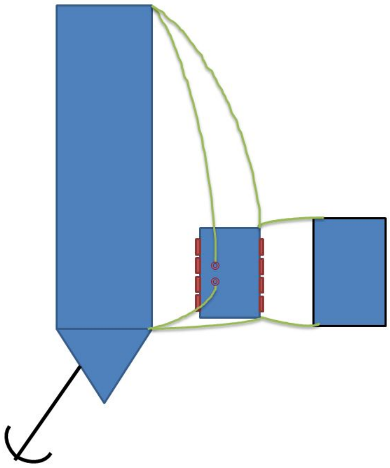


Figure 3.9.: Schematic drawing of $Phase\,5$

- $Phase\,6$: Production phase – floating crane starts transhipping;

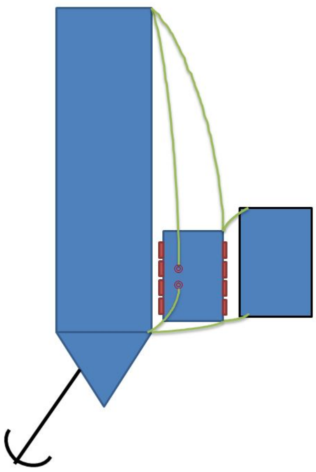


Figure 3.10.: Schematic drawing of $Phase\,6$

- $Phase\,7$: Hatch switching – after one cargo hold is (un)loaded to a desired level, floating crane will start to shift hatch. Mooring lines between vessels will be loosened to make sure there won't be friction due to fender. After enough margin is reached, winch will start to work and adjust length of mooring line on both bow and stern directions. By doing so, floating crane can move relatively along capesize vessel to reach the next cargo hold. Bulk barge will move together with floating crane. Once the desired position is reached, mooring lines between vessels will be tightened to a reasonable level again.

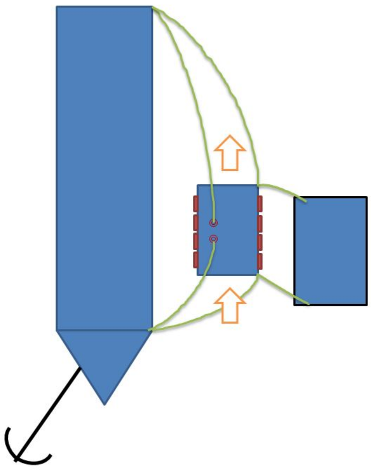


Figure 3.11.: Schematic drawing of $Phase\,7$

- $Phase\,8$: Barge substitution – after bulk barge is fully filled, another barge will replace the previous barge. It will be towed to the position as soon as possible after the previous barge is towed away sufficiently far away. Immediately after that, the second bulk barge will be moored to floating crane as previously did. Such operation has also been seen done assisted by crane grab.

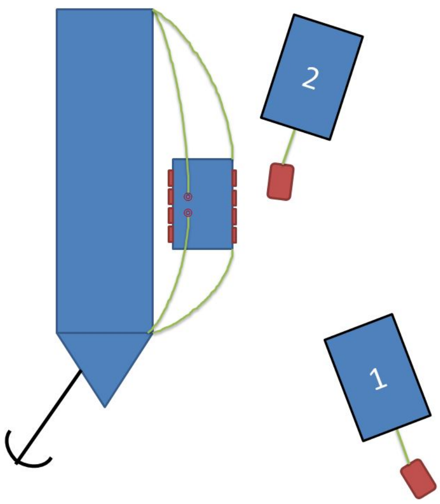


Figure 3.12.: Schematic drawing of $Phase\,8$:

- $Phase$ 9&10:
  - Floating crane & bulk barge are towed back by tugs;
  - Capesize vessel gets de-berthed;

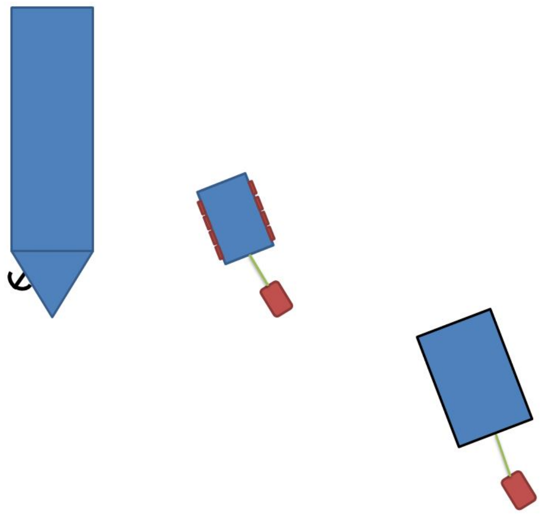


Figure 3.13.: Schematic drawing of $Phase$ 9&10:

In reality, $Phase$ 6, 7&8 will be repeated several times until required (un)loading amount is reached. The reason to shift hatch is to make sure the bulk carrier is (un)loaded uniformly over the length, which is based on safety concern of vessel longitudinal strength. Those 3 phases consume most part of operation time among all the operational phases. Table 3.1 presents an operational phase overview.

Phase	Action
1	Capesize berthing
2	Crane barge towing
3	Bulk barge towing
4	Crane barge mooring
5	Bulk barge mooring
6	**Production phase**
7	**Hatch switching**
8	**Bulk barge substitution**
...	...
9	Towing back floating crane & bulk barge
10	Capesize de-berthing

Table 3.1.: Operational phase overview

3.5. Criteria

Criteria have been collected through interviewing personnel from floating bulk transhipment operator companies and other experienced persons. They are summarized in Table 3.2.

Phase	Criteria	Comment
1, 2 & 3	-	Out of scope
4 & 5	Relative motion	Operational criteria
	Mooring line load	Critical criteria
6	Roll motion	Operational criteria
	Floating crane working range (relative motion)	Operational criteria
	Operator room motion	Operational criteria
	Crane tip motion	Operational criteria
	Mooring line load	Critical criteria
7 & 8	Relative motion	Operational criteria
	Mooring line load	Critical criteria
	Winch ability	Critical criteria
9 & 10	-	Out of scope

Table 3.2.: Criteria for different operational phases of FBTO

The criteria are categorized into:

- **Operational criteria**: if exceeded, the operation will not be operable but there won't be fatal damage to either human being or equipment on-board;
- **Critical criteria**: if exceeded, fatal damage to either human being or equipment on-board will occur.

Apparently, critical criteria are never allowed to be exceeded. Operational criteria might be acceptable to be exceeded if the operation allows suspension. More will be illustrated in Section 4.4.2.

More comments about Table 3.2 can be found below.

3.5.1. $Phase\ 1, 2\&3$ and $Phase\ 9\&10$

$Phase\ 1, 2\&3$ and $Phase\ 9\&10$ mainly cover (de)berthing and towing operation. They are considered as pre-phase or post-phase of the FBTO operation and thus no criterion is collected for those phases. To be clear, it is absolutely possible to incorporate these operational phases in the methodology, but a separate study about criteria needs to be done. If criteria about towing or (de)berthing operation are determined in the future research, they can be easily inserted into the table above and incorporated in the methodology using the same philosophy.

3.5.2. $Phase\ 4\&5$ and $Phase\ 7\&8$

What $Phase\ 4\&5$ and $Phase\ 7\&8$ share in common is that mooring system is in transient state during those phases.

During $Phase\ 4\&5$, attempts are made to get floating crane and bulk barge moored. It is understandable that too fierce relative motion between vessels is not favored during such operation. As a result of too profound relative motion, mooring line load might as well be overwhelming because mooring system is in transient state. In simple words, 1 mooring line might need to do the whole mooring system's job because not all mooring lines have been connected during those phases.

During $Phase\ 7\&8$, an extra limitation is from winch because it need to enable relative vessel movement. But winch breaking is rarely seen in real practice. It is because a special casing is designed on the mooring line. It will reach its breaking limit before actual damage can happen either for winch or for mooring line itself. Whether this casing will break or not depends on how large the mooring line load is, so it can also be interpreted as a mooring-line-load criterion.

One thing to state is that those phases are with comparatively short duration and rather strong criteria, which makes them less critical.

3.5.3. $Phase\ 6$

$Phase\ 6$, as the production phase, lasts the longest duration among all operational phases.

Roll motion

A typical roll criterion is set as 3 degree. It is based on two aspects.

Criteria for Accelerations and Roll (NORDFORSK, 1987)			
Description	RMS vertical acceleration	RMS lateral acceleration	RMS roll
Light manual work	0.20 g	0.10 g	6.0 deg
Heavy manual work	0.15 g	0.07 g	4.0 deg
Intellectual work	0.10 g	0.05 g	3.0 deg
Transit passengers	0.05 g	0.04 g	2.5 deg
Cruise liner	0.02 g	0.03 g	2.0 deg

Figure 3.14.: Nordforsk criteria for roll (adapted from [Ormala et al. [1987]])

The first aspect is from human-limit side of view. When high frequency motion like roll is too big, personnel on-board won't be able to work properly. Figure 3.14 is a list of relevant criteria. For crew aboard pontoon (floating crane), it requires not only the crane operator to control the crane properly, but also the winch man to adjust winch in time to provide sufficient slack. Both of them can be considered as "Intellectual work". Thus, the criterion should be $\phi \leqslant 3°$.

The second aspect is from crane-limit side of view. The on-board crane has its own design condition. When roll/pitch motion is too big, the life time of the crane will significantly decrease. As a result, the on-board crane might collapse unexpectedly, which will cause fatal damage. A specification of a widely-used on-board crane, as an example, can be found in Figure 3.15. It can be concluded that the heel requirement is also $\phi \leqslant 3°$.


Design conditions

Maximum admissible:
heel/side lead ——————— 3°/2° (<45 t grab/hook)

Figure 3.15.: Example crane specification (adapted from [Liebherr])

There is also criterion for high frequency motion like pitch, but, generally speaking, roll motion tends to be more dominant than pitch.

Thus, the criterion is set to be $\phi \leqslant 3°$.

Other criteria

- Floating crane working range (relative motion) is a criterion to guarantee the other vessel is within commercial working range of the floating crane. If the cargo hold is drifting too far away from the floating crane, it will not be operable. It can be interpreted as a relative-motion criterion.
- Operator room motion is a criterion to make sure the operator in that room can be confident to control the floating crane. Otherwise, it is not operable, which makes it an operational criterion. The reason why an operator loses confidence in controlling the crane is because the heel/trim angle is too big. As a result, the operator feels the risk of falling and thus loses confidence. In this sense, this can be interpreted as a similar criterion as roll motion (or pitch motion).
- Crane tip motion is a criterion to make sure the floating crane is still controllable. The reason why the operator can't control the floating crane is that the grab starts profound pendulum motion. This is induced by too much motion at crane tip. This criterion can be interpreted as a high frequency motion criterion.
- Mooring line load is a criterion to make sure that the mooring lines won't break. Breaking of mooring lines will cause fatal damage to either human beings or on-board equipment, which makes it a critical criterion. Supervisor on the floating crane deck will constantly check the status of the mooring lines. If the mooring line is too tight,

it can easily reach its breaking limit. If the mooring line is too slack, it can't provide required mooring force. A proper status between tight and slack is pursued.

4. Operability assessment methodology

4.1. Introduction

In the previous chapters, it has been clearly stated that the selected FBTO scenario for operability study is: 1 sea-going vessel, 1 floating crane and 1 feeder barge. The methodology works no matter what scenario is chosen. Different scenarios will lead to variance mainly in criteria and operational phases, which can be dealt with by the proposed methodology. Moreover, though here this methodology is designed to assess the operability of FBTO, the methodology serves for general offshore operation. Different offshore operations might have different operational phases, different criteria or require different assessment method (to determine the response of the system), but proper assessment of their operability can be done by choosing correct "Mechanism" and "Switch", which are two important concepts of this methodology.

A recommended way of adapting this methodology is listed as below. Step 2, 3 & 4 are important because they can actively control the quality of the assessment.

1. Collect project input
2. Construct an operability assessment table (see Section 4.2)
3. Choose desired operability assessment mechanism (see Section 4.3)
4. Select proper switches (see Section 4.4)
5. Perform assessment calculation (done by computer)

4.2. Operability assessment table

The starting point of this methodology is to construct an operability assessment table. Figure 4.1 shows an example of operability assessment table. The components of an operability assessment table are:

- Operational phase
- Assessment method
- Environmental data
- Assessment unit

An arbitrary offshore operation can be modeled as an operability assessment table if the above information is collected.

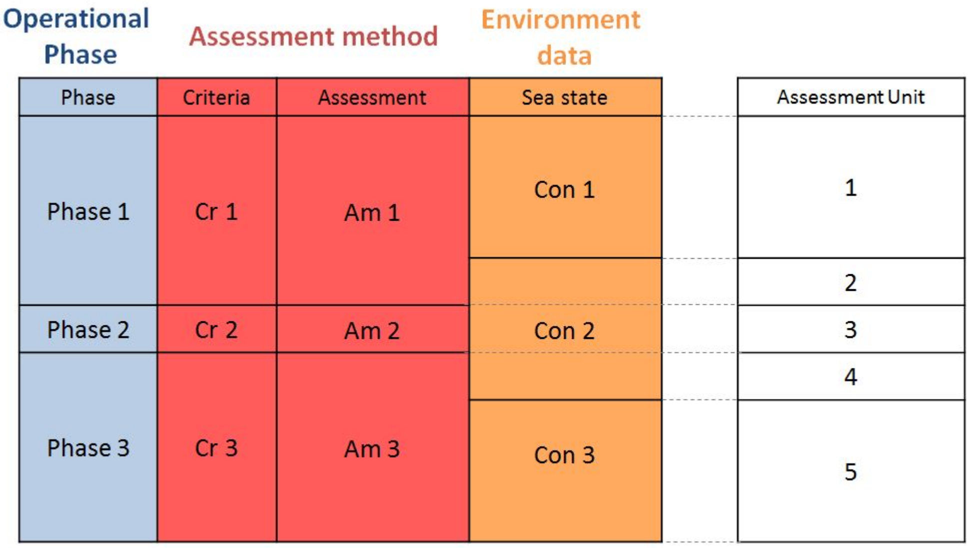


Figure 4.1.: Operability assessment table

Operational phase

Component operational phase contains two types of information:

1. Configuration
2. Duration

Configuration refers to vessel particular, mooring arrangement and position information of a floating system, which might change with different phases. Duration literally explains itself.

Table 4.1 contains operational phase information of an example operation.

Phase No.	Phase name	Phase duration
1	Production phase 1	6
2	Hatch switching	0.5
3	Production phase 2	2.5

Table 4.1.: Example FBTO operational phases

Apparently, all the above 3 phases have different configuration. For FBTO, duration of Phase No. 1 and No. 3 is determined by cargo hold capacity C, unloading requirement r and floating crane turnover T, as shown below:

$$Duration = \frac{C \cdot r}{T} \tag{4.1}$$

Unloading requirement r is present based on structural strength concern of the sea-going vessel. A typical value for r is 50%, indicating only 50% of this cargo hold can be unloaded at one time.

Duration of Phase No. 2 is an estimated value which will differ with distance between the two hatches.

Assessment method

Each operational phase should have its specific assessment method. Component assessment method can be divided into two parts:

1. Criteria
2. Assessment (method)

One typical assessment mechanism is to compare the calculated result to the criteria. If criteria are exceeded, the operation should be called off or suspended. The way to obtain such calculated results is called the assessment method. It can be categorized as below:

- For criteria such as Hs (significant wave height), which are called **environment criteria**, the assessment method is to **directly** compare respective environmental data with them;
- For criteria such as ϕ (vessel roll motion), which are called **response criteria**, the assessment method is to first perform analysis to calculate respective vessel response and then do comparison. Two possible ways to calculate such vessel responses are:
  - Frequency domain analysis (**FD**)
  - Time domain analysis (**TD**)

Phase No.	Criteria		Assessment	
1	$Cr\,1$	$\phi \leqq 3°$	$Am\,1$	FD
2	$Cr\,2$	$Hs < 2m$	$Am\,2$	Direct
3	$Cr\,3$	$\phi \leqq 3°$	$Am\,3$	FD

Table 4.2.: Example FBTO assessment method

Table 4.2 illustrates an example of “Assessment method” columns corresponding to Table 4.1.

Environment data

Environment data will be different for scatter analysis and for persistency analysis. To be clear, hereafter, environment data used in scatter analysis will be called scatter data while data used in persistency analysis will be called persistency data. Compared to scatter data, persistency data not only contains occurrence probability of a sea state but also shift probability from 1 sea state to another. In other words, persistency data contains occurrence probability of all possible sea-state sequences.

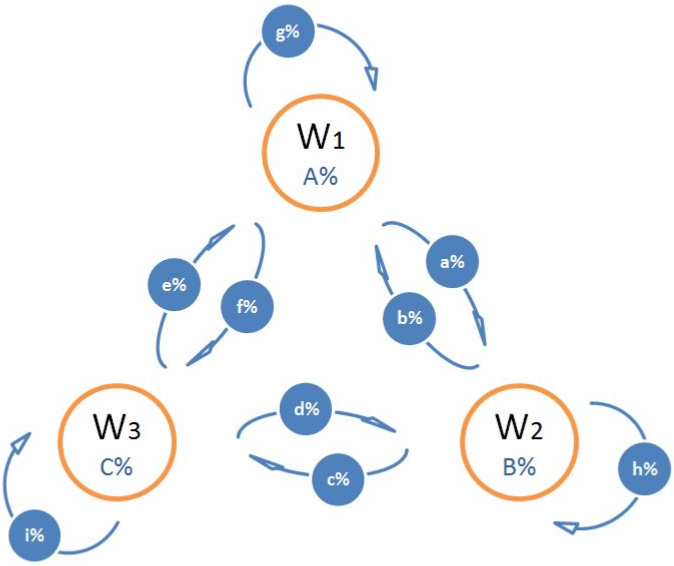


Figure 4.2.: Example persistency data

Assuming only 3 possible sea states $W1, W2\&W3$ to be encountered, each with a duration of 3 hours. The persistency data is as shown in Figure 4.2. Influence of wind and current is left aside in this report, which means only wave condition is taken into account.

In each circle, sea state Wi covers information of wave direction and wave spectrum, with a probability P^i_{start} of occurring as the starting condition. During every shift of sea-state window, there will be a shift probability of P^j_{shift}. Superscript j here indicates it is the j^{th} shift. Introducing shift probability indicates that sea state might change during an operational phase. As can be seen, $W_1, W_2\&W_3$ can shift to each others or itself in the assumed persistency data.

For FBTO example mentioned above, Table 4.3 constructs a persistency table containing all possible sea-state sequences to fill in the "Environment data" column. In this example, there exists 3 sea states in a sea state sequence (in total 9 hours) to cope with the duration of the whole operation.

How to prepare such persistency data can be found in Appendix A.1.

Assessment unit

Component assessment unit contains combined information of operational phase, assessment method and sea state. Due to difference in duration of each operational phase and each sea state, the number of assessment units will probably be more than number of operational phases and number of sea states. This is clearly shown in Figure 4.1. All necessary information have been collected to construct such an operability assessment table as in Table 4.4. Table 4.3 contains 27 possible sea state sequences. Operability under each sea state

No.	$Con1$	$Con2$	$Con3$	P_{occ}
1	W_1	W_1	W_1	$A\% \times g\% \times g\%$
2	W_1	W_1	W_2	$A\% \times g\% \times a\%$
3	W_1	W_1	W_3	$A\% \times g\% \times f\%$
4	W_1	W_2	W_1	$A\% \times a\% \times b\%$
$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
26	W_3	W_3	W_2	$C\% \times i\% \times d\%$
27	W_3	W_3	W_3	$C\% \times i\% \times i\%$

Table 4.3.: Example persistency table

sequence can be calculated and the summation of operability under all 27 sequences is the total operability.

Assessment unit	Operational phase	Assessment method		Sea states
1	$Phase\,1$	$\phi \leqq 3°$	FD	$Con\,1$
2	$Phase\,1$	$\phi \leqq 3°$	FD	$Con\,2$
3	$Phase\,2$	$Hs < 2m$	Direct	$Con\,2$
4	$Phase\,3$	$\phi \leqq 3°$	FD	$Con\,2$
5	$Phase\,3$	$\phi \leqq 3°$	FD	$Con\,3$

Table 4.4.: Example FBTO operability assessment table

4.3. Operability assessment mechanism

There are two mechanisms, which can be used depending on different types of operations, criteria and desired output.

4.3.1. Criteria type & operation type

Generally speaking, there are two types of operation:

- Type A: operation which does not allow disruption
- Type B: operation which allows suspension

As stated before, there are also two types of criteria:

- Critical criteria
- Operational criteria

Table 4.5 summarizes the relation between criteria type and operation type into 3 cases:

No.	If exceeded	Operation	Operation type
1	Critical criteria	Failed	For Type A and Type B
2	Operational criteria	Failed	For Type A
3	Operational criteria	Suspended	For Type B

Table 4.5.: Relation between criteria type and operation type

1. The operation fails when critical criteria are exceeded, no matter what type of operation it is ;
2. The operation fails when operational criteria are exceeded, if disruption is not allowed for the operation;
3. The operation is suspended (not failed) when operational criteria are exceeded, if disruption is allowed for the operation.

4.3.2. Two mechanisms

Two operability assessment mechanisms can be summarized as in Table 4.6. Because the second mechanism can provide extra information about operation duration, the second mechanism is defined as "duration mechanism" while defining the first one as "basic mechanism".

Name	For Case No. in Table 4.5	Operation duration
Basic mechanism	Case No. 1 and No. 2	= fixed duration
Duration mechanism	Case No. 3	$\leqq$ maximum allowable duration

Table 4.6.: Two operability assessment mechanisms

The following two statements can be concluded:

- Basic mechanism suits for Case No. 1 and Case No. 2 to quantify the probability that an operation can survive a fixed duration;
- Duration mechanism suits for Case No. 3 to quantify:
  - the probability that an operation can be finished within the maximum allowable duration;
  - the expected duration of the operation (including suspension).

Figure 4.3 presents a flow chart indicating when to use the two mechanisms.

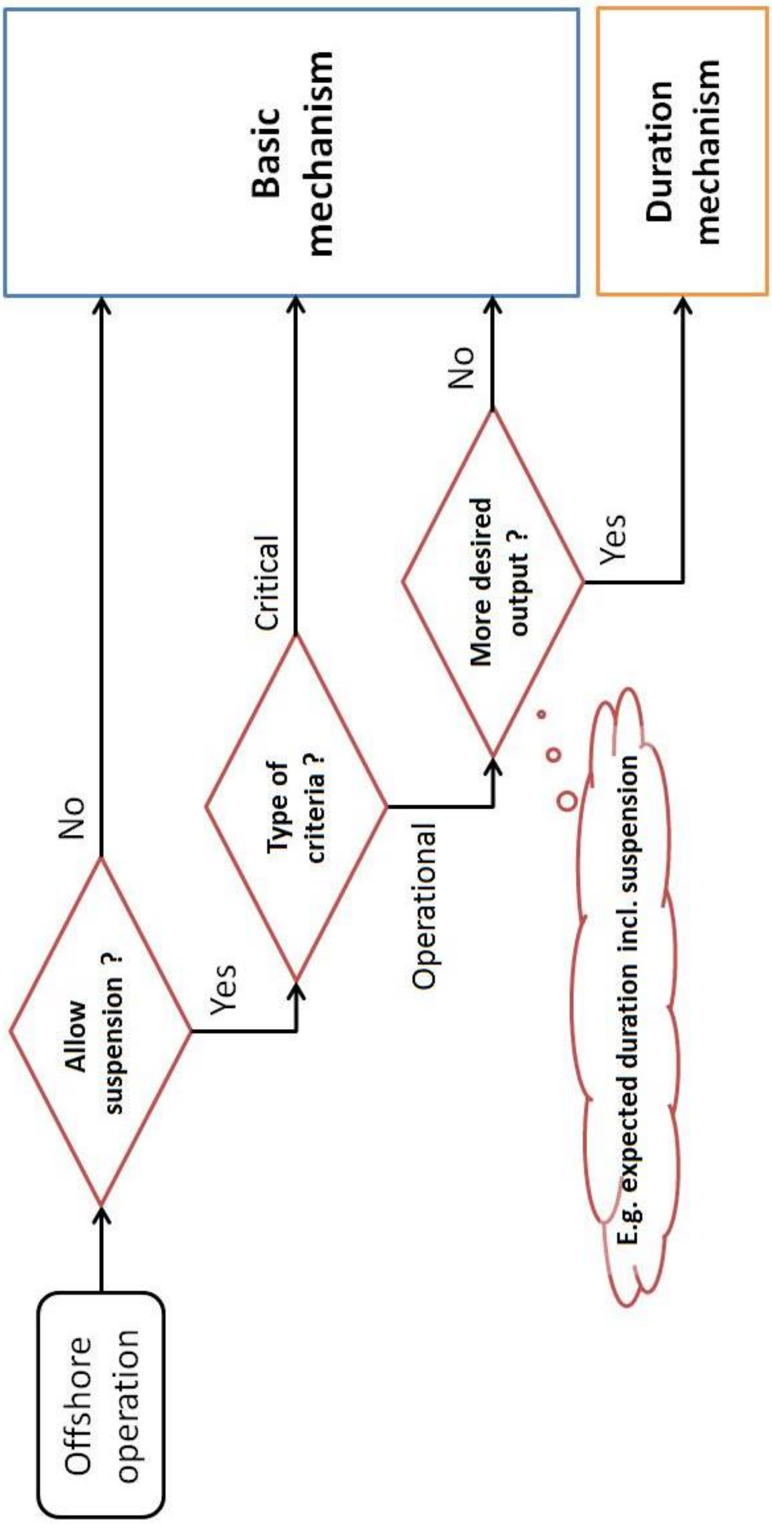


Figure 4.3.: Selection of two mechanisms

4.4. "Switch"

As can be seen in the previous sections, there are several choices to make during a complete operability assessment, e.g. either a scatter analysis or a persistency analysis, either a set of critical criteria or a set of operational criteria, either FD analysis or TD analysis. Et cetera. All the above choices should be made dependently based on input of each engineering project. Such choice provides this methodology versatility to handle various offshore operations and, hereafter, is defined as "Switch". Proper usage of switches, operability assessment table and operability assessment mechanism are the key to successfully assessing operability of an offshore operation using this methodology.

Figure 4.4 introduces in total 3 sets of switches:

- Switch 1: persistency analysis / scatter analysis
- Switch 2: veto analysis / probabilistic analysis
- Switch 3: frequency-domain analysis / time-domain analysis

4.4.1. Switch 1: persistency analysis / scatter analysis

The first switch is between persistency analysis and scatter analysis. A common method to assess operability of offshore operation is to do scatter analysis. Scatter analysis is a rather fast and mature engineering approach, which is widely used in assessing operability. Recent efforts have been made to introduce persistency analysis in offshore industry (see for example, [Feikens et al. [2011]]). Compared to scatter analysis, persistency analysis includes more than 1 operational phases and accounts the duration of each phase. Besides, it also takes into account probable shifts of sea states during the operation. By doing so, it tends to capture more reality and thus can produce more accurate result. More study about persistency analysis can be found in Chapter 5. Generally speaking, persistency analysis is recommended when:

1. The offshore operation consists of multiple operational phases and can not be represented by the ONE most critical phase;
2. The operation lasts a long duration, which might cause noteworthy influence to the operability;
3. Shift of sea states from a benign one to a severe one is probable to take place within duration of the operation.

Switch 1 is the most important switch of this methodology, because it decides whether to introduce persistency analysis. In Chapter 6, clear difference is spotted between assessment with persistency analysis and one with scatter analysis.

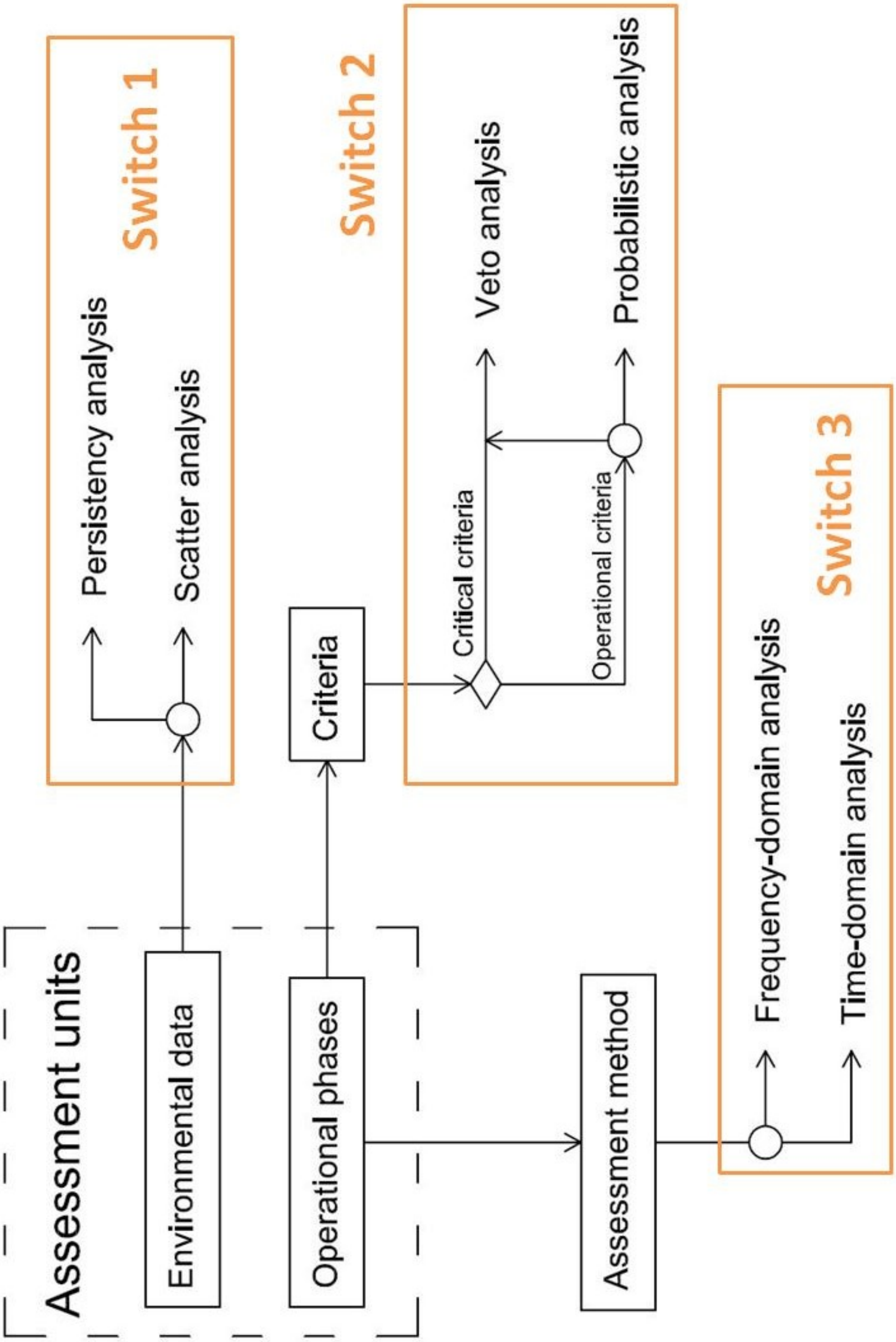


Figure 4.4.: Switches

4.4.2. Switch 2: veto analysis / probabilistic analysis

Though both of veto and probabilistic analysis can be used for both operability assessment mechanisms, there is still preference as shown in Table 4.7.

Name	For Case No. in Table 4.5	Recommended
Basic mechanism	Case No. 1 and No. 2	Veto analysis
Duration mechanism	Case No. 3	Probabilistic analysis

Table 4.7.: Veto or probabilistic analysis

Veto analysis (in basic mechanism) refers to the method that, for each assessment unit, Most Probable Maximum (MPM, check [Ochi [1981]]) value of the vessel response is compared to the respective criteria. If criteria are exceeded, survival rate Q^i is accounted 0. Else, $Q^i = 1$.

Briefly about probabilistic analysis (in duration mechanism), the first step is to describe a vessel response (or wave motion) in the pattern of a probability distribution for each assessment unit. If FD analysis is performed, then the vessel response (or wave motion) can be statistically represented by Rayleigh distribution (see e.g. [Journèe and Massie [2001]]). Else if TD analysis is performed, the simulated vessel response (or wave motion) needs to be fitted with an extreme value distribution (see e.g. [J.K. Vrijling [2002], Mahdi and Cenac [2012], Worden [2002], Incecik et al. [1998]]). Once the probability distributions are made clear, the survival probability of each assessment unit can be easily calculated. Thus, the required operation time (including suspension time) under one specific sea state sequence can be obtained. If there are multiple criteria for one assessment unit, a multi-criteria system reliability analysis will be performed. Monte Carlo simulation and Ditlevsen method can both be used to determine the survival probability under multi-criteria (see e.g [Vrijling et al. [1997], Naess et al. [2007]]). An example of choosing probabilistic analysis for Switch 2 can be found in Section 4.5.

4.4.3. Switch 3: frequency-domain analysis / time-domain analysis

Frequency-domain analysis and time-domain analysis are both mature engineering approach to simulate vessel response. Thus, they will not be explained into details here.

Generally speaking, frequency domain analysis is time-wise efficient but it neglects some of the reality. Time-domain analysis is recommended when:

1. Non-linearity of the system is too profound to be neglected. Non-linearity here might be due to:
    a) Non-linear mooring system
    b) Non-linear environmental load
    c) Non-linear coupling in multi-body geometry
2. Oscillating wave drift forces, as well as low frequency excursions, become important;

3. Influence of initial disturbance becomes important (initial-value problem).

4.5. Operability assessment scheme

The success in assessing operability using this methodology depends on making proper choices (mechanisms and switches) in the operability assessment scheme. In this section, examples of implementing this operability assessment methodology (with different combinations of mechanism and switches) step-by-step will first be introduced. After that, all possible combinations of mechanism and switches will be summarized.

4.5.1. Basic mechanism: persistency + veto + FD/TD

The procedure below is a basic guide for assessing operability using:

- Basic mechanism
- Persistency analysis (Switch 1) and veto analysis (Switch 2)
- Either FD or TD (Switch 3)

Use the operation described in Section 4.2 as an example:

1. The first step is to figure out clearly what are the operational phases to be assessed, what are the criteria for each phase and what assessment method to be used for each phase. In this example, there are 3 phases, $Ph\,1$, $Ph\,2$ & $Ph\,3$, 3 sets of criteria, $[Cr\,1]$, $[Cr\,2]$ & $[Cr\,3]$, and 3 assessment methods, $Am\,1$, $Am\,2$ & $Am\,3$ (no matter FD/TD). Persistency data are used here. After this step is finished, we should have an operability assessment table as shown in Table 4.4;

2. An imaginary persistency table should be made to make sure every possible sea-state sequence is accounted. As shown in Table 4.3, there will be in total 27 ($= 3^3$) sequences in this example. The occurrence probability of each sequence $P_{occ} = P_{start} \times P^1_{shift} \times P^2_{shift}$. After this step is finished, we should have a persistency table as shown in Table 4.3. From this step on, we take only sequence No. 4 as an example because we can do the same thing for all the other sea state sequences. The sea states shift as $W_1 \rightarrow W_2 \rightarrow W_1$, of which the occurrence probability is $A\% \times a\% \times b\%$ obviously;

3. If we fill in this sea-state sequence in Table 4.4, we can calculate the survival rate Q^i for each assessment unit (by directly comparing simulated response to criteria), as shown in Table 4.8. The total survival rate Q_{sur} under sea-state sequence No. 4 can be thus calculated: $Q^4_{sur} = Q^1 \times Q^2 \times Q^3 \times Q^4 \times Q^5$. By doing so, we are assessing whether a 3-phase operation with fixed duration can survive under sea-state sequence No. 4 or not;

Assessment unit	Operational phase	Sea states	Q_{sur}
1	$Phase\,1$	W_1	Q^1
2	$Phase\,1$	W_2	Q^2
3	$Phase\,2$	W_2	Q^3
4	$Phase\,3$	W_2	Q^4
5	$Phase\,3$	W_1	Q^5

Table 4.8.: Operability assessment unit for persistency analysis

4. The operability contribution of case 4 can now be calculated: $C_{op}^4 = Q_{sur}^4 \times P_{occ}^4$. Doing the same thing to the other 26 cases, the total operability will be $C_{op}^{total} = \sum_{i=1}^{27} C_{op}^i$.

4.5.2. Basic mechanism: scatter + veto + FD/TD

The procedure below is a basic guide for assessing operability using:

- Basic mechanism
- Scatter analysis (Switch 1) and veto analysis (Switch 2)
- Either FD or TD (Switch 3)

Use the operation described in Section 4.2 as an example:

1. For scatter analysis, the most critical phase is chosen to represent the whole operation and its duration is assumed to be 3 hours. In this example, production phase 1 is assessed, $Ph\,1$, accordingly with its criteria and assessment method, $[Cr\,1]\,\&Am\,1$ (no matter FD/TD). After this step is finished, we should have an operability assessment table as shown in Table 4.9;

Assessment unit	Operational phase		Assessment method		Sea state
1	$Phase\,1$	3 hours	$\phi \leqq 3°$	FD/TD	Scatter data

Table 4.9.: Example operability assessment table for scatter analysis

2. The survival rate under sea state W_i can be calculated (by directly comparing simulated response to criteria), as shown in Table 4.10;

Assessment unit	Operational phase	Sea states	Q_{sur}
1	$Phase\,1$	W_i	Q^i

Table 4.10.: Operability assessment unit for scatter analysis

3. The weighted operability under sea state W_i can now be calculated: $C^i_{op} = Q^i_{sur} \times P^i_{occ}$. Summing up all possible sea states, the total operability will be $C^{total}_{op} = \sum_{i=1} C^i_{op}$.

4.5.3. Duration mechanism: persistency + probabilistic + FD/TD

The procedure below is a basic guide for assessing operability using:

- Duration mechanism
- Persistency analysis (Switch 1) and probabilistic analysis (Switch 2)
- Either FD or TD (Switch 3)

Duration mechanism will follow different assessment procedure from basic mechanism. Use the operation described in Section 4.2 as an example:

1. The first step is still to figure out clearly the project input. In this example, we have 3 phases, $Ph\,1$, $Ph\,2\,\&\,Ph\,3$, 3 sets of criteria, $[Cr\,1]$, $[Cr\,2]$ & $[Cr\,3]$, and 3 assessment methods, $Am\,1$, $Am\,2\,\&\,Am\,3$ (no matter FD/TD). Besides, phase duration plays an extra important role here. We should notice that phase duration here means the **required duration** for this phase under perfect working condition, which indicates that the **real duration** might last longer than the required one. To cope with this feature, Figure 4.5 and Table 4.11 illustrate a rather different operability assessment table;

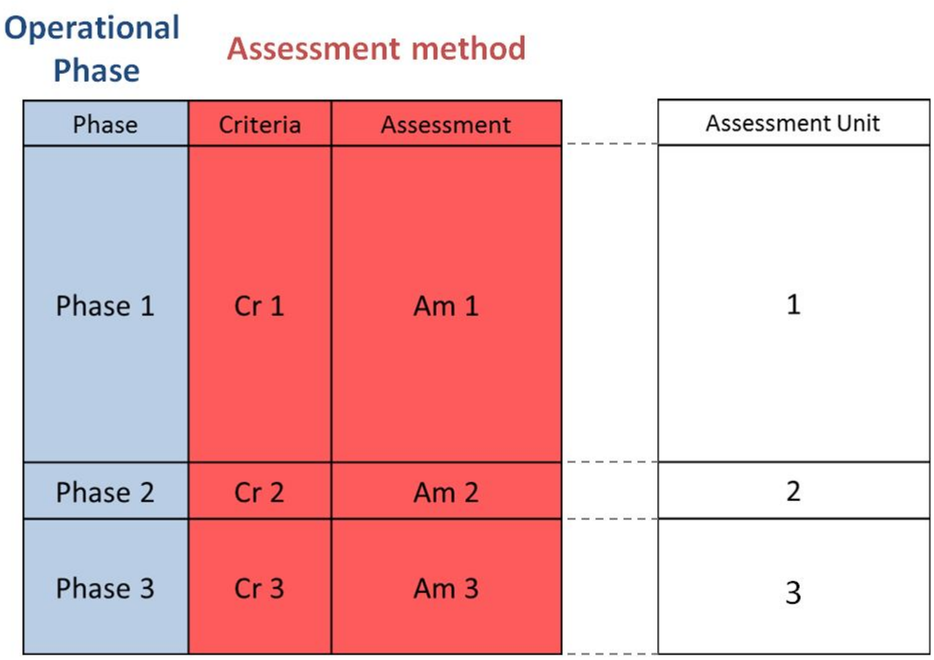


Figure 4.5.: Example FBTO operability assessment table under duration mechanism

Assessment unit	Operational phase		Assessment method	
1	$Phase\,1$	6 hours	$\phi \leqq 3°$	FD
2	$Phase\,2$	0.5 hours	$Hs < 2m$	Direct
3	$Phase\,3$	2.5 hours	$\phi \leqq 3°$	FD

Table 4.11.: Example FBTO operability assessment table under duration mechanism

2. An imaginary persistency table should be made to make sure every possible sea state sequence is accounted. Notice that here number of sea states in a sea state sequence should match **maximum allowable duration**. In this example, the required duration for this 3-phase operation is 9 hours. As an example, we set the maximum allowable duration to be 15 hours. Any operation lasting longer duration will be considered failed. Assuming each sea state with 3-hour duration, there will be in total 243 ($= 3^5$) different sequences, each with an occurrence probability, as shown in Table 4.12;

No.	$Con1$	$Con2$	$Con3$	$Con4$	$Con5$	P_{occ}
1	W_1	W_1	W_1	W_1	W_1	P_{occ}^1
2	W_1	W_1	W_1	W_1	W_2	P_{occ}^2
...	...	...	...	...	...	...
242	W_3	W_3	W_3	W_3	W_2	P_{occ}^{242}
243	W_3	W_3	W_3	W_3	W_3	P_{occ}^{243}

Table 4.12.: Example persistency table

3. For each sea state in sea state sequence No. i (occurrence probability P_{occ}^i), we can calculate the following (in the way described in Section 4.4.2) as shown in Figure 4.6 and Table 4.13;

   - $P^i\,(t \leq MAD)$: probability that the operation can be finished within maximum allowable duration (15 hours in this case),
   - D^i: expected duration of the operation (including suspension)

Assessment unit	Operational phase	Real duration	$P^i\,(t \leq MAD)$
1	$Phase\,1$	D_1	[a] $\begin{cases} P^i\,(t \leq MAD) = 1 & if\ D^i \leq MAD \\ P^i\,(t \leq MAD) = 0 & if\ D^i > MAD \end{cases}$
2	$Phase\,2$	D_2	
3	$Phase\,3$	D_3	
In total		$D^i = \sum_{k=1}^{3} D_k^i$	

[a] MAD stands for Maximum Allowable Duration.

Table 4.13.: Example operability assessment unit under duration mechanism

As an example, the following procedure shows how to calculate D_1(assuming using FD analysis). Table 4.14 illustrates all used symbols.

Symbol	Definition
D_1	Real duration of $Phase\,1$
R_1^i	Required duration of $Phase\,1$ after i^{th} sea state, $Con\,i$
T	Duration of each sea state
$D_{Con\,1}$, $D_{Con\,2}$	Required completion time of $Phase\,1$ under $Con\,1\,\&\,Con\,2$

Table 4.14.: Symbol definition

a) Calculate roll RAO of $Phase\,1$;

b) Calculate workable probability of $Phase\,1$ under $Con\,1$ using Rayleigh distribution:

$$P\left(roll \leq Cr\right) = 1 - e^{-\frac{Cr^2}{2m_0}}$$

c) Calculate required completion time of $Phase\,1$ under $Con\,1$:

$$D_{Con\,1} = R_1^0 \div P\left(roll \leq Cr\right)$$

$$\begin{cases} D_1 = D_{Con\,1} & If\ D_{Con\,1} \leq T \\ D_1 = 0 + T & If\ D_{Con\,1} > T \end{cases}$$

d) Two possibilities depending on $D_{Con\,1}$:

	$If\ D_{Con\,1} \leq T$	$If\ D_{Con\,1} > T$
D_1	$D_{Con\,1}$	T
R_1^1	0	$R_1^0 \times \left(1 - \frac{T}{D_{Con\,1}}\right)$

- $If\ D_{Con\,1} \leq T$:
  - $Phase\,1$ is 100% finished during the first sea state, $Con\,1$
  - Start from Step (a) for $Phase\,2$
- $If\ D_{Con\,1} > T$:
  - $Phase\,1$ is $\frac{T}{D_{Con\,1}} \times 100\%$ finished during the first sea state, $Con\,1$.
  - Start from Step (b) for $Phase\,1$ under $Con\,2$

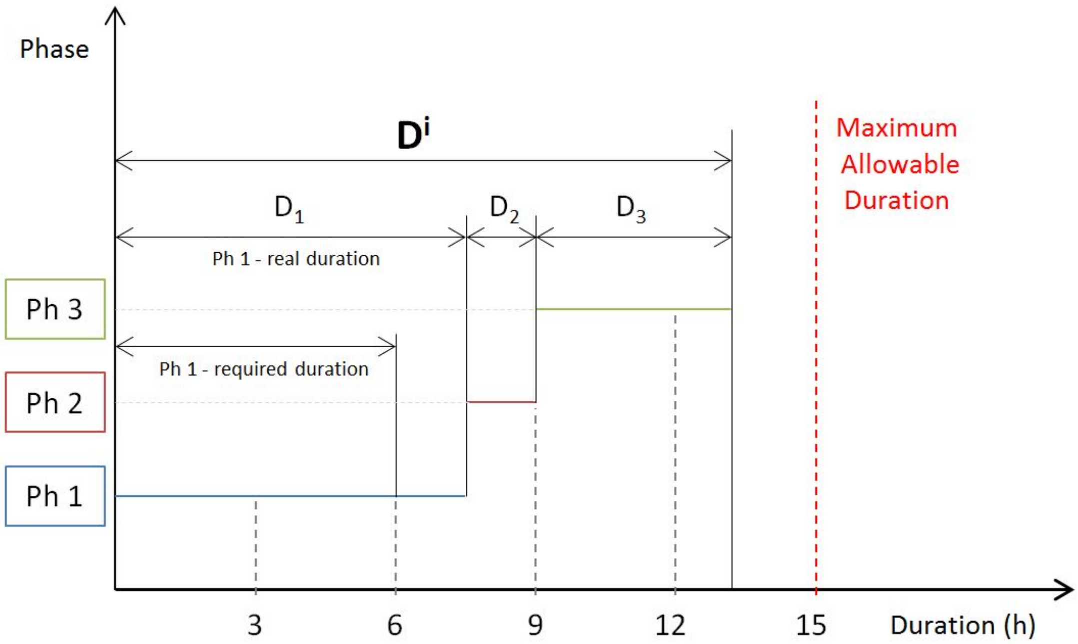


Figure 4.6.: Example operability assessment unit under duration mechanism

4. The weighted operability (probability that operation finishes within maximum allowable duration) under sea state sequence No. i can now be calculated: $C_{op}^{i} = P^{i}\left(t \leq MAD\right) \times P_{occ}^{i}$. And the weighted expected duration can also be calculated: $D_{weighted}^{i} = D^{i} \times P_{occ}^{i}$. Summing up all possible sea states, the total operability will be $C_{op}^{total} = \sum_{i=1}^{243} C_{op}^{i}$ and the expected total duration will be $D^{total} = \sum_{i=1}^{243} D_{weighted}^{i}$.

4.5.4. Overview: operability assessment scheme

Mechanism	Switch 1	Switch 2	Switch 3	Comment
Basic	persistency	veto	FD/TD	(1)
		probabilistic	FD/TD	(2)
	scatter	veto	FD/TD	(3)
		probabilistic	FD/TD	(4)
Duration	persistency	veto	FD/TD	(5)
		probabilistic	FD/TD	(6)
	~~scatter~~	~~veto / probabilistic~~	~~FD/TD~~	(7)

Table 4.15.: Overview operability assessment scheme

Table 4.15 summarizes all possible combinations of mechanism and switches.

1. Recommended when
   - Operation needs to be finished continuously.
   - Operation involves multiple operational phases with noteworthy duration.
   - How to implement see Section 4.5.1.
2. Not recommended
   - "Persistency + probabilistic" works better under duration mechanism.
   - Reason see Appendix A.2.
3. Conventional engineering approach
   - Faster than (1) but less accurate.
4. Conventional engineering approach
   - Not covered in this report.
5. Not recommended
   - "Duration + veto" produces very conservative result.
   - Reason see Appendix A.3.
6. Recommended when
   - Operation allows suspension.
   - Insight of expected operation duration is desired.
   - How to implement see Section 4.5.3.
7. Scatter analysis itself omits operation duration. Thus, it makes no sense to choose scatter for Switch 1 under duration mechanism which intends to predict expected operation duration.

As can be seen, either FD or TD can be used no matter what choices are made for mechanism and switches.

4.6. Conclusion

1. Operability assessment table (Figure 4.1 for basic mechanism and Figure 4.5 for duration mechanism):
   - Operational phase
   - Assessment method
   - Environmental data

- Assessment unit

2. 2 operability assessment mechanisms (Table 4.6):
   - Basic mechanism
   - Duration mechanism
3. 3 sets of switches (Figure 4.4):
   - Switch 1: persistency analysis / scatter analysis
   - Switch 2: veto analysis / probabilistic analysis
   - Switch 3: frequency-domain analysis / time-domain analysis
4. The methodology shows its versatility in assessing operability of any offshore operation, if the following are used properly:
   - Operability assessment table
   - Operability assessment mechanism
   - Switch
5. Conditions of
   - Operability assessment mechanism: Section 4.3.2
   - Switch: Section 4.4
6. Step-by-step guides of adapting this methodology under the following choices of operability assessment mechanism and switches are presented:
   - Basic mechanism: persistency + veto + FD/TD
   - Basic mechanism: scatter + veto + FD/TD
   - Duration mechanism: persistency + probabilistic + FD/TD

5. Persistency analysis

5.1. Introduction

This chapter intends to discuss the influence of adapting a persistency analysis. By decomposing the whole analysis and comparing individual variable, more insights towards persistency analysis can be revealed. Basically, there are two questions regarding persistency analysis:

- **Why is persistency analysis better than scatter analysis?**
- **What is the influence of persistency data quality?**

To make it clear, the switches chosen here are persistency analysis for Switch 1, veto analysis for Switch 2 and frequency domain analysis for Switch 3. The operability assessment mechanism is basic mechanism. The counterpart of the comparison is scatter analysis (under basic mechanism; with veto and frequency domain analysis). Thus, we are actually comparing operability assessment procedure as described in Section 4.5.1 with the one described in Section 4.5.2. The reason why the comparison is done only under basic mechanism not under duration mechanism is because scatter analysis itself doesn't fit duration mechanism (see Section 4.5.4).

As a recap, about veto analysis, the essence of calculating survival rate is to compare the MPM to the specific criteria. About operability, the following concept is used under each sea state sequence:

$$C_{op} = Q_{sur} * P_{occ} \tag{5.1}$$

Where C_{op} is the weighted operability (in percentage); Q_{sur} is the survival rate (either 1 or 0) under the sea state sequence; P_{occ} is the occurrence probability of the sea state sequence. And for total operability C_{op}^{total} under N possible sea state sequence:

$$C_{op}^{total} = \sum_{i=1}^{N} C_{op}^{i} \tag{5.2}$$

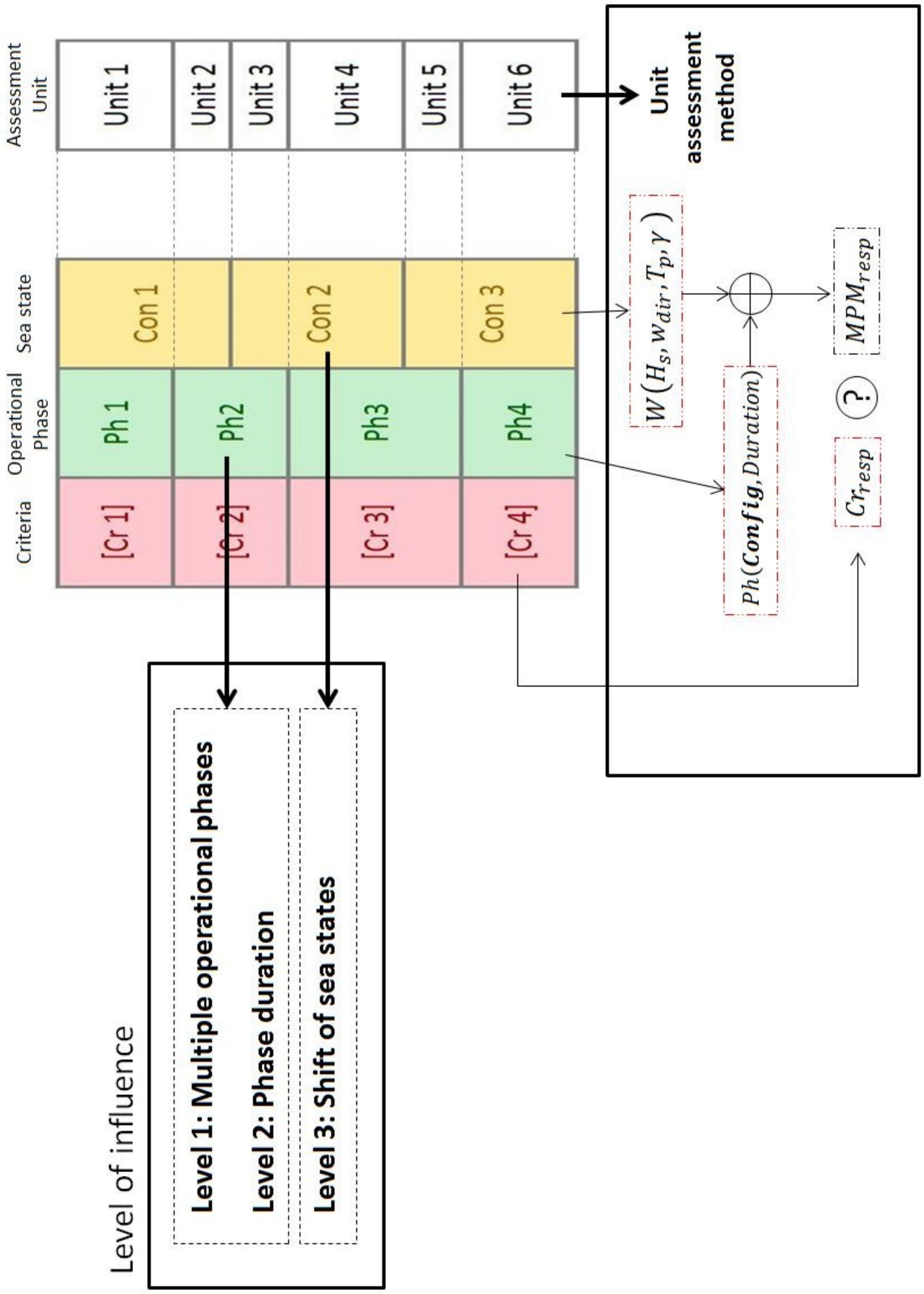


Figure 5.1.: Inside the nutshell of persistency analysis

5.2. Persistency vs scatter

Figure 5.1 is a schematic drawing of persistency analysis. As a recap, the first step of adapting persistency analysis is to construct an operability assessment table, e.g. as shown at top-right corner of Figure 5.1. The components of an operability assessment table are **persistency data** (sea state sequence), **operational phase** and **assessment method** (changing with different operational phases). One **assessment unit** contains combined information of operational phase, sea state and assessment method (criteria is a component of assessment method).

In simple words, persistency analysis can produce better result because it captures more reality. In scatter analysis, duration of operation is ignored while it is taken into account in persistency analysis. Because of that, when assessing operability of an offshore operation, it is necessary to consider more than 1 operational phases, to consider duration of each phase and to consider shift of sea states during the operation. The influence can thus be categorized in 3 levels. Higher level indicates that it has more critical influence to the output of persistency analysis and explains more why persistency analysis produces better results than scatter analysis.

1. Due to multiple operational phases
2. Due to phase duration
3. Due to shift of sea states

5.2.1. Unit assessment method

Unit assessment method is the way to calculate survival rate of each assessment unit. The method is suitable to calculate operability only under the same mechanism and switch choices as stated in Section 5.1.

To start with, survival rate will be calculated for each assessment unit, which will change with different phases, sea states and criteria. One important concept in the assessment method is MPM (see e.g. Ochi [1981]). The MPM can be expressed as:

$$MPM = \sqrt{2m_0 \times \ln\left(\frac{t}{\alpha \times T_Z}\right)} \tag{5.3}$$

Where m_0 is the zeroth-order moment of the motion spectrum $(S_m(\omega) = RAO^2 \cdot S_w(\omega))$. MPM will then be compared to criteria to calculate survival rate, Q_{sur}, as shown in Figure 5.1. Table 5.1 shows influence due to different phases, sea states and criteria.

More discussion about judging how critical an assessment unit can be found in Appendix A.4.

5.2.2. Level 1: Multiple operational phases

Level 1 captures the reality that during an offshore operation, more than 1 operational phases might play roles when assessing the operability. Scatter analysis, in contrast, only studies 1

Influence from	Description	Influence on Q_{sur}		
Sea state	$H_s, T_p \& \gamma$	$S_w(\omega)$	m_0	MPM_{resp}
Sea state	w_{dir}	RAO	m_0	MPM_{resp}
Operational phase	$Config$[a]	RAO	m_0	MPM_{resp}
Operational phase	$Duration$[b]	-	$\sqrt{\ln\left(\frac{t}{\alpha \times T_Z}\right)}$	MPM_{resp}
Criteria	Cr_{resp}	-	-	Cr_{resp}

[a] $Config$ refers to configuration of FBTO system, e.g. vessel position & mooring settings, under this operational phase

[b] Duration here refers to duration of the operational phase captured by this assessment unit.

Table 5.1.: Influence of different parameters on Q_{sur}

operational phase of the whole operation[1]. During an operation, if there exists 1 phase which is always more critical than all the others, then scatter analysis might be able to produce accurate result assuming phase duration doesn't play a significant role. But in reality, for those operations lasting long duration, there probably exist more than 1 critical operational phases. As a result, it makes limited sense when only 1 phase is assessed by adapting scatter analysis. Besides, accounting multiple operational phases in the operability study makes it possible to assess systematically how critical each operational phases is (with usage of operability assessment table). It is also more convenient for designer of the operation to optimize it at a specific operational phase directly.

In addition, multiple operational phases are kept in a sequence which resembles the operation in reality. This sequence, together with sea state sequence which will be described in Level 3, will lead to more accurate calculation of operability.

Conclusion

Level 1 influence can be summarized as:

- Including multiple operational phases in the assessment
- Introducing an operational phase sequence resembling the reality

5.2.3. Level 2: Phase duration

Level 2 captures the reality that phase duration, as well as duration of the whole operation, might last longer than 3 hours (3 hours is a typical value assumed when adapting scatter analysis). Scatter analysis, in contrast, assumes a 3-hour duration for the whole operation. Phase duration will influence how critical an operational phase is. Moreover, longer phase duration will enable more shifts of sea states. Both of them help capture more reality than scatter analysis.

[1] This statement is generally true, although there exists way to add modification to scatter analysis in order to account the influence of multiple critical operational phases.

MPM increases

The expression of MPM writes:

$$MPM = \sqrt{2m_0 \times \ln\left(\frac{t}{\alpha \times T_Z}\right)} \tag{5.4}$$

Seemingly, if duration increases, t will have bigger value. Thus, the MPM will be larger which might lead to exceedance of the criteria. To conclude, the longer the duration is, the more likely the criteria are to be exceeded. And as a result, the more likely that C_{op} calculated by persistency analysis gets smaller (and thus more accurate). Compared to scatter analysis, which always assumes 3-h duration for the whole operation, persistency analysis captures the influence of duration in the MPM formula. In-depth examples about how phase duration is accounted in the MPM formula can be found in Appendix A.5.

Table 5.2 shows the difference in value due to different duration, assuming $T_Z = 10s$ & $\alpha = 1$. Assume there are two operational phases with similar configuration but only difference in phase duration. If the MPM calculated for the phase with shorter duration under sea state, Wi, is slightly smaller than the criteria, the MPM of the phase with larger duration will probably be larger than the criteria. This indicates that the Q_{sur} calculated might be totally different for the two cases. Such sea state as Wi is thus defined as **duration-sensitive** sea state because different Q_{sur} can be observed for operational phases with only difference in duration.

Duration (h)	1	3	6	9
$\sqrt{\ln\left(\frac{t}{\alpha \times T_Z}\right)}$	2.426	2.546	2.771	2.843

Table 5.2.: Difference in MPM due to different duration

The conclusion is practically meaningful for FBTO. During the operation, there will be several production phases with only slight difference in configuration, e.g. floating crane is shifted 10m to reach the next hatch. The difference in configuration in this case plays a tiny role while duration of each phase is a more effective index to judge which phase is more critical.

Conclusion

1. Level 2 Influence can be summarized as:
   - Longer phase duration $\Longrightarrow$ MPM increases $\Longrightarrow$ C_{op} decreases
2. Influence due to phase duration is well captured by substituting proper values for t and α in Equation 5.4

5.2.4. Level 3: Shift of sea states

Level 3 captures the reality that sea states will probably change during the operation. Scatter analysis, in contrast, assumes constant sea state when calculating operability. If multiple sea states take place within the operation duration, the calculated C_{op} tends to decrease because of accounting probability of a benign sea state shifting to a severe one. There might be argument that, at the same time, the probability that a severe sea state might shift to a benign one, which will lead to a rise in C_{op}. This is not true because under the chosen assessment method (veto analysis using MPM), if the operational phase fails during the first sea state (severe) but survives all the rest (benign), this sea state sequence is still not operable. Thus, when including more shifts of sea states, C_{op} is only possible to get smaller.

Assuming an 1-phase operation represented by $Ph1$ and it might encounter only 3 possible sea states, $W1, W2\&W3$. After calculation (see Section 5.2.1), Table 5.3 shows how severe or benign each sea state is. Severe sea states refers to those which can provoke undesired vessel response while benign has the opposite meaning.

	$W1$	$W2$	$W3$
Q_{sur}	1	1	0
Comment	Benign	Benign	Severe

Table 5.3.: Response of $Ph\,1$ under $W1, W2\&W3$

Table 5.4 shows the start probability and shift probability . The persistency data is calculated based on an artificial time series with a sampling rate of per 3h.

	P_{start} [a]	$P_{shift\to W1}$	$P_{shift\to W2}$	$P_{shift\to W3}$
$W1$	0.66	0.95	0.01	0.04
$W2$	0.05	0.13	0.57	0.30
$W3$	0.29	0.08	0.04	0.87

[a] Note here P_{start} in persistency data is equal to P_{occ} (occurrence probability) in scatter data

Table 5.4.: $P_{start}\&P_{shift}$ of $W1, W2\&W3$

Consider the following 3 cases. Notice that property listed in Table 5.3 and Table 5.4 is assumed true for all 3 cases.

- Case 1: $Ph\,1$ is with a duration of 27h
- Case 2: $Ph\,1$ is with a duration of 9h (same configuration as in Case 1)
- Case 3: $Ph\,1$ is assumed a duration of 3h (same configuration as in Case 1). By doing so, Case 3 actually performs scatter analysis to both Case 1 and Case 2.

By comparing Case 1 and Case 2 to Case 3, difference between adapting persistency analysis and scatter analysis can be observed. Comparison between Case 2 and Case 1 shows the influence of operation duration.

	Possible sea states	Phase	Duration each sea state	Total duration	Length of sea state sequence	Analysis
Case 1	$W1, W2\&W3$	$Ph1$	3h	27h	9	persistency
Case 2	$W1, W2\&W3$	$Ph1$	3h	9h	3	persistency
Case 3	$W1, W2\&W3$	$Ph1$	3h	3h (assumed)	1	scatter

Table 5.5.: Case with different sea state duration

Table 5.5 summarizes the difference between 3 cases.

Based on input from Table 5.3, 5.4 & 5.5, Figure 5.2 & 5.3 present the results of the calculation.

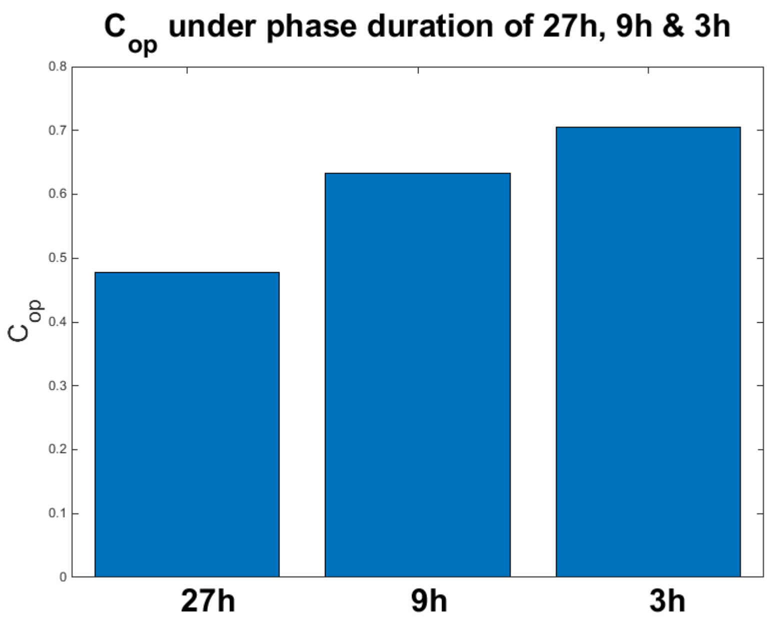


Figure 5.2.: Total operability under different cases

Figure 5.2 shows total operability of all 3 cases and Figure 5.3 shows how operability of the operation starting respectively from $W1, W2\&W3$ changes when phase duration changes.

1. Persistency analysis results in smaller C_{op}, thus more accurate result than scatter analysis.

   - In Figure 5.2, C_{op} decreases from 71% (Case 3) to 63% (Case 2) and 47% (Case 1), when persistency analysis is adapted compared to scatter analysis.
   - In Figure 5.3, most operability concentrates at $W1$ because it has the largest P_{start} and is very likely to shift to itself (95%) and, of course, because it is a benign sea state. Take operability starting from $W1$ as an example, C_{op} decreases from 66% (Case 3) to 61% (Case 2) and 47% (Case 1), when persistency analysis is adapted compared to scatter analysis. Same trend is spotted for $W2$.

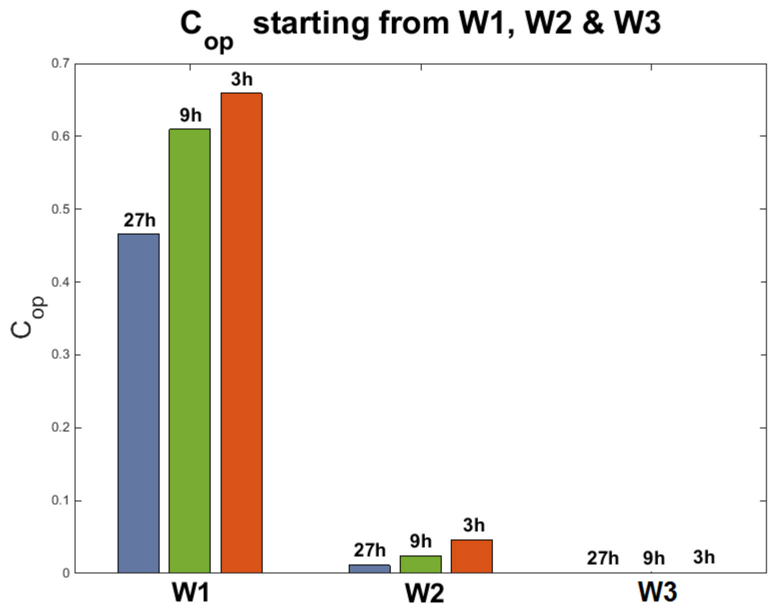


Figure 5.3.: Operability under different cases starting from $W1, W2\&W3$

2. The longer the duration is, the worse result scatter analysis will produce and the better it is to adapt persistency analysis.

   - In Figure 5.2, C_{op} of Case 1 decreases by 24% compared to Case 3 while C_{op} of Case 2 decreases by 8%.
   - In Figure 5.3, operability starting from $W1$ of Case 1 decreases by 19% compared to Case 3 while the one of Case 2 decreases by 5%.

Logically, if duration of an operation is larger, influence due to shift of sea states will be bigger. The more shifts of sea states are enabled, the more likely that a benign sea state changes to a severe one. That's why C_{op} drops when performing scatter analysis to operation with longer duration.

Conclusion

1. Level 3 Influence:

   - Accounting shift of sea states will result in better operability assessment (C_{op} decreases).

2. Longer operation duration $\Longrightarrow$ more shifts of sea states $\Longrightarrow$ more likely $W_{benign} \rightarrow W_{wild} \Longrightarrow C_{op}$ decreases

5.3. Quality of persistency data

In this section, influence due to quality of persistency data will be discussed. Finer persistency data here refers to those with smaller sampling interval (e.g. for each unit of record $3h \rightarrow 1h$). If sampling rate increases from every 3h to 1h, more shifts of sea states will be enabled for an operation with the same duration. This section will follow two logic steps:

1. 1-phase operation
2. Multi-phase operation

5.3.1. 1-phase operation

Assuming an offshore operation with only 1 operational phase represented by $Ph\,1$ and it might encounter only 2 possible sea states, $W1\&W2$. $Ph\,1$ lasts for 4 hours and it is only operable in $W1$. In other words, $Q_{sur} = 1$ only when there is a 4h-$W1$ window. In mathematical formula:

$$C_{op} = P_{W1:4h} \tag{5.5}$$

Where $P_{W1:4h}$ means probability that a 4h-$W1$ window occurs, which can be calculated from the time series of sea-state record.

Persistency data is obtained from time series of sea state record. From a coarse time series to a fine one, there are two possibilities as shown below. Assuming the coarse time series is with an interval of 4h, the two possibilities are:

1. Sea state **mildly** changes during each 4h window (as shown in Figure 5.4)
2. Sea state **dramatically** changes during each 4h window

Possibility 1. Assuming coarse and fine time series as shown in Figure 5.4, the possibility that dramatic change might occur within each interval is neglected. Based on this assumption, Table 5.6 does simple calculation to estimate the probability that a certain sea state sequence occurs during the 4-hour operation, $Ph\,1$, under sampling interval of 4h, 2h & 1h. As can be seen, $P_{W1:4h}$ decreases when sampling interval shortens from 4h to 1h, because possibility that a sea state sequence, with $W2$ in it, occurs becomes larger. This also means that, when adapting persistency data of different quality, the persistency property will change as well.

Table 5.7 shows total operability (calculated by Equation 5.5) under three different persistency data. As a conclusion, finer persistency data will lead to decrement in C_{op} in **mildly changing** sea.

Possibility 2. By accounting that dramatic change might occur within a 4h sea state, not only the probability that $W2$ (severe) might occur within a 4h interval previously represented by $W1$ (benign), but also $W1$ (benign) might occur within a 4h interval previously represented by $W2$ (severe), is included. Thus, C_{op} can either decrease or increase in **dramatically changing** sea. In reality, there will be some parts of time when sea state is mildly changing while some more dramatically. It is not predictable whether C_{op} will further

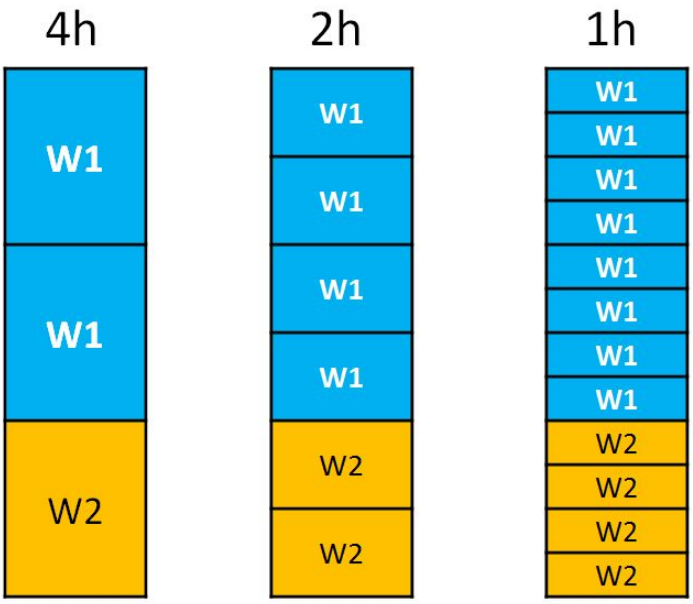


Figure 5.4.: Finer time series of mildly changing sea states

	4h	2h	1h
$P_{W1:4h}$	$\frac{2}{3}$	$\frac{3}{5}$	$\frac{5}{9}$
$P_{W2:4h}$	$\frac{1}{3}$	$\frac{1}{5}$	$\frac{1}{9}$
P_{else} [a]	0	$\frac{1}{5}$	$\frac{1}{3}$

[a] P_{else} refers to the sea-state sequence with both $W1\&W2$ in it.

Table 5.6.: Occurrence probability of sea-state sequence during $Ph\,1$

decrease or increase when using finer persistency data because persistency property will be different when sampling interval changes, though finer persistency data tend to result in C_{op} decrease because a majority part of time series will still be changing mildly in most cases. No matter drop or rise in C_{op}, finer persistency data will definitely lead to more accurate assessment of operability.

In reality, there are often a larger database of possible sea states and longer time series of sea state records. But the logic stays the same. In addition, if using persistency data with infinitely small sampling interval, the calculation will also be infinitely approaching the truth. But it is not possible and also not the purpose of the operability study. The purpose is to obtain an assessment result of desired accuracy and efficiency level. In other words, assuming a 1h or 3h sea state in the sea-state sequence, compared to half an hour or even less, will of course lead to less accurate assessment, but the result might still be satisfactory.

In conclusion, the effect describe above is due to resolution of persistency data. Using finer persistency data will lead to more accurate operability assessment. Thus, it is hereby defined as **resolution effect**. As a result, C_{op} tends to decrease when finer persistency data

	4h	2h	1h
C_{op}	$\frac{2}{3}$	$\frac{3}{5}$	$\frac{5}{9}$

Table 5.7.: C_{op} under $4h, 2h\&1h$ sampling interval

are adapted but the validation of this conclusion is very much dependent on time series of sea-state record. To conclude, when adapting finer persistency data,

1. C_{op} will decrease assuming **mildly changing** sea;
2. C_{op} can either decrease or increase assuming **dramatically changing** sea;
3. $\underline{C_{op}}$ <u>tends to decrease in reality</u> (mildly changing sea + dramatically changing sea).

5.3.2. Multi-phase operation

Besides resolution effect as described above, interaction between sea state sequence and operational phase sequence starts to play a role. Influence due to persistency data quality can be divided in two categories. They will be proven in this section.

- **Resolution effect**: smaller sampling interval (finer persistency data) $\Longrightarrow$ more accurate operability assessment (C_{op} tends to decrease)
- **Match effect**: proper choice of sampling interval $\Longrightarrow$ more accurate operability assessment (C_{op} increases)

To better describe these, several examples are given below.

Assume a 2-phase operation, $Ph\,1\&Ph\,2$ with duration 3h each (thus 6 hour in total), and assume only two possible sea states, $W1\&W2$, exist. The difference between Case A as in Figure 5.5a and Case B as in Figure 5.5b are shown below.

- Case A: **1** sea state in the sea state sequence lasting **6** hours;
- Case B: **2** sea states in the sea state sequence lasting **3** hours each.

Another important assumption is that persistency data are obtained using two time series of sea state record at the same location during the same period of time. The only difference is listed below, which shows that persistency data used in Case B is finer than those in Case A.

- Sampling interval for Case A is **6** hours;
- Sampling interval for Case B is **3** hours.

(a) (b)

Figure 5.5.: Multi-phase operation example

Resolution effect

For the example as shown in Figure 5.5, assume the benign sea states for each phase as shown in Table 5.8. Benign sea states here refer to those won't induce undesired ship response.

	All benign sea states
$Ph\,1$	$W1$
$Ph\,2$	$W1$

Table 5.8.: Resolution effect: benign sea states for each phase

Table 5.9 calculates C_{op} of both cases.

<table>
<tr><td></td><td colspan="2">Survival sequence[a]</td><td>P_{occ}</td><td>C_{op}</td><td>Comparison</td></tr>
<tr><td>Case A</td><td colspan="2">$W1$</td><td>$P\left(W1_{6h}\right)$</td><td>$P\left(W1_{6h}\right)$</td><td rowspan="2">$C_{op}^{A} > C_{op}^{B}$</td></tr>
<tr><td>Case B</td><td>$W1$</td><td>$W1$</td><td>$P\left(W1_{3h} \rightarrow W1_{3h}\right)$</td><td>$P\left(W1_{3h} \rightarrow W1_{3h}\right)$</td></tr>
</table>

[a] Survival sequence refers to sea state sequence leading to $Q_{sur}^{total} = 1$ for the operation

Table 5.9.: Resolution effect: C_{op} of Case A and Case B

$C_{op}^{A} > C_{op}^{B}$ because $P\left(W1_{6h}\right) > P\left(W1_{3h} \rightarrow W1_{3h}\right)$ and the reason why $P\left(W1_{6h}\right) > P\left(W1_{3h} \rightarrow W1_{3h}\right)$ is the same as stated in Section 5.3.1 (3 logical steps). Resolution effect states that adapting finer persistency data tends to result in decrease in total P_{occ} (total occurrence of all survival sea state sequences), thus decrease in C_{op}.

Match effect

For the example as shown in Figure 5.5, assume benign sea states for each phase as shown in Table 5.10.

	All benign sea states
$Ph\,1$	$W2$
$Ph\,2$	$W1$

Table 5.10.: Match effect: benign sea states for each phase

Table 5.11 calculates C_{op} of both cases.

	Survival sequence		P_{occ}	C_{op}	Comparison
Case A	None		0	0	$C_{op}^A < C_{op}^B$
Case B	$W2$	$W1$	$P\,(W2_{3h} \to W1_{3h})$	$P\,(W2_{3h} \to W1_{3h})$	

Table 5.11.: Match effect:C_{op} of Case A and Case B

$C_{op}^A < C_{op}^B$ because $0 < P\,(W2_{3h} \to W1_{3h})$. Match effect states that proper choice of sampling interval will lead to increase in C_{op}. This is because if a sea sate covers more than 1 operational phases, then the set of benign sea states should be the intersection of all covered operational phases. This will lead to an extra loss in C_{op}, which can be avoided if persistency data with proper sampling interval is used. Such false loss is due to mismatch between sea state sequence and operational phase sequence. Thus, proper choice of sampling interval will lead to more accurate operability assessment by avoiding false loss due to mismatch (C_{op} increases).

Food for thought: resolution effect + match effect

This example approaches more the reality. For the example as shown in Figure 5.5, assume benign sea states for each phase as shown in Table 5.12.

	All benign sea states
$Ph\,1$	$W1$
$Ph\,2$	$W1\&W2$

Table 5.12.: Food for thought: benign sea states for each phase

Table 5.13 calculates C_{op} of both cases.

Case	No.	Survival sequence		P_{occ}	C_{op}	Comparison
Case A	A	$W1$		$P\,(W1_{6h})$	$P\,(W1_{6h})$	C_{op}^{A} (?) C_{op}^{B}
Case B	$B1$	$W1$	$W1$	$P\,(W1_{3h} \rightarrow W1_{3h})$	$P\,(W1_{3h} \rightarrow W1_{3h})$	
	$B2$	$W2$	$W1$	$P\,(W1_{3h} \rightarrow W2_{3h})$	$P\,(W1_{3h} \rightarrow W2_{3h})$	

Table 5.13.: Food for thought:C_{op} of Case A and Case B

The following two influence in C_{op} can be spotted:

1. Due to resolution effect, component No. $B1$ in Table 5.13 will lead to decrease in C_{op}, compared to No. A in Case A;

2. Due to match effect, component No. $B2$ in Table 5.13 will lead to increase in C_{op}.

The above two effects balance each other.

- When assuming mildly changing sea, if there are in total only two possible sea states, $W1\&W2$, then $C_{op}^{A} = C_{op}^{B}$ (See Appendix A.6). If there are more than 2 possible sea states, then $C_{op}^{A} > C_{op}^{B}$;

- When assuming true sea, C_{op}^{A} can either be bigger or smaller than C_{op}^{B}. It depends on how persistency property changes (in both occurrence probability and shift probability) due to adapting persistency data of different sampling interval.

In reality, there will be more complicated combination of both operational phase duration and sea state duration, but the philosophy to deal with it will be the same. All influence due to resolution of persistency data can be clarified in either of the category: resolution effect or match effect.

Conclusion

1. Influence due to quality of persistency data can be summarized as
   - **Resolution effect**: smaller sampling interval (finer persistency data) $\Longrightarrow$ more accurate operability assessment (C_{op} tends to decrease)
   - **Match effect**: proper choice of sampling interval $\Longrightarrow$ more accurate operability assessment (C_{op} increases)

2. Sampling interval of persistency data changes together with duration of each sea state unit in the sea state sequence, which will result in different persistency property

5.3.3. A schematic overview

Figure 5.6 is a schematic drawing covering all level of influence described above.

A list of drawing illustrations can be found here:

- The operation consists of three operational phases, represented by $Ph\,1, Ph\,2\&Ph\,3$ and it lasts in total 12 hours ;

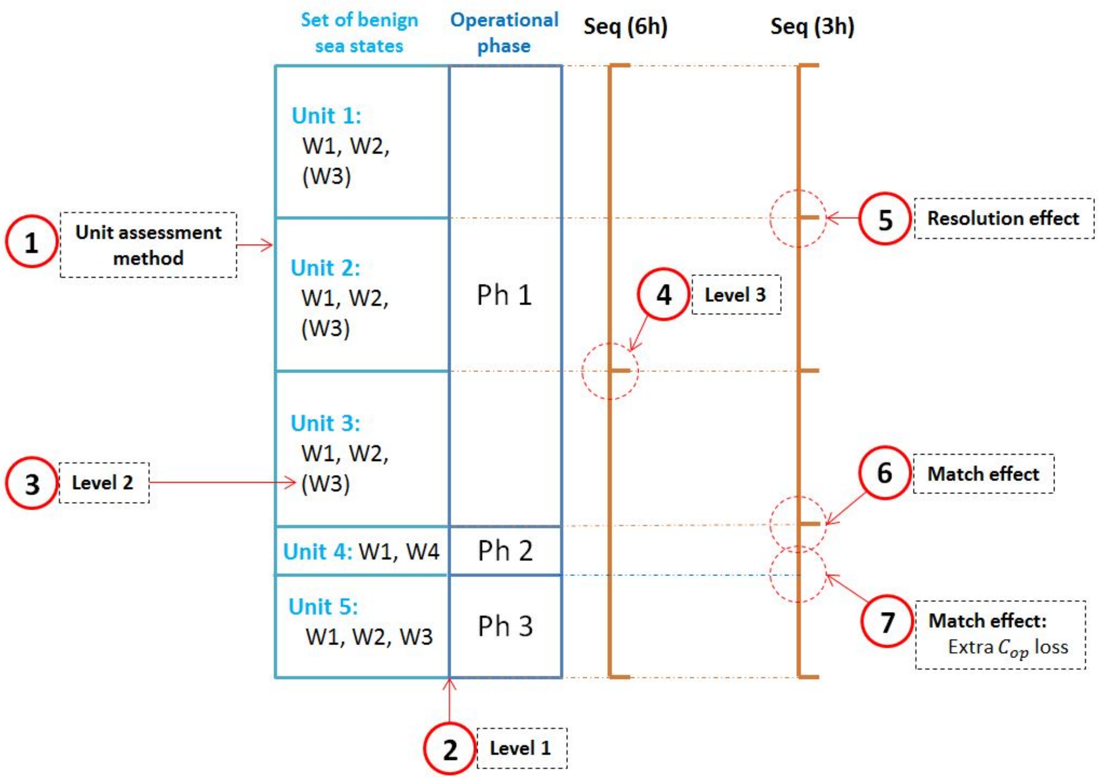


Figure 5.6.: A schematic overview of all influence

- $Ph\,1\&Ph\,3$ are with similar configuration but only difference in duration while $Ph\,2$ is totally different from the others;
- To show influence due to persistency data quality, two sea state sequences with different unit duration (6h or 3h) are considered here. Again, the persistency data are different only because the sampling intervals are different;
- For each operational phase, sea states, under which the operation can be operable, are listed. Those sea states are called the set of benign sea states as shown in the light blue box on the left side.

Figure 5.6 pin-points the following 7 comments. It also serves as a basic guide about how to understand the assessment output of persistency analysis and a schematic overview of this entire section.

1. **Section 5.2.1, Unit assessment method:** For each operational phase, the unit assessment method determines the set of benign sea states;
2. **Section 5.2.2, Level 1:** A sequence of operational phases with different sets of benign sea states enables users to assess systematically how critical each phase is;

3. **Section 5.2.3, Level 2:** $(W3)$ means $W3$ is a duration-sensitive sea state for phases configured as $Ph\,1\&Ph\,3$. $Ph\,1$ can not survive under $W3$ but $Ph\,3$ can only because $Ph\,1$ has longer duration. Level 2 adds modification to the set of benign sea states for each operational phase;

4. **Section 5.2.4, Level 3:** A benign sea state for $Ph\,1$ might shift to a severe sea state for either $Ph\,1$, $Ph\,2$ or $Ph\,3$, which will cause the whole operation not operable. C_{op} will thus decrease when adapting persistency analysis compared to scatter analysis because it takes into account such probability;

5. **Section 5.3.1, Resolution effect:** Adapting finer persistency data will result in more accurate operability assessment, in the form of C_{op} decreasing;

6. **Section 5.3.2, Match effect:** Adapting persistency data with proper sampling interval can avoid false loss in C_{op} and will lead to more accurate operability assessment, in the form of C_{op} increasing;

7. **Section 5.3.2, Match effect:** Even when adapting Seq(3h) (finer persistency data), there still exists false C_{op} loss because the circled sea state covers two operational phases, $Ph\,2\&Ph\,3$. Again, the purpose of this operability study is to obtain an assessment result of desired accuracy and efficiency level. Whether to use even finer persistency data is a choice to make.

5.4. Conclusion

Influence of persistency analysis is wrapped up nicely in Section 5.3.3.

Compared to scatter analysis, persistency analysis can produce better operability assessment result because:

1. Level 1: Multiple operational phases
   - Including multiple operational phases in the assessment
   - Introducing an operational phase sequence resembling the reality
2. Level 2: Phase duration
   - Longer phase duration $\Longrightarrow$ MPM increases $\Longrightarrow$ C_{op} decreases
   - Influence due to phase duration is well captured by substituting proper values for t and α in Equation 5.4
3. Level 3: Shift of sea states
   - Accounting shift of sea states will result in better operability assessment (C_{op} decreases).
   - Longer operation duration $\Longrightarrow$ more shifts of sea states $\Longrightarrow$ more likely $W_{benign} \rightarrow W_{wild}$ $\Longrightarrow$ C_{op} decreases

Influence due to quality of persistency data can be summarized as

- **Resolution effect**: smaller sampling interval (finer persistency data) $\Longrightarrow$ more accurate operability assessment (C_{op} tends to decrease)
- **Match effect**: proper choice of sampling interval $\Longrightarrow$ more accurate operability assessment (C_{op} increases)
- Sampling interval of persistency data changes together with duration of each sea state unit in the sea state sequence, which will result in different persistency property

6. Case study

6.1. Case setup

The selected case is a floating bulk transhipment operation during iron ore import. Involved vessels are: 1 capesize vessel + 1 floating crane (similar to Damen crane barge) + 1 bulk barge (similar to Damen STAN Pontoon B27). The operation takes place at an artificial near-shore location. Only wave condition at that artificial location is taken into account. Details of case setup can be found in the following sequence, among which some are listed in Appendix B.

- Operational phases & criteria
- FBTO system
- Environmental condition
- Important assumption

6.1.1. Operational phases & Criteria

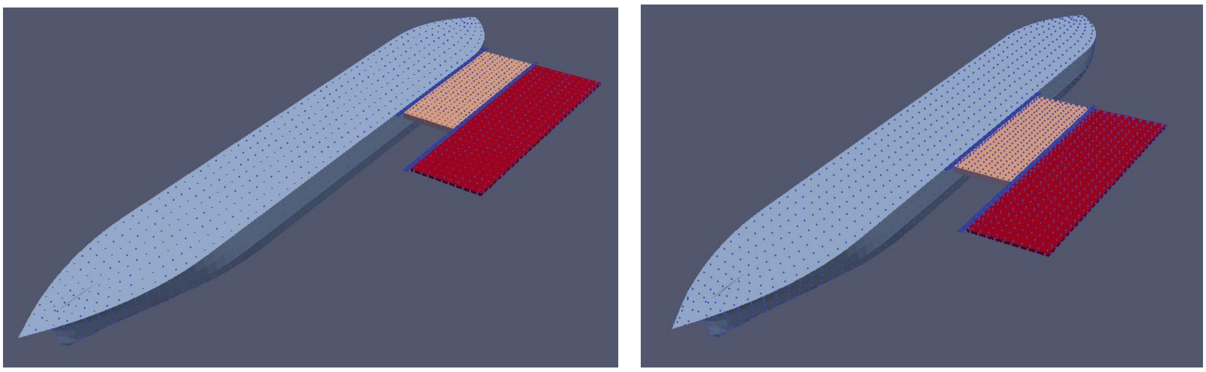
Table 3.1 shows a whole operation procedure of FBTO. As explained in Section 3.4, $Phase 6, 7\&8$ will take most part of total time and thus become the most interesting phases to look at. Table 6.1 describes all operational phases and criteria.

Phase No.	Operational phase		Criteria
1	Production phase 1	2.5 hours	$\phi \leqq 3°$
2	Hatch switching	0.5 hours	$Hs < 2m$
3	Production phase 2	6 or 9 hours	$\phi \leqq 3°$

Table 6.1.: Case study: operational phase & criteria

- Total duration is
  - 9 hours, for Case study 1 and Case study 3;
  - 12 hours, for Case study 2;
  - Both duration are typical values for lightening operation (e.g. [OVET]);
- Switching between hatches normally takes $10 \sim 15$ minutes. Here 0.5 hours is assumed because the floating crane is shifted a rather long distance (around 60 meters) from Hatch 1 to Hatch 3 (considering longitudinal strength of the capesize vessel);

- Criterion for Production phase 1 and 2 is selected to be $\phi \leqq 3°$ (reason see Section 3.5) and criterion for hatch switching is selected to be $Hs < 2m$, which is the average limitation of the tug.
- Figure 6.1 is a visualized model for Phase No. 1 and No. 3.



(a) Production phase 1 (b) Production phase 2

Figure 6.1.: Visual model for Phase No. 1 and No. 3

6.1.2. FBTO system

This FBTO system involves 1 capesize vessel, 1 floating crane and 1 bulk barge. Pictures of all those vessels can be found in Section 3.3 (only for demonstration purpose; not exactly the same vessels). Detail particulars of those vessels can be found in Appendix B.

The capesize is moored by anchor. The floating crane is moored next to it and the bulk barge is moored next to the floating crane by steel wires. Details about mooring system can be found in Appendix B.

6.1.3. Environmental condition

In this case study, only wave condition is taken into account while wind and current are left out. Wave condition, as project input, is collected in form of time series of sea state records. Example of such record can be found in Appendix B.

Several artificial time series of sea state record, similar to the record of locally-generated wave in Golf of Guinea (Ghana), are used in this case study. The time series has the following property:

1. Collected per 3 hours from 1st January 1992 till 31st December 2012
2. Highly uni-directional under 225 degree in global coordinating system

Later in Case study 2, a sensitivity study of persistency data quality will be done. This requires time series of different sampling intervals, which can be obtained (using weighted average method):

- Assuming mildly changing sea, as shown in Appendix A.7;
- Assuming true sea, as shown in Appendix A.7.

How to prepare persistency data from time series is explained in Appendix A.1.

6.1.4. Important assumption

1. Bin-size
   - Hs: per 1m (ceiling)
   - Tp: per 5s (round)
   - Direction: per 25 degree (round)
   - This assumption helps control amount of calculation.
2. Uni-directional wave
   - All sea states are assumed to be under 225 degree in global coordinating system.
   - This assumption is based on observation of time series property. More than 88% of sea states are under 225 degree.
3. Wave attack angle 270 degree
   - Waves described by all sea states will attack the FBTO system under 270 degree in vessel coordinating system as shown in Figure 6.2.

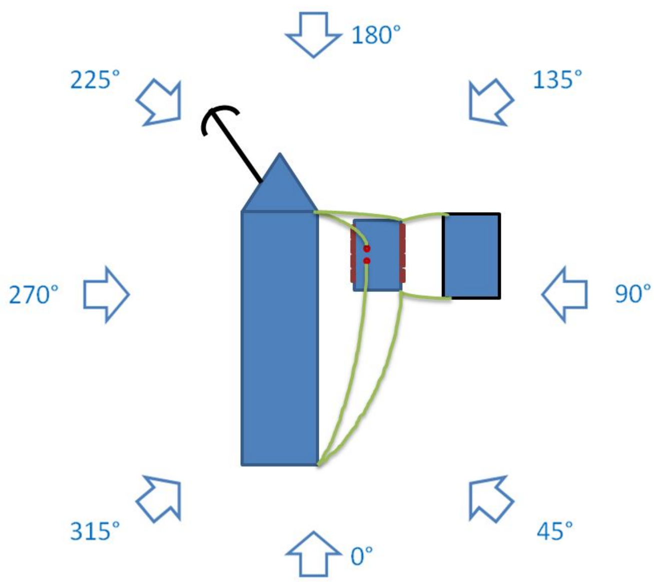


Figure 6.2.: Wave attach angle

   - Discussion about this assumption can be found below:

- Due to weathervane property of the mooring system, the FBTO system will reach its balance heading under combined loading of wind, current and wave.
- Wave will attack from a rather undesired angle (beam wave) with floating crane and bulk barge shielded by capesize vessel (common practice).
- This assumption makes up for neglecting wind & current and weathervane property of the mooring system in the operability assessment. It will lead to more conservative result compared to a full package of calculation including wind & current and weathervane.
- In reality, the balance heading can be approximated before performing simulation in each assessment unit, which makes this methodology extendable for including wind & current in the future.

4. $\phi \leqq 3°$
   - Only criterion regarding high frequency motion, roll of floating crane, is selected. No other criteria for phase No.1 and No. 3.
   - This assumption is based on feedback from interviewing operator companies.
5. Linear system
   - The whole FBTO system can be modeled as a linear system so that a frequency domain analysis can be adapted.
   - This assumption is valid because only high frequency motion (roll of floating crane) is important.

6.2. Case study 1: Persistency vs scatter

Persistency analysis is done as shown in Section 4.5.1, while scatter analysis is done as shown in Section 4.5.2. The time series is with sampling interval of 3 hours (hereby called time series (3h)).

Table 6.2 shows the occurrence probability. Figure 6.3a shows the shift probability, where Figure 6.3b describes numbering and property of unique sea states . Notice that grayscale indicates magnitude. From black to white, the probability is $0\% \rightarrow 100\%$. The sea states are described in vessel coordinating system.

The set of benign sea state is calculated for each operational phase and described in form of response survival table (Table 6.3).

Table 6.4 shows the operability calculated by scatter analysis and persistency analysis. Notice that the operability shown in each cell of persistency analysis table is the operability when the operation starts under this sea state.

Table 6.5 shows the workable probability of each operational phase calculated by persistency analysis. Workable probability here refers to the probability that this phase is operable given that all the preceding phases have been successfully performed.

Total occurrence = 100%

Tp (s)	0	5	10	15	20	25
Hs (m)						
0	0.03	0.00	0.00	0.00	0.00	0.00
1	0.00	0.01	1.27	44.70	3.51	0.01
2	0.00	0.00	1.75	32.62	11.23	0.02
3	0.00	0.00	0.30	1.07	2.14	0.03
4	0.00	0.00	0.00	1.22	0.07	0.01

Table 6.2.: Occurrence probability

Table 6.6 shows conditional operability calculated by scatter analysis and persistency analysis. Conditional operability refers to the operability if knowing which sea state to be encountered beforehand. If the cell is blank, it means conditional operability is equal to 0.

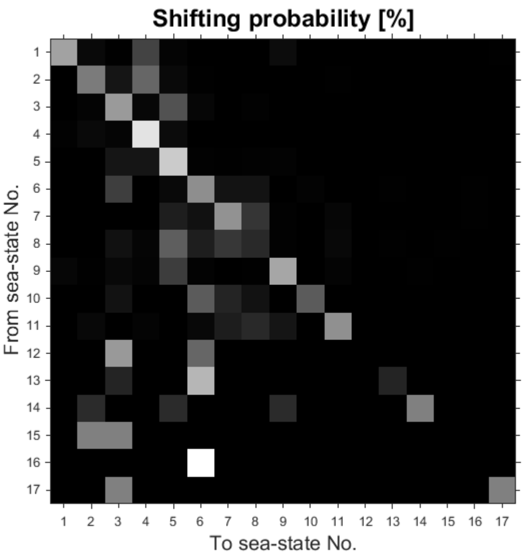
Discussion

1. Sea state with high occurrence probability tends to have a high shift probability to itself. Table 6.2 shows that the 3 sea state with highest occurrence probability are: $W\,(Hs = 1, Tp = 15) \sim 44.70\%$, $W\,(Hs = 2, Tp = 15) \sim 32.62\%$ and $W\,(Hs = 2, Tp = 20) \sim 11.23\%$, which correspond to unique sea state No. 4, No. 5 and No. 3 in Figure 6.3b. Figure 6.3a shows that they also have the highest shift probability to themselves among all sea states. The observation matches the logic;

2. Persistency analysis produces more accurate result (smaller operability) than scatter analysis. As can be seen in Table 6.4, the calculated total operability decreases by 17.32% from 60.78% (scatter analysis) to 43.46% (persistency analysis). Such decrement can be observed in every cell (each representing a sea state) of the table. This proves the statement as made in Section 5.2;

3. Level 1 influence, multiple operational phases, is proven. Table 6.5 shows that each operational phase is with a workable probability not equal to 100%, which indicates this FBTO can not be represented by the ONE most critical phase;

4. Level 2 influence, phase duration, is proven. Sea state, $W\,(Hs = 2, Tp = 20)$, is a duration sensitive sea state. In Table 6.3, the survival rate for the operation under sea state, $W\,(Hs = 2, Tp = 20)$, is 1 for Phase 1 while 0 for Phase 3, which indicates that $W\,(Hs = 2, Tp = 20)$ is a benign sea state for Phase 1 but a severe one for Phase 3. Phase 1 (production phase 1) and Phase 3 (production phase 3) have similar configuration. Thus, they have similar vessel response under the same sea state. The main difference is that the duration for Phase 1 is 2.5 hours while the one for Phase 3 is 6 hours. Such difference in duration leads to totally different survival rate under the same sea state;



(a) Shift probability

Unique sea state property (3h)

No.	Hs	Tp	Dir
1	1	10	270
2	1	20	270
3	2	20	270
4	1	15	270
5	2	15	270
6	3	20	270
7	4	15	270
8	3	15	270
9	2	10	270
10	4	20	270
11	3	10	270
12	2	25	270
13	3	25	270
14	0	0	270
15	1	25	270
16	4	25	270
17	1	5	270

(b) Unique sea states property

Figure 6.3.: Shift probability

5. Level 3 influence, shift of sea states, is proven. Table 6.3 shows that if the operation can be performed in both Phase 1 and Phase 2, then it must be able to survive in Phase 3 when no shift of sea states is accounted. This is because set of benign sea states of $Phase\,1 \cap Phase\,2 \in Phase\,3$. In this case, the workable probability for Phase 3 will be 100%. Table 6.5 doesn't show the expected result. The workable probability for Phase 3 is 93.20%. Such drop in workable probability is purely due to the existing probability that sea state might shift to a severe one for Phase 3.

   Another observation can be made if looking at Table 6.3 and Table 6.4. Table 6.3 shows that sea states $W\,(Hs = 0, Tp = 0)\,\&W\,(Hs = 1, Tp = 5 \sim 25)$ are benign sea states for all the three phases. Thus, if assuming no shift of sea states is accounted, operability under those sea states calculated by persistency analysis will be the same as those by scatter analysis. Table 6.4 presents that operability under $W\,(Hs = 0, Tp = 0)\,\&W\,(Hs = 1, Tp = 5 \sim 25)$ calculated by persistency analysis drops compared to scatter analysis. Such drop is due to taking into account the probability that the sea state might shift from those benign ones to severe ones for either of the 3 phases. By accounting such probability, operability gets smaller, thus more accurate operability assessment;

6. Clear difference is spotted between persistency analysis and scatter analysis when viewing conditional operability (Table 6.6). Scatter analysis indicates that if knowing sea

Persistency data (3h) - Response survival table - Phase 1

Tp (s)	0	5	10	15	20	25
Hs (m)						
0	1					
1		1	1	1	1	1
2			0	0	1	1
3			0	0	0	0
4				0	0	0

Persistency data (3h) - Response survival table - Phase 2

Tp (s)	0	5	10	15	20	25
Hs (m)						
0	1					
1		1	1	1	1	1
2			0	0	0	0
3			0	0	0	0
4				0	0	0

Persistency data (3h) -Response survival table - Phase 3

Tp (s)	0	5	10	15	20	25
Hs (m)						
0	1					
1		1	1	1	1	1
2			0	0	0	1
3			0	0	0	0
4				0	0	0

Table 6.3.: Response survival table

state, $W\,(Hs = 2, Tp = 20)$ (with an occurrence probability of 11.23%), is coming, then the operation can 100% be performed successfully. But when adapted persistency analysis, the probability that the operation can succeed is only 3.91%. Such remarkable difference proves persistency analysis's value in operability study of real engineering project. Similar observations can be made in all other cells of the table.

Scatter analysis (3h) - Total operability = 60.78%

Tp (s)	0	5	10	15	20	25
Hs (m)						
0	0.03	0.00	0.00	0.00	0.00	0.00
1	0.00	0.01	1.27	44.70	3.51	0.01
2	0.00	0.00	0.00	0.00	11.23	0.02
3	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00

Persistency analysis (3h) - Total operability = 43.46%

Tp (s)	0	5	10	15	20	25
Hs (m)						
0	0.01	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	1.11	39.10	2.79	0.00
2	0.00	0.00	0.00	0.00	0.44	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00

Table 6.4.: Operability: scatter vs persistency

Phase No.	Operational phase		Workable probability
1	Production phase 1	2.5 hours	60.78%
2	Hatch switching	0.5 hours	76.71%
3	Production phase 2	6 hours	93.20%

Table 6.5.: Workable probability of all operational phases

Scatter analysis (3h) - Conditional operability (%)

Tp (s)	0	5	10	15	20	25
Hs (m)						
0	100.00					
1		100.00	100.00	100.00	100.00	100.00
2					100.00	100.00
3						
4						

Persistency analysis (3h) - Conditional operability (%)

Tp (s)	0	5	10	15	20	25
Hs (m)						
0	48.00					
1			87.05	87.47	79.60	
2					3.91	
3						
4						

Table 6.6.: Conditional operability: scatter vs persistency

6.3. Case study 2: Persistency data quality

6.3.1. Mildly changing sea

Persistency analysis is done as shown in Section 4.5.1. Persistency data with different sampling interval (2h, 3h, 4h, 6h, 12h) are prepared assuming mildly changing sea, as described in Appendix A.7.

Table 6.7 shows the occurrence probability of each sea state. As can be understood, Figure 5.4 shows the way that time series of finer persistency data changes, when assuming mildly changing sea. Thus, the occurrence probability table for persistency data with only difference in sampling interval will be the same. When sampling interval gets smaller, probability that a sea state shifts to itself will be bigger. Figures of shift probability under different sampling interval assuming mildly changing sea can be found in Appendix B.3.

Persistency data (2h,3h,4h,6h&12h) - Total occurrence = 100%

Tp (s)	0	5	10	15	20	25
Hs (m)						
0	0.03	0.00	0.00	0.00	0.00	0.00
1	0.00	0.01	1.34	44.15	2.65	0.01
2	0.00	0.00	1.90	34.77	9.95	0.01
3	0.00	0.00	0.33	2.52	2.12	0.01
4	0.00	0.00	0.00	0.10	0.08	0.01

Table 6.7.: Occurrence probability

Table 6.3 shows the response survival tables.

Figure 6.4 shows how the operational phase sequence matches sea state sequence of different persistency data (sampling interval 2h, 3h, 4h, 6h & 12h). Symbols in each piece of sea state sequence mean the set of benign sea states for this particular piece. Those sea states are labeled in Table 6.8.

Sea state	Label
$W\,(Hs=0,Tp=0)\,\&W\,(Hs=1,Tp=5\sim25)$	$W1$
$W\,(Hs=2,Tp=25)$	$W2$
$W\,(Hs=2,Tp=20)$	$W3$

Table 6.8.: Labeling of benign sea states

Figure 6.5 shows the total operability of persistency data with sampling interval of 2h, 3h, 4h, 6h & 12h.

Table 6.9 shows the workable probability till each operational phase under different persistency data quality.

Table 6.10 shows the trend of decrease in total C_{op}.

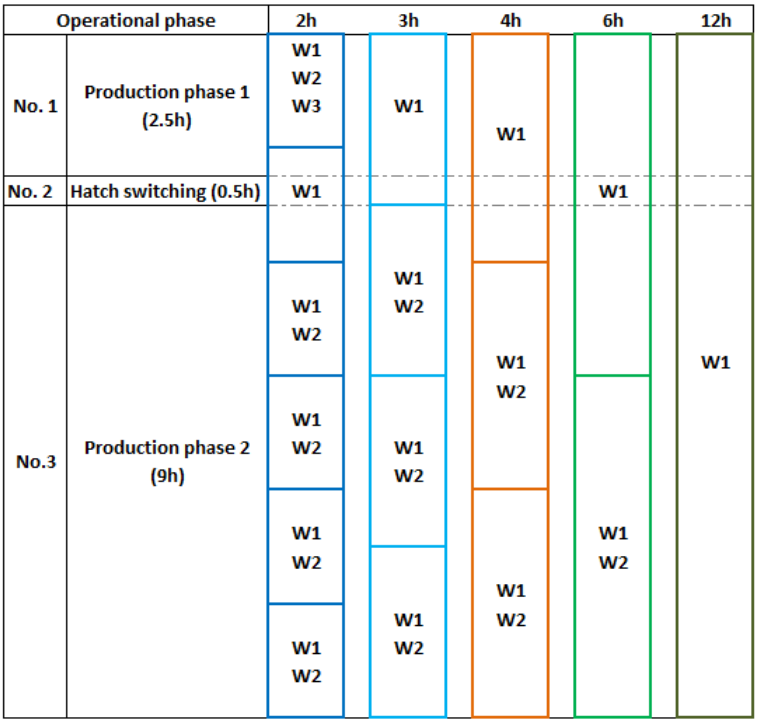


Figure 6.4.: Operational phase sequence with sea state sequence

Workable probability		12h	6h	4h	3h	2h
Phase No. 1	$\sim$ 2.5 hours	58.15%	58.15%	58.15%	58.15%	56.86%
Phase No. 1 & 2	$\sim$ 3 hours	48.18%	48.18%	48.18%	48.18%	47.58%
Phase No. 1, 2 &3	$\sim$12 hours	48.18%	46.13%	45.49%	45.17%	44.93%

Table 6.9.: Workable probability per phase under sampling interval 2h, 3h, 4h, 6h & 12h

Discussion

1. Figure 6.5 shows a clear trend of decrease in C_{op}, as finer persistency data are adapted;
2. Due to match effect, there is false loss in C_{op} under persistency data of every sampling interval. In Figure 6.4, the intersection of set of benign sea states between Phase No.1 and No. 2, as well as between Phase No. 2 and No. 3, is represented by $W1$;
3. Table 6.9 shows that workable probability of Phase No. 1 and Phase No. 1 & 2 stays the same under 12h, 6h, 4h, and 3h. This is logical because:

$$\begin{cases} Op\,(phase\,1) & = P_{occ}\,(W1, W2\&W3) \\ Op\,(phase\,1\&phase\,2) & = P_{occ}\,(W1) \end{cases}$$

   $P_{occ}\,(W1, W2\&W3)$ and $P_{occ}\,(W1)$ stays the same under all sampling interval;

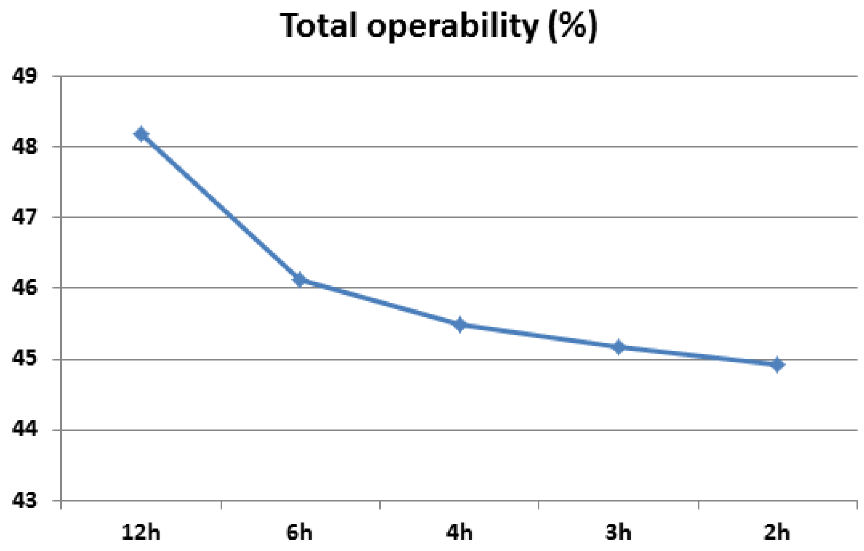


Figure 6.5.: Total operability of persistency data with sampling interval of 2h, 3h, 4h, 6h & 12h

	12h	6h	4h	3h	2h
C_{op}	48.18%	46.13%	45.49%	45.17%	44.93%
Decrease compared to 12h	0%	2.05%	2.69%	3.01%	3.25%
Proportional deviation from 2h[a]	7.23%	2.67%	1.25%	0.53%	0%

[a] As an example, proportional deviation of 12h from 2h = $\frac{48.18\%-44.93\%}{44.93\%} = 7.23\%$.

Table 6.10.: Decrease of C_{op} when adapting smaller sampling interval

4. Table 6.9 shows that workable probability of Phase No. 1 and Phase No. 1 & 2 under 2h is smaller than all the others because a shift of sea state takes place within Phase No.1. Resolution effect (C_{op} decrease) balances out match effect (C_{op} increase), which leads to decrease in C_{op}. This is explained in Section 5.3.2, Food for thought: resolution effect + match effect;

5. The trend of decrease in C_{op}, as mentioned above, is the balancing result of both resolution effect and match effect. Match effect is less observed here because:

   - Sea state sequence under every sampling interval has a sea state unit covering more than 1 operational phases, as shown in Figure 6.4;
   - Difference in response survival table between Phase No. 1, No. 2 and No. 3 is small, which indicates there is no significant difference in set of benign sea states for each operational phase, as shown in Table 6.3. The difference between Phase No. 1 and No.2 is $W2$ ($P_{occ}(W2) = 0.01\%$, as shown in Table 5.4) and $W3$ ($P_{occ}(W3) = 9.95\%$) , while the difference between Phase No. 2 and No.3 is

$W2$. Thus, increase in C_{op} due to match effect is not significant in this case;

6. Adapting finer persistency data will lead to more accurate assessment of C_{op} (smaller C_{op}). In order to raise the quality of the assessment, it is recommended to adapt persistency data with smaller sampling interval, when there exists no profound false loss in C_{op} due to match effect. Match effect is important when 2 or more phases (which are covered by one sea state unit) have quite different sets of benign sea states as explained in Section 5.3.2. In that case, there will be a rather significant false loss in C_{op}. To cope with that, persistency data with proper sampling interval needs to be adapted, which avoids covering those phases by one sea state unit. In reality, it is less likely to have several continuous operational phases with profound difference in set of benign sea states. Thus, resolution effect tends to play a more important role than match effect.

7. In Table 6.10, by adapting finer persistency data, decrease of total C_{op} slows down quickly. Maximum deviation in percentage is 7.23% (compared to 2h). Considering error band of statistical method (e.g. MPM) used in this operability assessment methodology, it requires attention when trying to obtain more accurate operability assessment by adapting finer persistency data. Notice that, there exists possibility that operability drops more dramatically when adapting finer persistency data (e.g. as shown in Section 5.2.4). Different time series of sea state record will lead to different extent of operability drop.

6.3.2. True sea

Persistency analysis is done as shown in Section 4.5.1. Persistency data with different sampling interval (2h, 3h, 4h, 6h, 12h) are prepared assuming true sea, as described in Appendix A.7. When adapting smaller sampling interval, probability that dramatic change might take place within larger interval is taken into account. Persistency property (both occurrence probability and shift probability) will change together with different sampling interval. Occurrence property under different sampling interval can be found in Appendix B.3.

The response survival table is the same as shown in Table 6.3. Using the same labeling as in Table 6.8, Table 6.11 shows the trend of occurrence probability of $W1$.

	12h	6h	4h	3h	2h
$P_{occ}(W1)$	41.01%	46.26%	48.18%	49.53%	50.73%

Table 6.11.: Trend of $P_{occ}(W1)$

Figure 6.6 shows the total operability of persistency data with sampling interval of 2h, 3h, 4h, 6h & 12h.

Table 6.12 shows the workable probability till each operational phase under different persistency data quality.

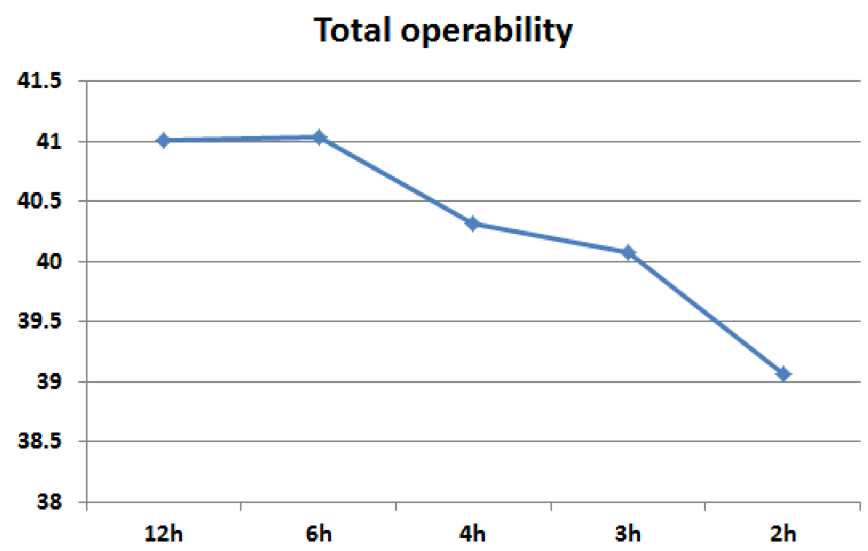


Figure 6.6.: Total operability of persistency data with sampling interval of 2h, 3h, 4h, 6h & 12h

Workable probability		12h	6h	4h	3h	2h
Phase No. 1	$\sim$ 2.5 hours	49.14%	55.94%	58.15%	60.78%	56.17%
Phase No. 1 & 2	$\sim$ 3 hours	41.01%	46.26%	48.18%	49.53%	48.53%
Phase No. 1, 2 &3	$\sim$12 hours	41.01%	41.04%	40.32%	40.08%	39.64%

Table 6.12.: Workable probability per phase under sampling interval 2h, 3h, 4h, 6h & 12h

Discussion

1. Adapting finer persistency data (assuming mildly changing sea), persistency property will change in shift probability, as described in Section 5.3.1. Adapting finer persistency data (assuming true sea), persistency property will change in both occurrence probability and shift probability;

2. Table 6.12 shows that workable probability of Phase No. 1 and Phase No. 1 & 2 doesn't stay the same under 12h, 6h, 4h, and 3h as in mildly changing sea. This is because occurrence of dramatically changed sea states leads to different persistency property under different sampling interval. In fact, $P_{occ}(W1)$ tends to increase in this case when sampling interval is smaller. This is shown in Table 6.11. The reason is because, in this case study, occurrence of benign sea states is bigger than occurrence of severe sea states. When sampling interval gets larger, a group of benign sea states, together with a few very severe ones, are very likely to be labeled as a severe sea state in the time series. Thus, when sampling interval gets smaller, the occurrence probability of benign sea states become bigger. As a result, workable probability of Phase No. 1 and Phase No. 1 & 2 becomes bigger when sampling interval gets smaller

from 12h to 3h;

3. Figure 6.6 shows similar trend as stated in mildly changing sea. Difference in trend is due to noteworthy change in persistency property when adapting finer persistency data assuming true sea. For example, from 12h to 6h, occurrence probability of $W1$ (referring to$W\left(Hs=0,Tp=0\right)\&W\left(Hs=1,Tp=5\sim 25\right)$ as shown in Table 6.8) increases from 41.01% to 46.26%. Table 6.13 shows all the effects contributing to the trend of C_{op} when sampling interval gets smaller (assuming true sea). Notice that when assuming mildly changing sea, there is only resolution effect (1), but no resolution effect (2);

Influence	Comment
Resolution effect (1)	Assuming mildly changing sea
Resolution effect (2)	Persistency property changed assuming true sea
Match effect	False loss in C_{op} due to mismatch between SSS[a] and OPS[b]

[a]SSS: Sea State Sequence
[b]OPS: Operational Phase Sequence

Table 6.13.: Various influence on C_{op} trend

4. Table 6.14 presents contribution of each component to the trend of C_{op}.

Sampling interval	C_{op}	Resolution effect (1)	Resolution effect (2)	Match effect	In total
$12h \rightarrow 6h$	$41.01\% \rightarrow 41.04\%$	$C_{op} \downarrow$	$C_{op} \uparrow$	$C_{op} \uparrow$	$C_{op} \uparrow$
$6h \rightarrow 4h$	$41.04\% \rightarrow 40.32\%$	$C_{op} \downarrow$	$C_{op} \uparrow$	$C_{op} \uparrow$	$C_{op} \downarrow$
$4h \rightarrow 3h$	$40.32\% \rightarrow 40.08\%$	$C_{op} \downarrow$	$C_{op} \uparrow$	$C_{op} \uparrow$	$C_{op} \downarrow$
$3h \rightarrow 2h$	$40.08\% \rightarrow 39.64\%$	$C_{op} \downarrow$	$C_{op} \uparrow$	$C_{op} \uparrow$	$C_{op} \downarrow$

Table 6.14.: Trend of C_{op}

6.4. Case study 3: Duration mechanism

Persistency analysis is done under basic mechanism (persistency + veto + FD/TD) and duration mechanism (persistency + probabilistic + FD/TD) as shown in Section 4.5.1 and Section 4.5.3.

As a recap, for persistency + probabilistic + FD/TD analysis under duration mechanism, the two interesting outputs are:

- Probability that the operation can be finished within maximum allowable duration
- Expected duration of the operation (including suspension) and of each phase

Table 6.1 describes all operational phases and criteria. Notice that the duration in the table means required duration, which indicates real duration might be longer.

Table 6.15 shows that C_{op} calculated under basic mechanism with different risk parameter, α, together with C_{op} calculated under duration mechanism with maximum allowable duration equal to 9 hours . Notice that there is slight difference in definition between C_{op} under duration mechanism and C_{op} under basic mechanism. C_{op} under duration mechanism is the probability that the operation can be completed within maximum allowable duration, while C_{op} under basic mechanism refers to the probability that the operation can be successfully performed (without any interruption) within a (fixed) required duration.

Mechanism	Total C_{op}
Basic $(\alpha = 1)$	0.4514
Basic $(\alpha = 0.5)$	0.4514
Basic $(\alpha = 0.3)$	0.4514
Basic $(\alpha = 0.2)$	0.4324
Basic $(\alpha = 0.1)$	0.4324
Basic $(\alpha = 0.01)$	0.4323
Duration $(MAD = 9h)$	0.4346

Table 6.15.: C_{op} under basic mechanism with different α and C_{op} under duration mechanism

Table 6.16 makes a detailed comparison of operability between basic mechanism $(\alpha = 0.1)$ and duration mechanism $(MAD = 9h)$.

Basic mechanism + veto (α=0.1) - Sum = 43.24%

Tp (s)	0	5	10	15	20	25
Hs (m)						
0	0.01	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	1.11	39.29	2.82	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00

Duration mechanism + probabilistic (MAD=9h) - Sum = 43.36%

Tp (s)	0	5	10	15	20	25
Hs (m)						
0	0.01	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	1.11	39.10	2.79	0.00
2	0.00	0.00	0.00	0.00	0.44	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00

Table 6.16.: Operability table calculated under basic mechanism $(\alpha = 0.1)$ and duration mechanism $(MAD = 9h)$

Table 6.17 calculates results under duration mechanism of different maximum allowable duration, 9h and 12h.

Duration mechanism	C_{op} (%)	Phase No. 1 (h)	Phase No. 2 (h)	Phase No. 3 (h)	Total duration (h)
$MAD = 9h$	43.46	2.500	0.500	6.000	9.00
$MAD = 12h$	100.00	2.516	0.501	6.041	9.058

Table 6.17.: Results under duration mechanism with MAD of 9h, 12h and 15h

Table 6.18 shows the expected duration of operation starting from each unique sea state under duration mechanism $(MAD = 12h)$.

Duration mechanism (MAD=12h) - Expected duration=9.0578 h						
Tp (s)	0	5	10	15	20	25
Hs (m)						
0	9.00					
1		9.00	9.01	9.00	9.01	9.01
2			9.17	9.04	9.02	9.09
3			10.49	9.62	9.34	9.20
4				10.57	9.94	9.41

Table 6.18.: Expected duration under duration mechanism $(MAD = 12h)$

Discussion: duration mechanism vs basic mechanism

Basic mechanism calculates the probability that an operation can be successfully performed (without any interruption) within a fixed duration. Duration mechanism calculates the probability that an operation can be completely finished within the maximum allowable duration. Thus, if maximum allowable duration is equal to 9 hours, both are calculating the same thing and similar results can be expected. Table 6.15 and Table 6.16 prove that results under two different mechanisms match each other.

Table 6.15 shows the result of a sensitivity study about risk parameter, α. Difference in α won't result in too much difference in C_{op} . Difference in α will lead to change in C_{op} because it will influence MPM and thus result in change in set of benign sea states for some operational phases. Once a sea state, which used to be considered benign for an operational phase, is regarded as severe now, a part of C_{op} is lost. That's also the reason why C_{op} won't change continuously with α (as shown in the very right column in Table 6.15), because such loss won't occur if difference in α isn't big enough to lead to a real difference in set of benign sea states. Such influence is small because only sea states with MPM very close to criteria will be affected. The occurrence probability of those sea states is small in this case study. That's why difference in α won't result in too much difference in C_{op}.

Discussion: what duration mechanism can produce

As described above, besides $P\left(t \leq MAD\right)$, duration mechanism can also calculate expected duration of the operation and of each phase. As shown in Table 6.17, operation under all possible sea state sequences can be finished within 12 hours $\left(P\left(t \leq MAD\right) = 100\%\right)$.

Duration mechanism allows suspension and captures it in the expected duration. Table 6.18 presents the expected duration of operation starting from each unique sea state. Larger Hs with smaller Tp tends to result in longer expected duration, which means longer suspension is required. Based on table like this, floating bulk transhipment operator companies can understand more about the operation limits and have a clear reference about when to start the operation.

7. Conclusion and recommendation

This thesis addresses a methodology originally designed to assess the operability of FBTO, but can be extended for other offshore operations. Inspired by previous practice of adapting persistency analysis, an in-depth study is performed to understand influence of persistency analysis. In addition, this thesis proposed an operability assessment scheme with systematically-categorized choices (mechanisms and switches) which can be used dependently on project input. It makes sure the most relevant techniques are used in the operability assessment.

Serving the thesis objective and supported by the results of case study, the following can be concluded for this thesis report.

Conclusion

1. A benchmark study about FBTO has been done in aspects such as type of operation, type of transhipping vessel, mooring configuration, equipment on-board, worldwide existence, operational procedure and operation criteria;

2. The focus of this report is adapting the proposed operability assessment methodology to FBTO, but the methodology shows its versatility in assessing operability of an arbitrary offshore operation, if the following are used properly:

    - Operability assessment table
    - Operability assessment mechanism
    - Switch

3. The following techniques used in operability study are systematically categorized as mechanism or switch in the operability assessment scheme to be used dependently on project input:

    - Operability assessment mechanism
        - Basic mechanism calculates probability that an operation survives a fixed duration
        - Duration mechanism produces expected operation duration including suspension time
    - Switch
        - Persistency analysis versus scatter analysis
        - Veto analysis versus probabilistic analysis

- Frequency domain simulation versus time domain simulation

4. Compared to scatter analysis, persistency analysis can produce better operability assessment result because of the following effects:
   - Level 1: Multiple operational phases
   - Level 2: Phase duration
   - Level 3: Shift of sea states
5. Influence due to quality of persistency data can be summarized as:
   - Resolution effect: smaller sampling interval (finer persistency data) $\Longrightarrow$ more accurate operability assessment (C_{op} decreases)
   - Match effect: proper choice of sampling interval $\Longrightarrow$ more accurate operability assessment (C_{op} increases)
6. For operation allowing suspension, duration mechanism is able to produce output such as expected operation duration including suspension time, which is a beneficial index to look at when designing the operation.

Recommendation

- To obtain more reliable persistency property, persistency data needs to be prepared in a more dedicated way taking into account memory of weather completely;
- Comparison between frequency domain analysis and time domain analysis is not the focus of this report. Implementation of this methodology based on time domain simulation needs to be done and researched in the future;
- To adapt this methodology in general engineering practice, environmental conditions such as wind and current need to be incorporated. They are left aside in this report but they can be dealt with in a straight forward manner by introducing fast heading analysis before each assessment unit.

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A. Food for thought

A.1. Preparing persistency data (Section 4.2)

Let's assume a time series of sea state record, with only 3 sea states $W1, W2\&W3$, as shown in the "Time series" column of Table A.1.

No.	Time series		$W1$ occurrence	Shift to $W1$	Shift to $W2$	Shift to $W3$
1	$00:00$	$W1$	1			
2	$03:00$	$W2$			1	
3	$06:00$	$W3$				
4	$09:00$	$W1$	1			
5	$12:00$	$W1$	1	1		
6	$15:00$	$W1$	1	1		
7	$18:00$	$W3$				1
8	$21:00$	$W1$	1			
9	$24:00$	$W2$			1	
Sum			5	2	2	1

Table A.1.: Example: preparation of persistency data

For example, if we want to know the persistency property of $W1$. We can count the occurrence of $W1$ and then $P_{start} = \frac{Occurrence(W1)}{Total\ anount\ of\ sea\ states} = \frac{5}{9}$. We can then count how many times Wi occur after $W1$, as shown in Table A.1. Shift probability can thus be calculated: $P_{W1 \to Wi} = \frac{Occurrence(Wi|W1)}{Occurrence(W1)}$. The result can be found in Table A.2.

	To $W1$	To $W2$	To $W3$
$W1$	$\frac{2}{5}$	$\frac{2}{5}$	$\frac{1}{5}$

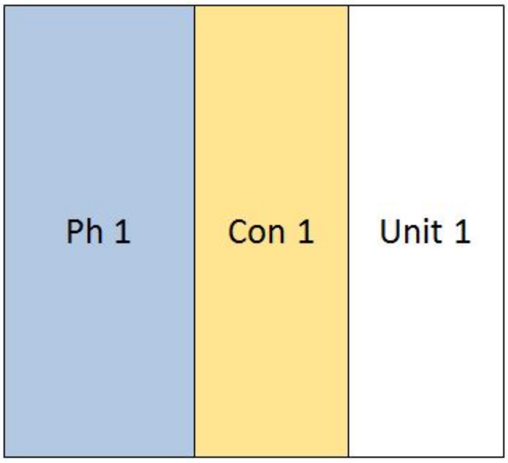
Table A.2.: Shift probability of $W1$

We can do the same things to all other sea states.

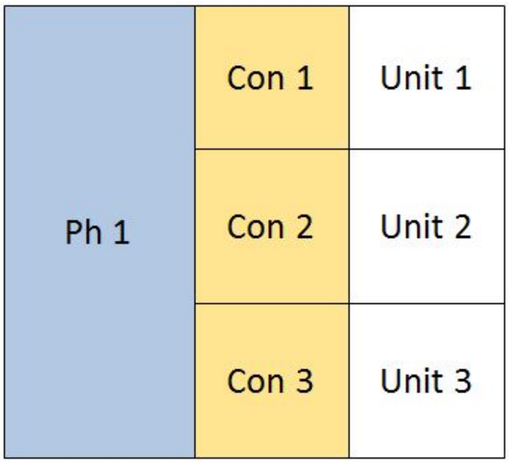
The proposed way of preparing persistency data takes into account memory of sea states. By doing so, we are considering occurrence of the next sea state as a dependent incident of the first one. But such consideration of dependency is not complete because we neglect that sea state No. 3 might still have memory of sea state No. 1. Thus, treating occurrence of sea state No. 1 and sea state No. 3 as totally independent incidents is a simplification of the memory feature of the time series. Better way to prepare persistency data needs to be researched in the future.

A.2. Persistency + probabilistic under basic mechanism (Section 4.5.4)

As a recap, using probabilistic method, we can represent vessel response of each operational phase with a Rayleigh distribution. Knowing the criteria of the phase, we can calculate the probability that the phase is operable under each sea state, which is defined as survival probability, Q_{sur}.



(a)



(b)

Figure A.1.: Food for thought: persistency + probabilistic under basic mechanism

Now, let's think of example shown in Figure A.1. There is an 1-phase operation represented by $Ph\,1$. If assuming sea state $W1$ (with $w_{dir}^1, H_s^1, T_p^1\&\gamma^1$) for $Con\,1$(duration 9h) as in FigureA.1a and the same sea state $W1$ (with $w_{dir}^1, H_s^1, T_p^1\&\gamma^1$) for all $Con1 \sim Con3$(duration 3h each) as in FigureA.1b, it is logical that the Q_{sur} calculated for $Ph\,1$ should be the same for both figures because every input is actually the same.

The survival probability can be calculated by the equation.

$$P\,(x \leq Cr) = 1 - e^{-\frac{Cr^2}{2m_0}} \tag{A.1}$$

Where Cr is the criterion and $m_0 = \int_0^{\inf} S_m\,(\omega)\,d\omega$. $S_m\,(\omega)$ will stay the same if sea state and RAO don't change. So survival probability, $P\,(x \leq Cr)$, will stay the same for the same phase $(Ph\,1)$ under same sea state $W1$, no matter duration.

Let's assume $P\,(x \leq Cr) = 90\%$ for $Ph\,1$ under $W1$. We can calculate Q_{sur} for the case as shown in FigureA.1a:

$$Q_{sur}^a = P\,(x \leq Cr) = 90\%$$

We can also calculate Q_{sur} for the case as shown in Figure A.1b:

$$Q_{sur}^b = Q_1 \cdot Q_2 \cdot Q_3 = 90\% \times 90\% \times 90\% = 72.9\%$$

The result, $Q_{sur}^{a} \neq Q_{sur}^{b}$ is against common sense. The above calculation procedure is apparently wrong because what Equation A.1 calculates is not the probability that this operational phase succeeds within a fixed duration, but the percentage of downtime for an operation under a certain sea state. In other words, if $P\,(x \leq Cr) \neq 100\%$, then the probability that this operational phase succeeds within the fixed duration will be 0, not 90%.

Thus, if the fixed duration is 9 hours and $P\,(x \leq Cr) = 90\%$, then the real duration of this operation will be $\frac{9}{90\%} = 10\, hours$. Such extension of the operation duration indicates that basic mechanism, which assumes fixed duration for each operational phase, doesn't fit switch choice of "persistency + probabilistic". Such switch choice works better under duration mechanism where suspension time (extension of operation duration) is allowed.

A.3. Persistency + veto under duration mechanism (Section 4.5.4)

The procedure of assessing operability using the choice below basically go through the same steps as in Section 4.5.3.

- Duration mechanism
- Persistency analysis (Switch 1) and veto analysis (Switch 2)
- Either FD or TD (Switch 3)

The only difference is at Step 3 when assessing expected duration of each operational phase. Assume a 2-phase operation represented by $Ph\,1$ & $Ph\,2$ and a sea state sequence to be encountered represented by $W1 \rightarrow W2 \rightarrow W3$. The calculation using veto analysis goes through the steps below:

1. Calculate MPM of the current operational phase, $Ph\,1$, under sea state, $W1$;
2. Compare the MPM to the respective criteria;
3. If $MPM > Cr$, $Ph\,1$ needs to be suspended for the entire time window of $W1$;
4. Calculate MPM of $Ph\,1$ under $W2$;
5. If $MPM \leq Cr$, $Ph\,1$ can work under $W2$. The remaining operation duration for $Ph\,1$ $= duration_{Ph\,1} - duration_{W2}$;
6. If $Ph\,1$ is completely finished, start from Step 1 again for $Ph\,2$.

As can be observed, the above method is too conservative because during the entire time window of $W1$, which is under suspension as stated above, there will probably be pieces of time window that $Ph\,1$ can operate. Such pieces of time window can not be capture by veto analysis. Thus, methodology with the choice for mechanism and switches as made here will produce very conservative result.

A.4. Unit assessment method (Section 5.2.1)

An example is given here about judging how critical each assessment unit is. Think of the following as shown in Figure A.2:

- One sea state $Con\,1$ lasts for 3 operational phases $Ph\,1 \sim Ph\,3$
- One operational phase $Ph\,1$ experiences 3 sea states $Con\,1 \sim Con\,3$ in a row

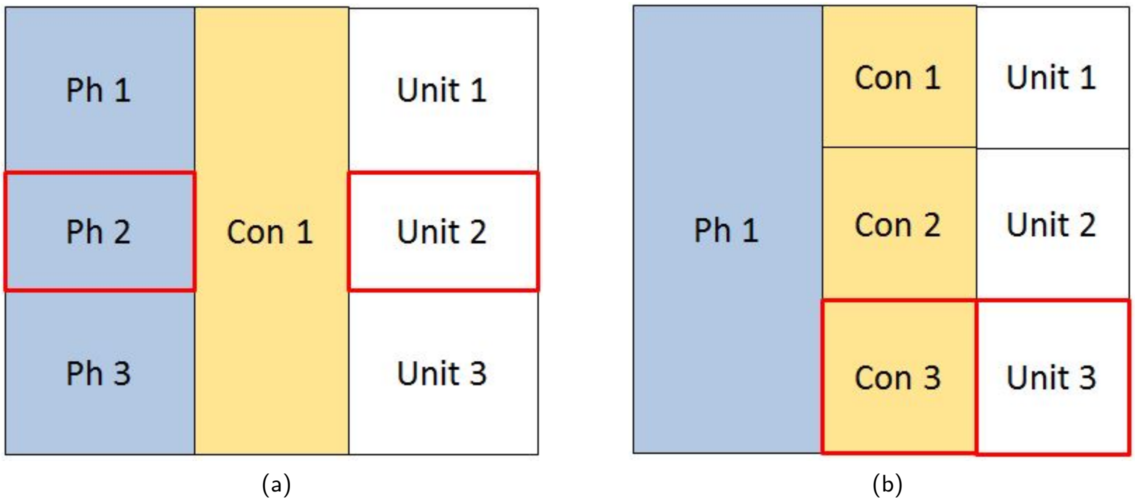


Figure A.2.: Food for thought: Unit assessment method

For the first case as in Figure A.2a, how critical each assessment unit is can be judged by considering:

- Configuration of each phase

  Comment: for example, if the vessel is more shielded in $Ph\,1$ than $Ph\,2$, then $Ph\,2$ is more critical given that under the same sea state $Con\,1$. This aspect has considerable influence on judging how critical an assessment unit is.

- Criteria of each phase

  Comment: for example, assuming $Ph\,1$ and $Ph\,2$ have the same configuration, if Cr_{resp} for $Ph\,1$ is larger than $Ph\,2$, then $Ph\,2$ is more critical given that under the same sea state $Con\,1$. This aspect has significant influence on judging how critical an assessment unit is.

- Duration of each phase

  Comment: if duration of one phase is significantly longer than the others, then it would be more critical than others given that all the other inputs are the same. This aspect has limited influence on judging how critical an assessment unit is.

These aspects are also summarized in Table 5.1. As shown in Figure A.2a, if $Ph\,2$ is with the most critical combination of the above aspects, then respectively, $Unit\,2$ is the most critical one.

For the second case as in Figure A.2b, how critical each assessment unit is can be judged by considering:

- Wave spectrum characteristics $H_s, T_p \& \gamma$

  Comment: for example, if the wave described by these characteristics is severer in $Con\,3$ than in the others, then $Con\,3$ is the most critical sea state given that under the same operational phase $Ph\,1$. Characteristic like H_s is more explicit to judge a sea state, while $T_p \& \gamma$ are more implicit.

- Wave direction w_{dir}

  Comment: for example, if wave attacks in a more unfavored angle in $Con\,3$ than in $Con\,1$, then $Con\,3$ is more critical, comparatively speaking.

These aspects are also summarized in Table 5.1. As shown in Figure A.2b, if $Con\,3$ is with the most critical combination of the above aspects, then respectively, $Unit\,3$ is the most critical one.

In a real operability assessment, judging how critical an assessment unit is will be more difficult since all the above aspects function at the same time.

A.5. Accounting phase duration in MPM (Section 5.2.3)

Food for thought 1

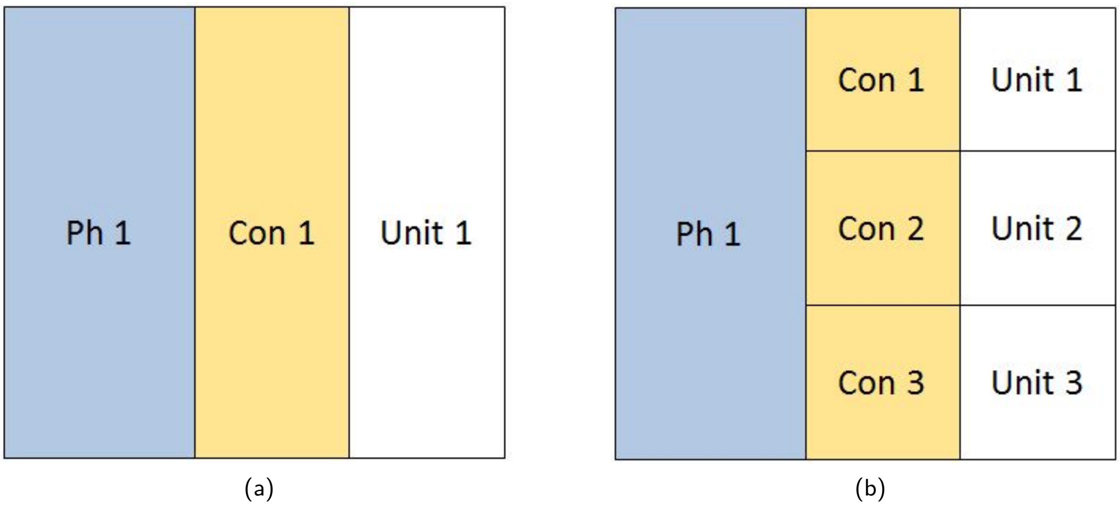


Figure A.3.: Level 2 food for thought 1

Let's think of example shown in Figure A.3. There is an 1-phase operation represented by $Ph\,1$. If assuming sea state $W1$ (with $w^1_{dir}, H^1_s, T^1_p \& \gamma^1$) for $Con\,1$(duration 9h) as in FigureA.3a and the same sea state $W1$ (with $w^1_{dir}, H^1_s, T^1_p \& \gamma^1$) for all $Con1 \sim Con3$(duration 3h each) as in FigureA.3b, it is obvious that the Q_{sur} calculated for $Ph\,1$ in both figures should be the same. But if substituting t into Equation 5.4, the calculated MPMs will be different. Here, m_0 stays the same no matter duration. Thus, the difference will be only due to $\sqrt{\ln\left(\frac{t}{\alpha \times T_Z}\right)}$. For those with MPM very close to criteria, the Q_{sur} calculated might be totally different for two cases. This is against common sense.

The above doubt is logical but ignored usage of risk parameter, α. If sea state $W1$ will be encountered N times during the whole operation, the risk parameter should also be divided by N, thus is equal to $\frac{\alpha}{N}$ (see e.g. [Ochi [1981]]). For a typical offshore operation, it is appropriate to assume risk parameter, $\alpha = 1$, if the specific sea state will be experienced once during the operation. For the cases shown in Figure A.3a and FigureA.3b, we have:

$$\begin{cases} t_a &= 9h \\ \alpha_a &= 1 \end{cases} \begin{cases} t_b &= 3h \\ \alpha_b &= \frac{1}{3} \end{cases} \tag{A.2}$$

$\alpha_b = \frac{1}{3}$ is simply because $W1$ is encountered 3 times during the whole operation. Substitute Equation A.2 into Equation 5.4, we can thus conclude $MPM^a_{unit\,1} = MPM^b_{unit\,1,2\&3}$. This leads to the result that the Q_{sur} calculated for both cases will be the same.

Food for thought 2

The following example, as shown in Figure A.4, will present more insights about how phase duration is incorporated. FigureA.4 shows an 1-phase operation under two possible sea state sequences and we assume that's the only difference between Figure A.4a and Figure A.4b. The P_{occ} for two cases might probably be different since shift probability is different. Such influence due to shift of sea states will be captured in Level 3. Here, we only think about Q_{sur} under the two cases. The calculation is presented in Table A.3.

	$MPM_{unit\,1}$	$MPM_{unit\,2}$	$MPM_{unit\,3}$	$Q^{total}_{sur} = Q_1 \times Q_2 \times Q_3$
Figure A.4a	$t^a_1 = 3h$	$t^a_2 = 3h$	$t^a_3 = 3h$	$Q^a_1 = Q^b_1$
	$\alpha^a_1 = \frac{1}{2}$	$\alpha^a_2 = \frac{1}{2}$	$\alpha^a_3 = 1$	$Q^a_2 = Q^b_3$
Figure A.4b	$t^a_1 = 3h$	$t^a_2 = 3h$	$t^a_3 = 3h$	$Q^a_3 = Q^b_2$
	$\alpha^b_1 = \frac{1}{2}$	$\alpha^b_2 = 1$	$\alpha^b_3 = \frac{1}{2}$	$Q^{total}_{sur,a} = Q^{total}_{sur,b}$

Table A.3.: Example MPM calculation

Bear in mind that the Q_{sur} is calculated using concept of MPM, which is raised from statistical point of view. The conclusion that the Q_{sur} for both cases are the same, as shown in Table A.3, is logical.

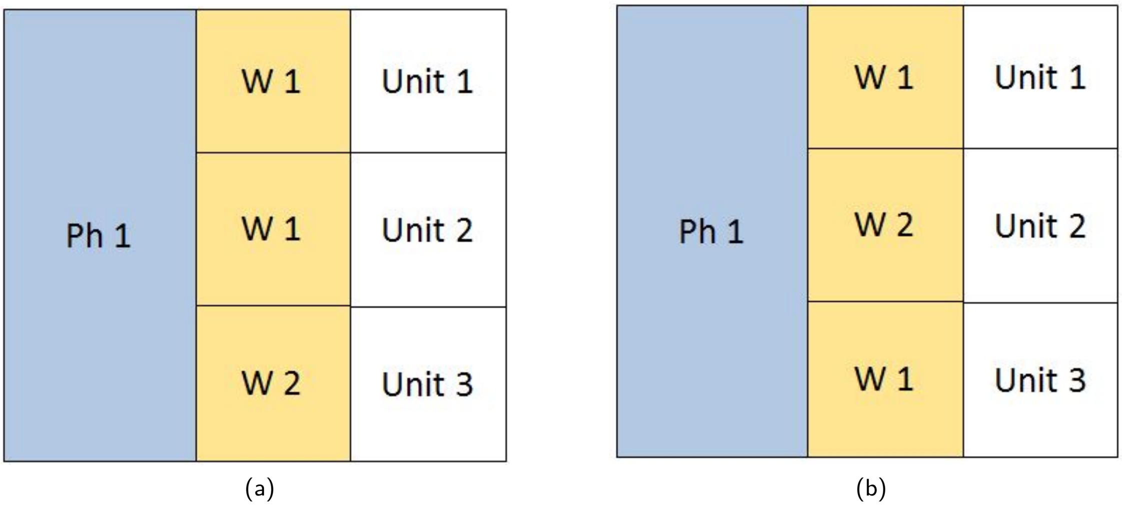


Figure A.4.: Level 2 food for thought 2

A.6. Derivation box (Section 5.3.2)

Derivation

For Case A,

$$P\left(W1_{6h}\right) = P_{6h}\left(W1\right) \tag{A.3}$$

For Case B,

$$\begin{cases} P\left(W1_{3h} \rightarrow W1_{3h}\right) & = P_{3h}\left(W1\right) \cdot P_{3h}\left(W1 \rightarrow W1\right) \\ P\left(W2_{3h} \rightarrow W1_{3h}\right) & = P_{3h}\left(W2\right) \cdot P_{3h}\left(W2 \rightarrow W1\right) \end{cases} \tag{A.4}$$

A recap of the assumption:

- There exists only two possible sea states, $W1\&W2$;
- The only difference of the two persistency data is sampling interval;
- Time series of sea state record is long enough;
- Sea is assumed to be mildly changing as shown in Figure 5.4.

Based on those assumptions, we will have the following equations:

$$\begin{aligned} P_{6h}\left(W1\right) &= P_{3h}\left(W1\right) \\ P_{3h}\left(W1\right) + P_{3h}\left(W2\right) &= 1 \\ P_{3h}\left(W1 \rightarrow W1\right) + P_{3h}\left(W2 \rightarrow W1\right) &= P_{3h}\left(W1\right) \end{aligned} \tag{A.5}$$

Thus we will have:

$$\begin{aligned} Case\,A &= P_{3h}\left(W1\right) \\ Case\,B1 &= P_{3h}\left(W1\right) \cdot P_{3h}\left(W1 \rightarrow W1\right) \\ Case\,B2 &= P_{3h}\left(W1\right) \cdot \left(P_{3h}\left(W1 \rightarrow W2\right)\right) \end{aligned} \tag{A.6}$$

To judge which one is bigger, we take away $Case\,B$ from $Case\,A$:

$$\begin{aligned} Case\,A - Case\,B &= P_{3h}\left(W1\right) - P_{3h}\left(W1\right) \cdot \left(P_{3h}\left(W1 \rightarrow W2\right) + P_{3h}\left(W1 \rightarrow W1\right)\right) \\ &= P_{3h}\left(W1\right) - P_{3h}\left(W1\right) \\ &= 0 \end{aligned} \tag{A.7}$$

As can be seen,

$$Case\,A = Case\,B \tag{A.8}$$

Thus, we conclude that C_{op}^{A} and C_{op}^{B} are equal in this case.

A.7. Preparation: time series of different sampling interval (Section 6.1.3)

Assuming mildly changing sea

Assume the original time series we have is with sampling interval of 6 hours, represented by TS_{6h}. Thus, time series with sampling interval of 3 hours can be obtained:

$$\begin{cases} TS_{3h}\left(2\cdot i-1\right) & = TS_{6h}\left(i\right) \\ TS_{3h}\left(2\cdot i\right) & = TS_{6h}\left(i\right) \end{cases}$$

Where $TS_{6h}\left(i\right)$ means the i^{th} piece of record in the time series and "=" means all the sea state property (HS, Tp, wave direction, etc...) should be the same.

Assuming true sea

Assume the original time series we have is with sampling interval of 3 hours, represented by TS_{3h}. Property of the i^{th} piece of record in the time series $TS_{3h}\left(i\right)$, can be represented by $\left(Hs_{3h}\left(i\right), Tp_{3h}\left(i\right) \& Wdir_{3h}\left(i\right)\right)$. Thus, time series with sampling interval of 9 hours can be obtained:

$$\begin{cases} Hs_{9h}\left(i\right) & = \frac{\frac{Hs_{3h}(3i-2)}{Tp_{3h}(3i-2)}+\frac{Hs_{3h}(3i-1)}{Tp_{3h}(3i-1)}+\frac{Hs_{3h}(3i)}{Tp_{3h}(3i)}}{\frac{1}{Tp_{3h}(3i-2)}+\frac{1}{Tp_{3h}(3i-1)}+\frac{1}{Tp_{3h}(3)}} \\ Tp_{9h}\left(i\right) & = \frac{3}{\frac{1}{Tp_{3h}(3i-2)}+\frac{1}{Tp_{3h}(3i-1)}+\frac{1}{Tp_{3h}(3)}} \end{cases}$$

Assuming uni-directional wave, thus $Wdir_{9h} = Wdir_{3h}$.

B. Case study

B.1. FBTO system

B.1.1. Vessel particulars

Designation	Symbol	Unit	Operational phase 1	Operational phase 3
Length between perpendiculars	Lpp	m	256.00	256.00
Breadth	B	m	40.42	40.42
Depth	D	m	24.0	24.0
Draft	T	m	15.40	14.27
Displacement weight	Δ	tonnes	136740	126740
Centre of gravity from st.10	LCG	m	6.26	-0.06
Centre of gravity above keel	KG	m	12.04	11.37
Transverse metacentric height	GMt	m	4.57	4.93
Longitudinal metacentric height	GMl	m	320.16	345.42
Roll radius of gyration	kxx	m	14.1	14.1
Pitch radius of gyration	kyy	m	64.0	61.8
Yaw radius of gyration	kzz	m	64.0	61.8
Extra viscous damping as % Bcritical	B44	-	3%	3%

Table B.1.: Capesize vessel particulars

B.1.2. Mooring system

length	m	63
Breadth	m	23.5
Depth	m	4.5
Draft	m	2.5
Displacement	tonnes	3794
LCG	m	0.00
KG	m	3.02
GMt	m	12.03
GMl	m	97.45
kxx	m	7.8
kyy	m	12.3
kzz	m	11.8
B44 viscous	/	5%

Table B.2.: Floating crane particulars

Designation	Unit	Operational phase 1	Operational phase 3
length	m	95	95
Breadth	m	30	30
Depth	m	6	6
Draft	m	1.08	2.79
Displacement	tonnes	3155	8180
LCG	m	0.00	0.00
KG	m	0.83	1.73
GMt	m	54.33	22.34
GMl	m	524.53	203.70
kxx	m	6.9	4.5
kyy	m	13.0	8.2
kzz	m	14.5	9.1
B44 viscous	/	5%	5%

Table B.3.: Bulk barge particulars

Configuration	Capsize vessel		Crane Barge		Bulk Barge	
	x(m)	y(m)	x(m)	y(m)	x(m)	y(m)
Production phase 1	0	0	68.3	-33.96	52.3	-62.71
Production phase 2	0	0	39.5	-33.96	23.5	-62.71
Production phase 3	0	0	10.7	-33.96	-5.3	-62.71

Table B.4.: Vessel position in ship coordinating system

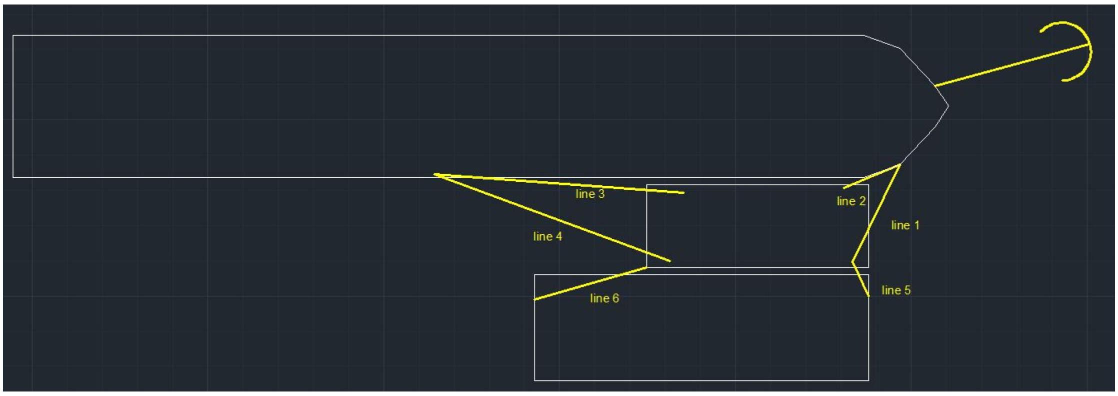


Table B.5.: Schematic drawing of mooring system

	Diameter (mm)	Mass per unit length (Kg/m)	MBL (KN)
Steel wire	40	6.69E-02	1009.4
Mooring chain	172	647	18876

Table B.6.: Mooring line property

Fender type		Truck tyre with chain
Diameter	m	1.1
Width	m	0.3
Thickness	mm	15.2
Material	-	chloroprene/neoprene rubber

Table B.7.: Fender property

B.2. Environmental condition

Binsize		0.25	0.50	22.5
Date	Time	Hs	Tp	WDir
01 January 1992	00:00:00	0.50	4.5	225.0
01 January 1992	03:00:00	0.50	8.0	225.0
01 January 1992	06:00:00	0.50	8.0	225.0
01 January 1992	09:00:00	0.50	8.0	225.0
......				
31 December 2012	21:00:00	1.5	15.0	225.0

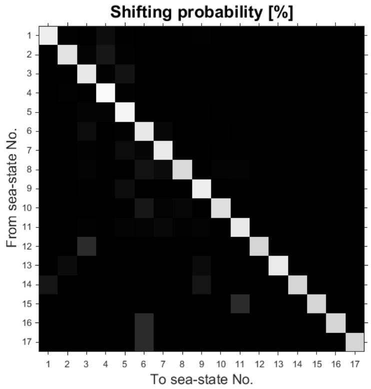
Table B.8.: Example time series

B.3. Persistency property

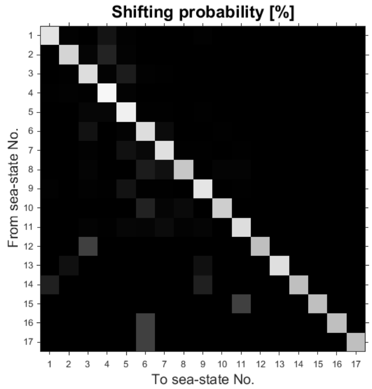
Shift probability assuming mildly changing sea

Notice that the grayscale indicates magnitude of shift probability. From white to black, it ranges from $100\% \rightarrow 0\%$.

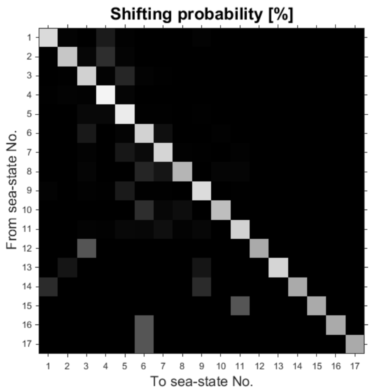
Occurrence probability assuming true sea



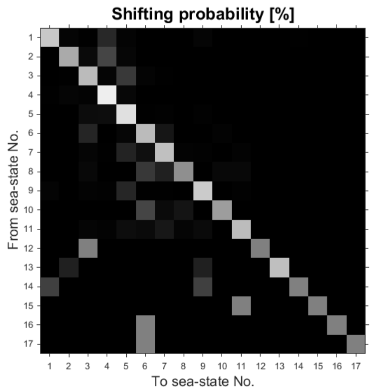
(a) Sampling interval 2h



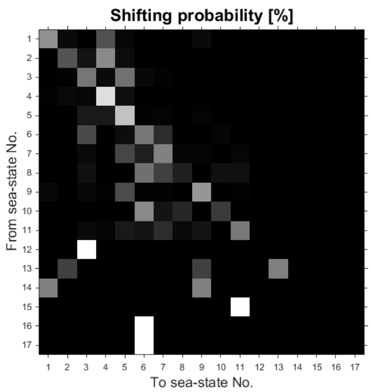
(b) Sampling interval 3h



(c) Sampling interval 4h



(d) Sampling interval 6h



(e) Sampling interval 12h

Figure B.1.: Shift probability under different sampling interval used in case study 2 - mildly changing sea

Persistency data (2h) - Total occurrence = 100%

Tp (s)	0	5	10	15	20	25
Hs (m)						
0	0.04	0.00	0.00	0.00	0.00	0.00
1	0.00	0.02	1.42	46.20	3.03	0.02
2	0.00	0.00	1.95	32.94	9.99	0.02
3	0.00	0.00	0.31	2.11	1.82	0.01
4	0.00	0.00	0.00	0.03	0.09	0.01

Persistency data (3h) - Total occurrence = 100%

Tp (s)	0	5	10	15	20	25
Hs (m)						
0	0.03	0.00	0.00	0.00	0.00	0.00
1	0.00	0.01	1.27	44.70	3.51	0.01
2	0.00	0.00	1.75	32.62	11.23	0.02
3	0.00	0.00	0.30	1.07	2.14	0.03
4	0.00	0.00	0.00	1.22	0.07	0.01

Persistency data (4h) - Total occurrence = 100%

Tp (s)	0	5	10	15	20	25
Hs (m)						
0	0.03	0.00	0.00	0.00	0.00	0.00
1	0.00	0.01	1.34	44.15	2.65	0.01
2	0.00	0.00	1.90	34.77	9.95	0.01
3	0.00	0.00	0.33	2.52	2.12	0.01
4	0.00	0.00	0.00	0.10	0.08	0.01

Persistency data (6h) - Total occurrence = 100%

Tp (s)	0	5	10	15	20	25
Hs (m)						
0	0.01	0.00	0.00	0.00	0.00	0.00
1	0.00	0.01	1.28	42.56	2.40	0.00
2	0.00	0.00	1.93	36.25	9.68	0.01
3	0.00	0.00	0.35	2.81	2.37	0.02
4	0.00	0.00	0.03	0.16	0.15	0.00

Persistency data (12h) - Total occurrence = 100%

Tp (s)	0	5	10	15	20	25
Hs (m)						
0	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	1.21	38.42	1.37	0.01
2	0.00	0.00	2.01	41.30	8.13	0.01
3	0.00	0.00	0.43	3.87	2.87	0.01
4	0.00	0.00	0.02	0.29	0.06	0.01

Figure B.2.: Occurrence probability under different sampling interval used in case study 2 - true sea