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## RISK ASSESSMENT OF DELAYS DURING DEEP WATER PIPE-LAYING

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### ABSTRACT
The methodology for minimising the risk of delays during deep water pipe-laying operations has been developed within the framework of Quantitative Risk Assessment, and applied to pipe-laying project in the Gulf of Mexico. It is shown that hazards specific to pipe-laying operations, most of which cannot be considered to be major hazards, contribute more to the overall risk profile of delays than the major hazards. The approach offers an insight into the main contributors to risk and the measures that can minimise or control these risks. The management of operations and improved personnel training can significantly reduce the risk of small delays, while reliable extreme weather forecasting reduces the risk of long delays due to vessel and/or pipeline damage.

### INTRODUCTION
The construction and installation phases of an offshore project are normally characterised by a very tight project schedule. There are several examples in the offshore industry of project delays and losses caused by failures in the construction and installation phases. A methodology has been developed to assess the risk of delays during a deep water pipe-laying in order to minimise and control the delays.

The methodology for the risk assessment of delays has been developed within the framework of Quantitative Risk Assessment (QRA). A QRA-based approach was considered a useful tool to identify high risk or critical operations in the pipe-laying process. The methodology is based on the approach that has been used with success for offshore construction projects, Ref. 1, and its merits in assessing risks during the design phase of offshore projects have been assessed, (Trbojevic, 1994).

It should be noted that the objective here is to assess the probability and the consequences of failures which would cause delays, which is different from so called ‘project risk assessment’ in which scheduling of work and the uncertainties of task duration are investigated. In this approach it has been assumed that the uncertainties about task duration have been minimised, and the emphasis is on potential unexpected failures which could cause problems. Therefore, this approach offers the detailed insight into the main contributors to risk of delays, which can then be targeted by remedial measures. On the financial side, this approach gives a better handle in deciding on which risk a company should bear, and which risks should be insured.

### METHODOLOGY FOR RISK ASSESSMENT
The main steps of the methodology are as follows:

- System definition - which defines the boundaries of the analysis and the engineering operations, the pipe-laying vessel, the number and type of pipelines, etc. to be analysed.
- Hazard identification - two sets of hazards are considered: the major hazards which are mostly vessel related, and the pipe-laying hazards which are related to pipe laying operations.
- Hazard analysis - in which the causes of hazard release, and the possible escalation paths are investigated; the frequencies of each outcome are evaluated and associated with the corresponding number of delay days.
- Risk summation - the integration of risk and consequence information for each outcome yields the risk profile of the pipe-laying operations.
- Risk assessment - risk criteria are used to assess the significance of the estimated risks, the main contributors

(drivers) to risk are identified, and the risk reducing measures are developed targeting risk drivers.

By adopting the QRA-based approach for this assessment, the first task however was to develop the risk acceptability criteria for the project.

## Risk acceptability criteria

Due to a very tight project schedule, it has been decided that the frequency per project of an outcome causing one day delay should not exceed 1. The next point is defined as the frequency of an outcome causing 100 days delay, the frequency of which is 1 in 100 (per project), and these two points define the maximum tolerable boundary, Figure 1. A desirable target is two order of magnitude smaller to account for uncertainties, hence it is broadly acceptable (desirable) to have less than one delay day per 100 projects. These two boundaries define a region where risk is considered tolerable only when it has been made 'As Low As Reasonably Practicable' (ALARP). This requires risk reduction measures to be implemented when they are reasonably practicable, as evaluated by cost-benefit analysis. The fatalities risk criteria follow the typical North Sea practice.

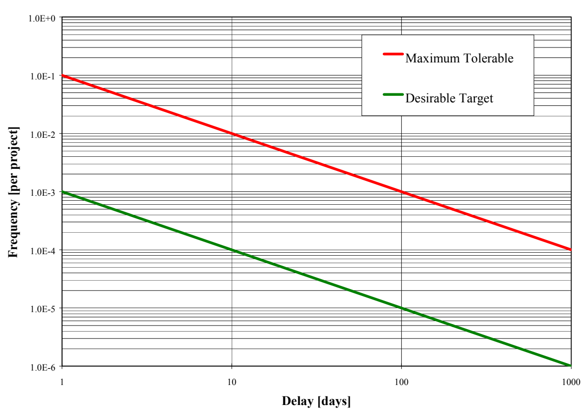


**Figure 1 Delay risk criterion**

## System definition

The main components of the system for which the risk profile is to be evaluated are as follows:

**The Heavy Lift Vessel (HLV)** - a semi-submersible crane vessel comprising two floaters and six columns supporting the upper deck structure. The pipelines are to be laid using a J-lay tower. The tower is mounted at the stern of the HLV, which is equipped with a Dynamic Positioning System (DPS). The main components of the J-lay system are: **stinger** which is designed for deep water pipe-laying and can operate at any departure angle within the range of 20 to 100 degrees relative to the vessel deck, together with the weld/NDT and the coating stations, **strong-back** which is an extension on the top of the stinger to hold and line-up a new pipe string, and **upending ramp** which is a hinged ramp for upending a new pipe string from the deck (zero angle) to the strong-back (tower angle). The number of personnel on board is 235.

**Pipe barge** - which carries typically between 84 and 156 pipe strings depending on the pipe diameter. The pipe strings are stored in to racks which are lifted onto the vessel.

The engineering operations from the pipeline initiation, the actual pipe-lay and pipeline termination are as follows:

**Stab and hinge over** - is used for the pipelines to provide the connection to the wellhead trees. The pipelines will be formed by welding together 240 ft pipe strings. A 'stabbing' pin with the appropriate hinge head and connection hub is attached to the first pipe string. During the operation, the 'stabbing' pin is stabbed vertically into the pre-installed receiver cone on the sea bed. During the 'hinge over' operation, the pipeline develops a buckling force which is directed vertically downwards onto the stab tool hinge head, and as the hinge over progresses, the curvature of the sag-bend increases, reaching the maximum bending strain. This means that the pipeline will bend plastically during the hinge-over but should be in no danger of a buckling failure. Continuing pay-out of the pipeline from the vessel results in hinge-over of the pipeline from vertical to a horizontal position on the sea floor, followed by the laying of the pipeline along a specified route.

**J-lay** operations comprise of transferring pipe string from upending ramp to strong-back, lining and welding of the new pipe string onto the suspended pipe, lowering the pie weld to a coating station, and lowering (pay-out) pipe until top of the pipe is in the welding station; the process is then repeated until pipeline termination, riser installation, etc.

**Pipeline termination** comprises of welding the end-piece and coating of pipe-ends, connecting the abandonment and recovery (A&R) wire, and lowering the pipeline with simultaneous movement of the vessel and pay-out of the A&R wire.

**Steel catenery riser installation** consists of suspending the riser from the vessel using A&R wire, and transferring the attached pull-in chain to the platform, and pulling the riser through the pull-tube from the platform.

**Pipeline crossing** procedure is used to provide safe crossing over the existing pipelines; it requires specially designed concrete 'mattresses' to be installed over the existing pipelines, before laying the new pipeline (over the mattress).

**Abandonment and recovery** of the pipe-lay may be required by the extreme weather conditions, or by any other major accident on the vessel. It is similar to pipeline termination, i.e. the pipeline is lowered by the A&R wire, and the buoy is attached for the recovery at the later stage. In the recovery phase, the pipeline is pulled back to the vessel by A&R wire, and the pipe-lay re-started.

**Contingency procedures** are required if a buckle develops during pipe-lay. During pipeline installation, continuous stress monitoring will be performed in order to safely lay the pipeline and avoid any over-stressing or buckling. However, it is possible that a buckle may occur due to ovalisation of the pipeline, material defect, human error or mechanical failure; the buckle can be ‘dry’ (without rupture), or ‘wet’ when the pipeline fills with water. In both cases, the pipeline needs to be retrieved back string by string, the damaged section removed, and the pipeline re-installed. In the case of a flooded pipeline which cannot be retrieved back to the vessel, pipeline has to be laid onto the sea bed, cut below the damaged part, and then retrieved back to the vessel, etc.

The described activities are pipeline and project specific, as shown in Table 1. The activity applicable to a pipeline is marked by ‘x’, while ‘o’ denotes possible abandonment and recovery, and contingency repair procedures.

**Table 1 Pipelines and Related Activities**

| No. | Activity / Pipeline Description | Stab & Hinge Over | J-lay | Steel Catenary Riser Installation | Termination | Pipeline crossing installation | Abandon. and recovery | Contingency procedures |
|---|---|---|---|---|---|---|---|---|
| 1 | Production lines 1 | x | x | | | | o | o |
| 2 | Delivery pipelines 1 | x | x | x | | | o | o |
| 3 | Infield production lines 2 | x | x | x | x | | o | o |
| 4 | Export pipelines 2 | | x | x | | x | o | o |
| 5 | Infield water injection lines 2 | x | x | x | | | o | o |

## Hazard identification

The approach adopted for hazard identification and classification differs from a standard method used in the offshore industry which typically deals with ‘major’ hazards. The approach in this study is based on the following classification of hazards:

- Vessel related, background, hazards - these hazards are related either to the vessel or the location, and not to pipe laying, for example, passing vessel collision, flooding of compartments, loss of power, etc. Most of these hazards are so called ‘major’ hazards in the North Sea safety regime.
- Pipe laying hazards are related to pipeline laying operations, for example, J-lay system failure, A&R wire failure, loss of station keeping, etc. These are operation specific hazards.

A list of vessel related (background) and pipe laying hazards and the corresponding initiating events is shown in Table 2. Historical data on failures during pipeline installation phases is sparse and therefore not viable for analysis. The available option is to identify all causes and their combinations which could lead to failure (or an initiating event), and integrate those by means of a fault tree analysis. In developing the failure models for pipeline laying operations, the following factors were identified:

- possibility of human operational error
- possibility of mechanical failure (due to human error, material or design failure)
- possibility of human failure to recover from a failure/error.

Another group of hazards called here ‘composite hazards’ represent a combination of several initiating events specific to the operation. For example, a ‘termination failure’ comprise ‘wire failure’, ‘pipeline installation failure’ and ‘manoeuvring failure’.

**Table 2 Hazards and initiating events related to pipe-laying**

| Generic Hazards | Specific hazard | Initiating Event | No. |
|---|---|---|---|
| **Vessel Related (Background) Hazards** | | | |
| Operations in water | Collision with passing vessel | Collision with passing vessel | H.1.1 |
| | Collision with supply vessel | Collision with supply vessel | H.1.2 |
| | Collision with pipe barge | Collision with pipe barge | H.1.3 |
| | Loss of buoyancy | Flooding of compartments | H.1.4 |
| | Loss of power | Loss of power | H.1.5 |
| | Ballasting failure | Ballasting failure | H.1.6 |
| Structural failure | Vessel structural failure | Vessel structural failure | H.2.1 |
| | Deck failure | Deck failure | H.2.2 |
| Elevated objects | Dropped objects | Dropped objects | H.3.1 |
| Environmental | Hurricanes | Hurricanes | H.4.1 |
| | Tropical storms and squalls | Tropical storms and squalls | H.4.2 |
| Fire and explosion | Fire on vessel | Fire on vessel | H.5.1 |
| | Gas storage explosion | Gas storage explosion | H.5.2 |
| Engineering calculations | Error in calculations/design | | H.6.1 |
| **Pipelaying Related Hazards** | | **Initiating Event** | **No.** |
| Loss of tension | Loss of tension | Wire failure | H.11.1 |
| | | Winch failure | H.11.2 |
| | | Tensioner failure | H.11.3 |
| Structural failure | Structural failure of J-lay system | J-lay system failure | H.12.1 |
| | | Upending ramp failure | H.12.2 |
| | Pipeline slippage | Gripper failure | H.12.3 |
| | Shift of pipe rack | Pipe rack failure | H.12.3 |
| Hot work on deck | Welding system failure | Faulty welding | H.13.1 |
| Installation (pay-out) failure | | Pipe overstressing/buckling | H.14.1 |
| Operations in water | Station keeping failure | Station keeping failure | H.15.1 |
| | Manoeuvring failure | Thruster/steering failure | H.15.2 |
| **Composite Hazards** | | **Initiating Event** | **No.** |
| Riser installation | Riser installation failure | Riser installation failure | H.16 |
| Termination | Termination failure | Termination failure | H.17 |
| Pipeline crossing | Pipeline crossing failure | Pipeline crossing failure | H.18 |

## Hazard analysis

The initiating event failure frequencies are estimated from historical failure rate data for components, or from statistical data for extreme events such as extreme weather, or from a detailed examination of possible causes of system failure typically carried out by means of fault tree analysis. For example, ‘aggregate failure modes’, are analysed using the historical failure rate data for mechanical failures, and judgmental probabilities for human/operator errors. In order to evaluate human failure frequencies, the opportunities for error have to be identified from analysis of tasks performed. The errors are classified according to the type of behaviour, e.g. error of omission, commission, etc. This error rate is combined with the performance shaping factor which takes account of important features in the task context, such as situation novelty, or time on task, which may increase or decrease the likelihood of error. The product of a generic error rate and the performance shaping factor yields the required human error rate.

The hazard analysis proceeds with analysing the paths of hazard realisation and the corresponding consequences. Since all events have the potential to cause delays, an attempt is made to distinguish between causes of delay which may be as follows:

- Vessel related which are governed by the extent of vessel damage and the required repair time.

- Welding quality related which are related to the time required to pull up the pipe spool, repair the weld and continue pipe lay.
- Delays depending on contingency operations such as pipeline buckle repair; in this category four categories of delays are identified corresponding to the type of damage.
- Delays corresponding to pipeline abandonment and recovery which may be governed by the duration of severe weather, warranty surveying and/or legal aspects, etc.

Delay categories used in this study are presented in Table 3. An event tree approach has been utilised to explore all the possible paths along which an event can propagate to unwanted consequences, and therefore an event has the potential to lead to a different combination of delay days, as shown later in the text.

**Table 3 Delay categories**

| Category | Dealy [days] |
|---|---|
| D1 | 0.25 |
| D2 | 1 |
| D3 | 2 |
| D4 | 5 |
| D5 | 10 |
| D6 | 15 |
| D7 | 30 |
| D8 | 60 |
| D9 | 90 |
| D10 | 180 |

Some typical hazards for the Gulf of Mexico and deep water pipe laying are described below.

**Hurricanes** - this event relates to the hurricane forecast which would cause pipe laying operations to stop, and therefore, the project completion will be delayed. The following activities are assumed to constitute this event:

- Pipeline abandonment activities would be initiated.
- Vessel would move to a secure location outside the hurricane's path.
- Pipeline lying operation continues with pipeline recovery operations.

It has been assumed that this event results in delays which are proportional to the duration of the severe weather. The corresponding wind speeds in excess of 25 m/s (50 knots) and the wave height in excess of 4 m have been assumed. Pipe laying operations would be abandoned, and the vessel would move to a shelter. The possible consequences could mean delays of between 5 and 15 days, the potential for damage to the vessel if the weather changes without sufficient warning time for the vessel to shelter, with a corresponding delay up to 60 days, which is an extreme case and corresponds to wind speeds in excess of 100 knots.

**Pipeline installation (pay-out) failure** - The stress levels in the pipeline need to be within the defined specification throughout pipe-laying operations. If the stress levels are exceeded, the pipeline may buckle or develop permanent (plastic) deformation resulting in ovalling. The pipeline stresses depend on the geometry of the sag bend. The geometry control of the pipeline during pipe-lay is based on monitoring the position of the pipeline relative to the stinger, movement of the vessel, paid-out length, etc. It has been assumed that over-stressing/buckling of the pipeline can be caused by pay-out monitoring failure - which is described by three main parameters as follows:

- monitoring of the horizontal distance between the pipeline touch-down point to pipeline departure point, which has to be within specified boundaries,
- monitoring of the pipeline sag bend geometry such as stinger angle, pipeline departure relative to the bottom rollers, paid-out pipe length, and tension load.
- monitoring of tension in the pipeline.

It should be noted that failure in the associated operations such as manoeuvring, station keeping and ballasting could also lead to pipeline over-stressing or buckling.

The 'pipeline installation failure' event is defined as exceeding the parameters required for safe pipeline laying operations, or in other words, creating the conditions in which pipeline buckle can be formed. In order to analyse this event, two component failure modes are combined to obtain the initiating frequency for this event. These modes are as follows:

- Failure/error in monitoring the horizontal distance between the pipeline touch-down point to pipeline departure point,
- Failure/error in monitoring the pipeline sag bend geometry and tension in the pipeline.

It is assumed that any of these events would trigger the top event, i.e. 'pipeline installation failure'. Therefore, this initiating event triggers the contingency procedure which can escalate along one of the following paths: inspection and no repair, inspection and dry buckle repair, inspection and wet buckle repair, and abandonment of the pipeline.

## Risk summation

Risk summation results in the risk profile for all pipeline laying operations on per project basis, while the fatality risks are evaluated on an annual basis to facilitate comparison with other offshore activities. The following risk measures have been evaluated:

- Risk of delays in terms of the expected number of delay days (which is a sum of the products of outcome frequency and the corresponding delay over all outcomes and events)
- Frequency of categories of delays
- Risk of fatalities in terms of the Fatal Accident Rate (FAR), and the Individual Risk Per Annum (IRPA).

The total expected number of delay days is 2.74 days per project, and its breakdown by delay categories is presented in Figure 2.

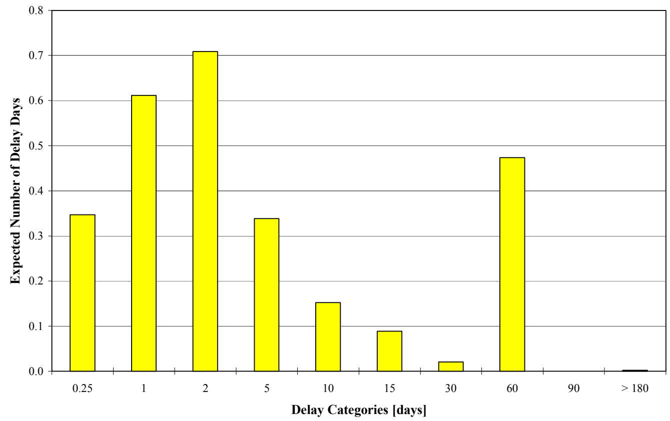


**Figure 2 Risk profile in terms of expected number of delay days**

Five delay categories (up to 10 delay days) account for 78.7% of the risk of delays. The events contributing to the frequency of these five delay categories are presented in Figure 3.

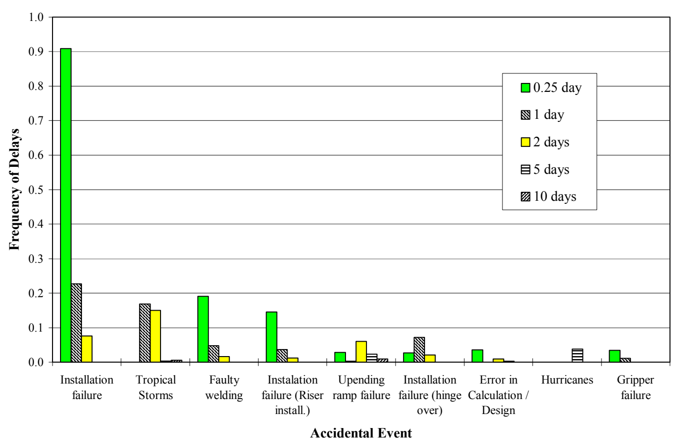


**Figure 3 Breakdown of delay frequency by accidental event**

The contribution of a selected number of events to the overall risk of delays is presented in Table 4 (the numbers in the table denote percentage contribution). The overall contribution of the selected events is 97%, out of which hurricanes contribute 24.8%, pipeline repairs due to installation failures 22.1%, tropical storms 19.9%, and upending ramp failure contributes 12.4%.

Risk of fatalities was as expected below the average for the offshore industry, i.e. in terms of FAR between 4.5 and 5.5, which corresponds to IRPA between $1.5 \times 10^{-4}$ to $1.85 \times 10^{-4}$ per year.

**Table 4 Main contributors to risk of delays**

| Event Name | 0.25 day | 1 day | 2 days | 5 days | 10 days | 15 days | 60 days | 180 days | Total |
|---|---|---|---|---|---|---|---|---|---|
| Hurricanes | 0.0 | 0.0 | 0.0 | 6.9 | 0.0 | 1.2 | 16.7 | 0.0 | 24.8 |
| Installation failure | 8.3 | 8.3 | 5.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 22.1 |
| Tropical Storms | 0.0 | 6.2 | 11.0 | 0.6 | 2.1 | 0.0 | 0.0 | 0.0 | 19.9 |
| Upending ramp failure | 0.3 | 0.1 | 4.4 | 4.2 | 3.4 | 0.0 | 0.0 | 0.0 | 12.4 |
| Faulty welding | 1.7 | 1.7 | 1.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 4.6 |
| Installation failure (hinge over) | 0.2 | 2.6 | 1.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 4.4 |
| Instalation failure (Riser install.) | 1.3 | 1.3 | 0.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 3.5 |
| Error in Calculation / Design | 0.3 | 0.0 | 0.7 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 1.5 |
| A&R wire failure (Riser install.) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.7 | 0.3 | 0.0 | 1.4 |
| Manoeuvring failure | 0.1 | 0.8 | 0.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.3 |
| Tensioner failure | 0.0 | 0.4 | 0.0 | 0.0 | 0.0 | 0.7 | 0.0 | 0.0 | 1.1 |
| **Total** | **12.2** | **21.4** | **25.6** | **12.3** | **5.5** | **2.6** | **17.0** | **0.0** | **97.0** |

## Risk assessment

The cumulative frequency F of N or more delay days (F-NDD curve) compared against the risk acceptability criteria (Figure 5), indicated that risk of one day delay is slightly above the maximum tolerable criterion, while most of the risk of delays longer than one day is within the ALARP zone. It should be noted at this stage that it has been assumed in the analysis that personnel are relatively inexperienced in pipe-laying operations, the effect of which was to increase the performance shaping factor influencing human error rates. Therefore, an obvious risk reduction measure relates to the benefits of additional personnel training in pipe-laying operations which would reduce the human factor contribution to failure modes. This measure reduces the risk of delay from 2.74 to 1.74 delay days per project, which represents a reduction of 36.6%. The breakdown of risk of delays by delay categories is presented in Figure 4. All events related to a combination of mechanical failure and operator error exhibit the largest decrease in the contribution to the overall risk of delays.

This indicates that the quality (safety) management measures such as improved personnel training are most efficient in reducing risk of delays up to 10 days. The main contribution to risk of delays of 60 and more days is due to hurricanes, which at this stage is not affected by risk reduction measures.

The F-NDD curves for the two cases analysed are presented in Figure 5. It can be seen that the risk reduction targets several peaks in the base case at one and two days delay which were either slightly above or very near the maximum tolerable boundary. The overall risk profile is now in the tolerability zone, and any further risk reduction can be measured against the corresponding cost.

In general, the results indicate that in pipeline laying operations, the delays are governed by hazards related to pipe-laying operations and not by the 'major' hazards. Out of 'major' hazards, the most dominant is the 'extreme weather', i.e. hurricanes. Therefore, it is interesting to revisit some of the assumptions made in modelling of hurricanes.

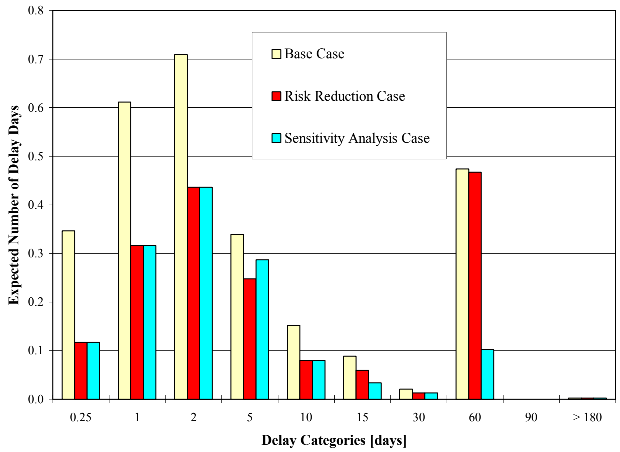


**Figure 4 Risk profile in terms of expected number of delay days before and after risk reduction**

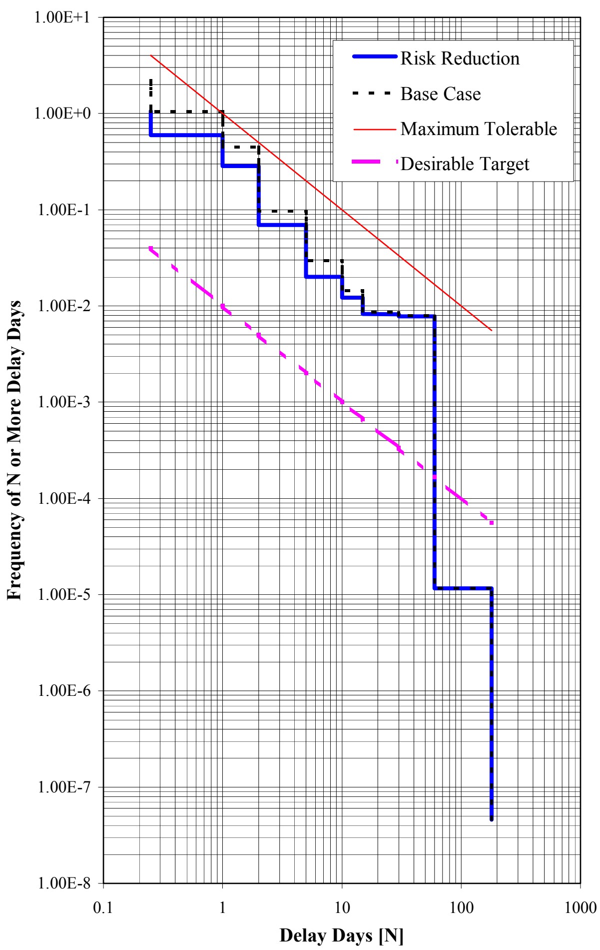


**Figure 5 F-NDD curves before and after risk reduction**

It has been assumed that the probability of hurricane forecast given in time for the vessel to abandon pipe-laying and shelter, is 0.75, in which case the delay will be 5 days. Otherwise, depending on the scenario (outcome), the delays could be between 5 and 60 days. If this assumption is considered conservative, since the hurricanes are being tracked by satellites, and the vessel has its own weather forecast service. In order to investigate the influence of this assumption, the sensitivity analysis has been carried out in which the probability of a sufficient hurricane warning is increased to 0.95. The number of expected delay days for this case becomes 1.38, and the delay risk profile is presented in Figure 4.

## CONCLUSIONS

The following can be concluded from this study:

1. The methodology can successfully be applied to minimise the risk of delays during deep water pipe-laying operations.
2. The risk of delays for this pipeline laying operations is within the acceptability criteria. The expected number of delay days for the base case has been estimated as 2.74 days per project. This value is pessimistic since it is based on the assumption that personnel do not have experience in pipe laying operations.
3. The effects of improved training of personnel in pipe laying operations can reduce the expected number of delay days to 1.74 days, which represents a 36.6% reduction.
4. More reliable severe weather (hurricane) forecasting could reduce the expected number of delay days to 1.38 days, which represents a 49.5% reduction with respect to the base case.
5. In general, four areas for risk management and possible further improvements are: avoidance of pipeline buckles by monitoring pipeline sag bend geometry, pipeline stresses and vessel movement, minimisation of welding faults, improvement in pipe spool upending, and more reliable hurricane forecast. This means that most of the operational risk can be retained by suitable management controls, while only a small portion of rare events such as extreme weather may need to be transferred.
6. Risk of fatalities is comparable to other vessel operations.

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