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FPSO/LNG hawser system lifetime assessment by Gaidai multivariate risk assessment method

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Abstract

Floating Production Storage and Offloading (FPSO) unit being an offshore vessel, storing and producing crude oil, prior to crude oil being transported by accompanying shuttle tanker. Critical mooring/hawser strains during offloading operation have to be accurately predicted, in order to maintain operational safety and reliability. During certain types of offloading, excessive hawser tensions may occur, causing operational risks. Current study examines FPSO vessel's dynamic reactions to hydrodynamic wave-induced loads, given realistic in situ environmental conditions, utilizing the AQWA software package. Current study advocates novel multi-dimensional spatiotemporal risks assessment approach, that is particularly well suited for large dataset analysis, based on numerical simulations (or measurements). Advocated multivariate reliability methodology may be useful for a variety of marine and offshore systems that must endure severe environmental stressors during their intended operational lifespan. Methodology, presented in this study provides advanced capability to efficiently, yet accurately evaluate dynamic system failure, hazard and damage risks, given representative dynamic record of multidimensional system's inter-correlated critical components. Gaidai risk assessment method being novel dynamic multidimensional system's lifetime assessment methodology. In order to validate and benchmark Gaidai risk assessment method, in this study it was applied to FPSO and potentially LNG (i.e., Liquid Natural Gas) vessels dynamics. Major advantage of the advocated approach is that there are no existing alternative risk assessment methods, able to tackle unlimited number of system's dimensions. Accurate multi-dimensional risk assessment had been carried out, based on numerically simulated data, partially verified by available laboratory experiments. Confidence intervals had been given for predicted dynamic high-dimensional system risk levels.

Keywords: FPSO, Energy, Reliability, Risk, LNG, Offshore operations

Introduction

One of the most widely used technologies at the moment for exploring offshore oil and gas potential is FPSO technology. This study places a particular emphasis on numerical analysis of critical hawser tensions. Since offloading operations constitute essential part of oil and gas exploration and production process, mooring/hawser

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systems play significant role in the overall FPSO design. Tandem offloading being popular method, suitable for offshore deep-water areas. However, it was shown that SBS (i.e., Side-By-Side) offloading being more feasible, cost-efficient, as compared with tandem offloading for FPSOs operating for example in Bohai Bay offshore area, which being main focus of the current study.

During SBS offloading operations, it's necessary to consider how 2 vessels move relative to each other, accounting for fenders' response forces, along with tensions in the mooring hawsers. In-situ ecology might suffer potential damage and there could be considerable financial losses, if the SBS offloading system malfunctions in a difficult climate. Hawser mooring tensions, which are our primary reliability concern here, hence being the focus of this study, (Stanisic et al. 2018). Numerous researches on hydrodynamic interactions between 2 nearby floating objects had been conducted within recent decades, for more FPSO accident analysis details, (Cho et al. 2012; Wu et al. 2022). Utilizing Wigely-type model, the authors (Bhardwaj et al. 2021) have evaluated the second order pressures and moment for the SBS arrangement. In (Bhardwaj et al. 2022) authors used a time-domain numerical modeling, to assess hydrodynamic interactions of an LNG-FPSO with its moored LNG (i.e., Liquid Natural Gas) carrier. In (Kashiwagi et al. 2005; Kim et al. 2003) authors focused on the hydrodynamic reactions between the driving LNG-FPSO along with its SBS positioned LNG carriers by using linear 3D (i.e., 3-Dimensional) potential theory. In (Hagen et al. 2015; Hong et al. 2005) reliability approach has been utilized, to study FPSO offloading operations, while in Zhang et al. 2016a; Zhang et al. 2019; Zhang et al. 2023) weakest failure/hazard/damage modes were studied for in-situ SBS offloading operations. For recent research on excessive mooring and hawser FPSO tensions include following studies, (Buchner et al. 2001). In this work, the offloading process between the FPSO and its ST (shuttle tanker) was accurately numerically modelled utilizing FEM (i.e., Finite Element Method) AQWA software, (AQWA user's manual 2013; AQWA theory manual 2013).

Note that aforementioned methods could not handle multi-dimensional risk assessment problems for SBS dynamic offloading and mooring system. Each hawser is essential for operational safety because of the unique features of the SBS offloading process. Due to the linked dynamic mooring system's complexity along with high dimensionality, new, precise, and reliable methods are needed throughout the SBS offloading process. Any hawser failure might have detrimental effects on the environment in addition to monetary losses. In order to handle all hawser concurrently during SBS offloading operations, the authors have created a unique approach. Applying a unique multi-dimensional risk assessment approach to the complicated SBS offloading processes of the FPSO and ST under actual in-situ environmental circumstances was the main goal of this work. To tackle various mechanical nonlinear effects associated with FPSO hawser mooring/hawser line tensions, without any reductions beyond those already present in numerical models, this research has concentrated on utilizing a simple yet highly applicable enhanced numerical MC (i.e., Monte Carlo) based technique, (Naciri et al. 2007). Major engineering benefit of the advocated MC-based approach, being that there are no existing alternative matching reliability methods, able of tackling large number of dynamic system's components/dimensions.

The reliability evaluation approach for SBS offloading FPSO mooring system, which is based on identifying the weakest failure mechanism, refer to Zhang et al. 2016b.

For experimental study on SBS offloading operations of FSRU, LNGC vessels, see (Failed 2012). For experimental investigations on FLNG connection system's dynamic response, during SBS offloading operations see (Zhao et al. 2017). For experimental investigations on influence of liquids inside FLNG tanks subjected to wave loads during SBS offloading operation, see (Vieira et al. 2018; Wang et al. 2012). For contemporary practices and relevant research directions within hydrodynamics for FLNG-SBS offloading, see (Zhao et al. 2018a). For hydrodynamics aspects of conceptual FLNG system in SBS offloading operations, see (Jin et al. 2019).

Figure 1 provides schematic flow diagram for the MC-based multivariate system reliability analysis.

Wave statistics

The in-situ wave scatter diagram in the Bohai Bay (also called Bohai Sea) region (within potential FPSO area of operations) had been obtained, using satellite-based in-situ areal wave statistics, (Global wave statistics (2024); OCIMF 1994). Annually-averaged spatial PDF (i.e., Probability Density Function) of wave heights, and associated wave periods within the Bohai Sea in situ planned operational area, (Lv et al. 2014) had been used to produce relevant load case scenarios for MC simulations. For each in-situ environmental sea-state $\left(H_s, T_p\right)$, corresponding environmental conditions have been used to identify relevant environmental sea-states, assuming for simplicity head-wind's and wave's 180° direction, as in Fig. 2.

In the next section numerical modelling details will be presented.

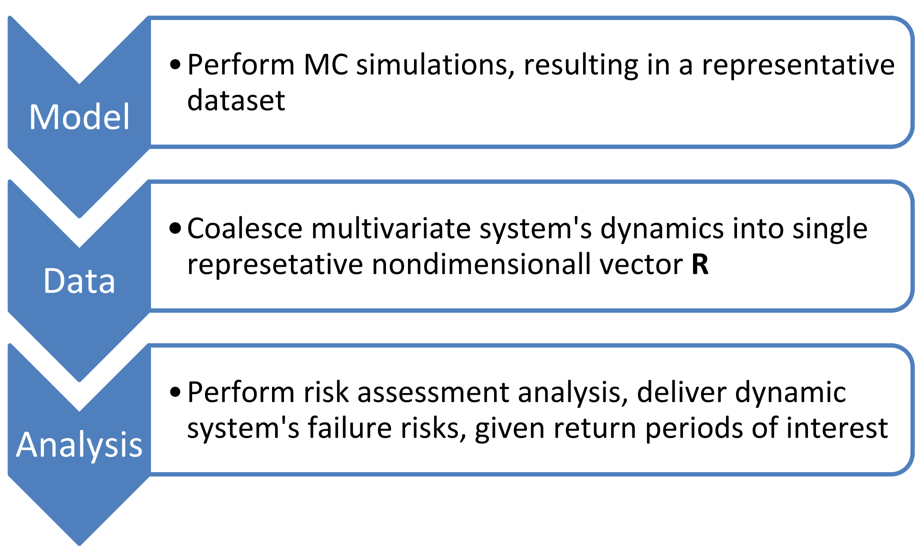


Fig. 1 Flowchart describing long-term MC-based risks evaluation methodology

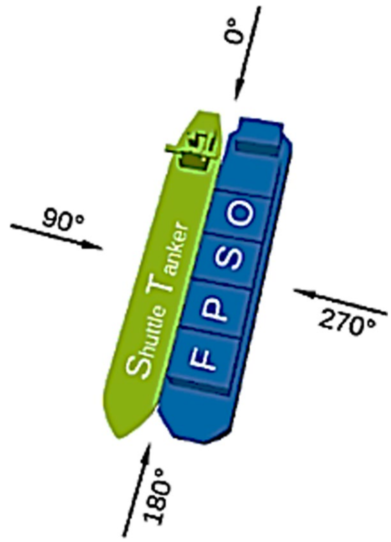


Fig. 2 FPSO vessel with ST positioning during SBS, (Yoo et al. 2022)

Numerical modeling of SBS operation of FPSO next to its SBS ST

Non-linear impacts between the time- and frequency-domains have been combined using the FEM software programme AQWA to precisely evaluate vessel movements, according to recommended practices, (DNV-RP DNV 2010; Veritas 2012, 2011; Design API 2005). The main FPSO parameters, along with its ST are shown in Table 1. Figure 3 left shows the SBS offloading system and the multi-point an FPSO mooring system.

Hawser lines arrangement presented in Fig. 3 left. Figure 3 right schematically illustrates the connected panel concept for FPSO, positioned next to its ST. As this study was

Table 1 Main particulars of FPSO vessel along with its ST

Designations	Symbols	Units	FPSO	ST
Length overall	L_{OA}	m	235.6	207.0
Length between perpendicular	L_{PP}	m	225.0	194.0
Breadth	B	m	46.0	36.0
Depth	D	m	24.1	16.1
FPSO draft	T	m	11.2	8.7
FPSO displacement	Δ	t	$1.1{\cdot}10^5$	$4.9{\cdot}10^4$

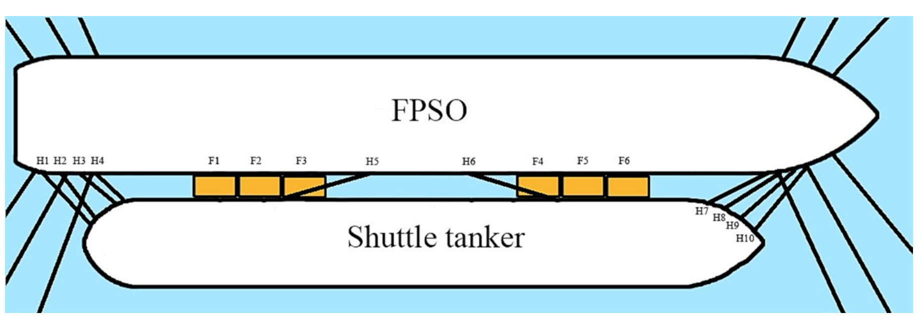


Fig. 3 SBS offloading system layout, along with its multi-point SBS hawsers (marked $H_1, \ldots, H_{10}$), (Xu et al. 2023)

focused on a general applicability of the advocated lifetime assessment methodology, only few most critical load cases, corresponding to particular sea states, within in-situ scatter diagram, had been taken into consideration in MC simulation. The significant wave-height range has been selected to be between 1.5 m and 2.5 m, with 4 random seeds calculated for each significant wave-height.

Experimental validation notes

Experimental setup for ST model next to its FPSO in the laboratory tank, with fitted SBS hawser system, has been described in more detail in Xu et al. (2023). While being activated by regular waves of various in-situ frequencies, vessel RAO (i.e., Response Amplitude Operator) of 2 vessels had been experimentally measured. The motion RAOs of the FPSO estimated, using software package AQWA and associated experimental data had been compared, (Xu et al. 2019, 2023; Balakrishna et al. 2022); AQWA numerical results had been found to be in quite good agreement with available experimental dataset, the latter acted as software package AQWA partial validation. CFD (i.e., Computational fluid dynamics), software tools like ANSYS Fluent had been utilized to estimate current-related force coefficients, see (Fan et al. 2014). Ten hawsers (H_1,..., H_{10}), as shown in Fig. 3, constitute SBS hawser system. These contained 110 mm diameter nylon ropes. Figure 4 illustrates load-extension curve for the nylon rope.

Proper friction model for nylon ropes may account for inner friction effects, contributing to fatigue—the latter, however, was beyond the scope of this study.

Gaidai risk assessment method

This section briefly presents methodology, suitable for LTD (i.e., Life Time Distribution) estimation, suitable for complex environmental or energy dynamic systems, given multiple hazard/failure/risk modes, active during entire pre-designed operational time. When hazard/failure thresholds are selected, successive time spans (i.e., lifetimes) between data points show crossings of the relevant hazard/failure threshold. These crossings are represented as ’s, which show the sequential life durations L_i of the dynamic, where $i = 1,2,\ldots$, multi-dimensional FPSO vessel system. Thus, L,

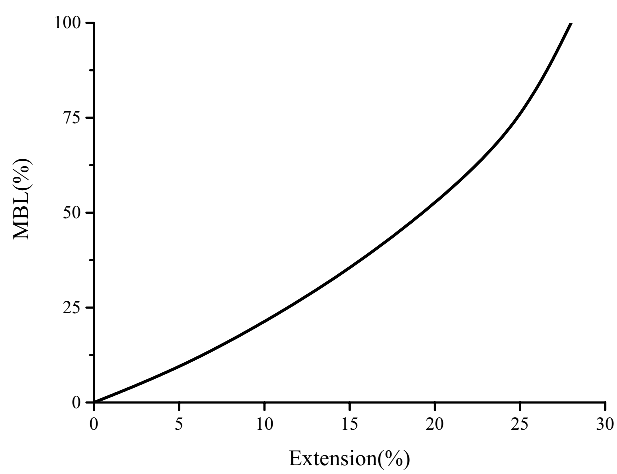


Fig. 4 The load-extension relationship of the nylon rope, (Xu et al. 2019). MBL is the Minimum Breaking Load

which represents the lifespan of a dynamic system, being a random variable. In for instance, modern engineering risk assessment approaches do not necessarily provide readily applied solutions to evaluate the LTD of complicated energy or high-dimensional environment systems, particularly if the number of important dimensions/components (failure modes) of a system is significant. Let one assess CDF (i.e., Cumulative Distribution Function)

$$\text{LTD}\,(L) \equiv \text{Prob}(\text{Lifetime} \leq L) \tag{1}$$

this CDF may be directly assessed through either enough measurement data, or through direct extensive MC simulations, (Gaidai et al. 2021, 2022b, 2023a, 2022a, 2022c, 2022d, 2022e; Gaidai and Xing 2022). Both potential experimental expenses, as well as computing costs may be well prohibitive for many engineering complex offshore energy systems. The authors have proposed a unique way for evaluating the limited computational and measurement expenditures that are necessary during the design phase of a system. This innovative LTD method is appropriate for complicated multidimensional environmental, engineering, and energy systems.

Let one examine a structurally dynamic MDOF (i.e., Multi-Degree-Of-Freedom) that is depicted by a response/load (a component) vector $(X(t), Y(t), Z(t), \ldots)$,. This vector is composed of the critical/key flexible components of the system $(X(t), Y(t), Z(t), \ldots)$, that are either calculated or mathematically simulated through a representative $(0, T)$ timelapse that is long enough. The global maxima of a multidimensional vessel systems component or 1D (unidimensional) dynamical energy are then indicated below, as $X_T^{\max} = \max\limits_{0 \leq t \leq T} X(t)$, $Y_T^{\max} = \max\limits_{0 \leq t \leq T} Y(t)$, $Z_T^{\max} = \max\limits_{0 \leq t \leq T} Z(t), \ldots$. By sufficiently long (namely, representative) timelapse T one primarily means large enough T value, with respect to the dynamic or vessel system's auto-correlation, as well as dynamic vessel system's relaxation times. With $X_1, \ldots, X_{N_X}$ being temporally increasing vessel system's critical component's process $X = X(t)$ local maxima, extracted from the raw time-series, recorded at discrete time-increasing temporal instants $t_1^X < \cdots < t_{N_X}^X$ spotted throughout $(0, T)$. The other essential components of the MDOF system are defined in the same way:$Y(t), Z(t), \ldots$ specifically $Y_1, \ldots, Y_{N_Y}$; $Z_1, \ldots, Z_{N_Z}$ etc. The local maxima of every system with dynamics were taken to be positives for the purpose of simplification, and

$$P = \iiint\limits_{(0,0,0,,\ldots)}^{(\eta_X,\eta_Y,\eta_Z,\ldots)} p_{X_T^{\max},Y_T^{\max},Z_T^{\max},\ldots}\left(x_T^{\max}, y_T^{\max}, z_T^{\max}, \ldots\right) dx_T^{\max} dy_T^{\max} dz_T^{\max} \ldots \tag{2}$$

having been a possibility of surviving for the target dynamical system, possessing critical levels of that system's essential components, represented as$\eta_X,\eta_Y,\eta_Z,\ldots$ and $p_{X_T^{\max},Y_T^{\max},Z_T^{\max},\ldots}$ being the joint PDF of individual vessel system critical component's global maxima. High dimensionality of complex systems means that most complicated dynamic offshore environmental, mechanical, and offshore energy systems could be much beyond the reach of both experimental expenditures and computing expenditures. With a conditional probability decomposition, non-exceedance chances/probability $P(\lambda)$ may now be evaluated

$$P(\lambda) = ProbR_N\eta_N^{\lambda},\ldots,R_1\eta_1^{\lambda} = \\ =\text{Prob}\{R_N \le \eta_N^{\lambda}|R_{N-1} \le \eta_{N-1}^{\lambda},\ldots,R_1 \le \eta_1^{\lambda}\}\cdot\text{Prob}\left\{R_{N-1} \le \eta_{N-1}^{\lambda},\ldots,R_1 \le \eta_1^{\lambda}\right\} = \\ =\prod_{j=2}^{N}\text{Prob}\{R_j \le \eta_j^{\lambda}|R_{j-1} \le \eta_{1j-}^{\lambda},\ldots,R_1 \le \eta_1^{\lambda}\}\cdot\text{Prob}\left(R_1 \le \eta_1^{\lambda}\right) \tag{3}$$

Since neighboring R_j dependencies are not always insignificant in reality, the a single-step (level of conditioning $k = 1$) memory approximations that follows is presented.

$$\text{Prob}\{R_j \le \eta_j^{\lambda}|R_{j-1} \le \eta_{j-1}^{\lambda},\ldots,R_1 \le \eta_1^{\lambda}\} \approx \text{Prob}\{R_j \le \eta_j^{\lambda}|R_{j-1} \le \eta_{j-1}^{\lambda}\} \tag{4}$$

With $2 \le j \le N$ (conditioning level $k = 2$), the approximate result provided by Eq. (4) may be precisely stated as

$$\text{Prob}\{R_j \le \eta_j^{\lambda}|R_{j-1} \le \eta_{j-1}^{\lambda},\ldots,R_1 \le \eta_1^{\lambda}\} \approx \text{Prob}\{R_j \le \eta_j^{\lambda}|R_{j-1} \le \eta_{j-1}^{\lambda},R_{j-2} \le \eta_{j-2}^{\lambda}\} \tag{5}$$

wherein $3 \le j \le N$ (the conditioning level $k = 3$), etc. The later derivation's primary goal was to avoid locally inter-correlated exceeds from cascades or clustering by recording each individual failed or hazard that happened directly initial and on time, (Gaidai et al. 2023b, 2022f, 2022g, 2023c, 2023d, 2023e, 2023df; Gaidai et al. 2023g, 2023h, 2023i, 2023j, 2023k). Updates to the statistical independence assumptions in Eq. (5). The latter category of approximations enables a more precise representation of statistical dependence effects among neighboring maxima. Assuming that the first MDOF process, $\boldsymbol{R}(t)$, is ergodic and thus stationary, the probability $p_k(\lambda) := \text{Prob}\{R_j > \eta_j^{\lambda}|R_{j-1} \le \eta_{j-1}^{\lambda},R_{j-k+1} \le \eta_{j-k+1}^{\lambda}\}$ for $j \ge k$ is dependent on the conditioning level k and independent of j. Consequently

$$P_k(\lambda) \approx \exp\left(-N\cdot p_k(\lambda)\right), k \ge 1. \tag{6}$$

Equation (6) deviates from Eq. (1) by eliminating $\text{Prob}(R_1 \le \eta_1^{\lambda}) \approx 1$, as $N \gg k$ and the expected failure/hazard probability needs to be modest. It is rather obvious that there is converging with respect to the level of conditioning k

$$P = \lim_{k\to\infty} P_k(1); p(\lambda) = \lim_{k\to\infty} p_k(\lambda) \tag{7}$$

With a non-exceedance probability connection, Eq. (6) for $k = 1$ yields the commonly used means up-crossing rates function as well.

$$P(\lambda) \approx \exp\left(-\nu^{+}(\lambda)\,T\right); \nu^{+}(\lambda) = \int_0^{\infty}\zeta p_{R\dot{R}}(\lambda,\zeta)d\zeta \tag{8}$$

The authors have proposed a unique approach for LTD assessment, which may reduce the expenses associated with experimentation, measurement, and calculation. This technique is particularly appropriate for a range of high-dimensional offshore environmental and energy systems. It may not always be practically sensible to estimate the joint PDF $p_{X_T^{\max},Y_T^{\max},Z_T^{\max},\ldots}$ of the target system, and thus the target dynamic system survival probability$P$, using sufficient lab measurement data or by conducting extensive direct (or enhanced) MC simulations when the number of degrees of freedom of the environmental or offshore energy dynamic system is large (Gaidai et al. 2023l, 2023m, 2023on 2023o, 2023p, 2023q, 2023r, 2023s, 2023t, 2023u, 2023v, 2024a). Following Eq. (1), it is simple to determine the damage/hazard/failure risk/probability P_{failure} of a system as well as the predicted L_{expected} of a connected dynamic system from the lifespan CDF distribution $\text{LTD}(L)$ of an underlying dynamic system.

$$\frac{T}{P_{\text{failure}}} = L_{\text{expected}} \equiv E[L] = \int_0^{\infty} L d\text{LTD}(L) \tag{9}$$

having the damage/failure/hazard risk/probability of the system$P_{\text{failure}} = 1 - P$, which is supplementary to the longevity probability P of the dynamic system. The dynamical technology is now considered to have failed or been damaged instantly (or to have reached a hazardous condition), if either of its critical components$X(t)$, or$Y(t)$, or $Z(t)$ etc., once exceededη_X, orη_Y, orη_Z, etc., respectively. Fixed damage/hazard/failure levelsη_X,η_Y ,η_Z,... this is determined for each 1D system separately dynamic system critical components$X_{N_X}^{\max} = \max\{X_j\,; j = 1, \ldots, N_X\} = X_T^{\max}$,$Y_{N_Y}^{\max} = \max\{Y_j\,; j = 1, \ldots, N_Y\} = Y_T^{\max}$,$Z_{N_z}^{\max} = \max\{Z_j\,; j = 1, \ldots, N_Z\} = Z_T^{\max}$, ... Dynamic system's 1D critical components $X, Y, Z, \ldots$ being now re-scaled, and non-dimensionalized

$$X \to \frac{X}{\lambda\eta_X}, Y \to \frac{Y}{\lambda\eta_Y}, Z \to \frac{X}{\lambda\eta_X}, \ldots \tag{10}$$

making all dynamic system's components non-dimensional, and having same target hazard/failure limits, when $\lambda = 1$, with dynamic system's target damage/hazard/failure risk/probability $P = P(1)$. $P(\lambda)$ to be a normal function of the inserted non-dimensional levels may be defined using Eq. (9).

The localized maxima of the 1D dynamical system's critical component are then combined to form the 1D temporally not declining systems vector $\boldsymbol{R}(t) \equiv \overrightarrow{R} = (R_1, R_2, \ldots, R_N)$ in line with the merging temporal-vector $t_1 < \cdots < t_N$, $N \leq N_X + N_Y + N_Z + \ldots$, of the associated dynamic system. The local maxima of R_j for each dynamical system component, which are associated with $X(t)$ or $Y(t)$, or $Z(t)$, or any other dynamic system's crucial component, are actually confronted by the local maxima of the dynamical or environmental system's crucial components, [Gaidai et al.]. It is absolutely essential to note that the generated synthetic 1D $\overrightarrow{R}$ -vector has an overall 0 (zero) losses on the data set. Having now introduced increasing in time, synthetic system 1D vector $\overrightarrow{R}$, along with its increasing occurrence time instants $t_1 < \cdots < t_N$, the LTD random variable L may be now presented as

$$L_i = t_i - t_{i-1} \tag{11}$$

for $i = 2, \ldots, N$. Hence, composed 1D synthetic dynamic system process $\boldsymbol{R}(t)$ holds a key information about the target dynamic system LTD. Survival probability $P = P(1)$ may be expressed via associated mean up-crossing-rate-function

$$P(\lambda) \approx \exp\left(-\nu^{+}(\lambda)\,T\right);\ \nu^{+}(\lambda) = \int_{0}^{\infty} \zeta p_{R\dot{R}}(\lambda,\zeta)d\zeta \tag{12}$$

with $\nu^{+}(\lambda)$ being the mean up-crossing-rate of damage/limit/failure threshold level λ for the above discussed synthetic non-dimensional structure vectors $R(t)$ in 1D. The Rice formula is used to express the mean of the up-crossing-rate-function in Eq. (12), where $p_{R\dot{R}}$ represents the combined PDF for $\left(R,\dot{R}\right)$ and $\dot{R} = R\prime(t)$ is the appropriate time-derivative (if it is easily distinguished), (Wang et al. 2012; Wu et al. 2022; Xu et al. 2018; 2019; 2023; Yakimov et al. 2023). When $\lambda \to 1$, a dynamic system will get closer to its specified damage, failure/hazard state

$$\lim_{\lambda\to1}P_{\text{failure}} = \frac{T}{L_{\text{expected}}} = \nu^{+}(\lambda)\,T \Rightarrow L_{\text{expected}} = \frac{1}{\nu^{+}(1)} \tag{13}$$

in line with Eq. (12). Here, we suppose that the MDOF dynamical system is jointly-stationary. Each unique environmentally short-term environment phase has a distinct probability q_m and $\sum_{m=1}^{M} q_m = 1$ considering an in-situ environmentally scatter-diagram having $m = 1,..,M$ environment-sea-states. The conventional long-term probabilities the equation is that

$$\text{LTD}(L) \equiv \sum_{m=1}^{M} LTD_m(L)q_m \tag{14}$$

Having $p_k(\lambda,m)$ denoting the same functions that are used in Eq. (6), and m standing for a particular short-term surrounding sea condition. The next section will provide examples of how the relevant LTD $q-$ quantiles

$$L_q = \text{LTD}^{-1}(q) \tag{15}$$

may be evaluated using the Poisson assumptions and $q \in (0,1)$ from the observed or simulated timeseries of the fundamental dynamic systems. Function LTD^{-1} is the LTD function's inverse, or LTD $\text{LTD}^{-1} = 1$, where $^{\circ}$ denotes functional composition and 1 is the identity operator. The dynamic system's breakdown, risk, and danger events become almost independent at high or severe damage, collapse, and hazardous levels. As a result, the system's lifespan PDFs closely resemble the distribution of Poisson, with parameter $\nu^{+}(\lambda)\,T$. Although this research's primary foundation is the previously mentioned Poisson procedures concept, it may have broader applicability if dynamic system critical components that are approaching breakdown or hazards levels do not indicate an impending system breakdown or destruction; rather, they merely reflect streaming critical/damaging inter-correlated/clustered actions. The PDF-tail extrapolation method is based on an improved (4-parameter) Weibull extrapolation technique, (Yakimov et al. 2023a; 2023b; Yan and Gu 2010; Yoo et al. 2022; Yue et al. 2020; Zhang et al. 2016a; 2016b).

Table 2 lists main benefits of the advocated Gaidai risk assessment methodology.

Classic reliability methods being mostly restricted to 2D, whereas Gaidai risk assessment methodology having no restriction on NDOF, (Zhang et al. 2019; 2023; Zhao et al. 2014; 2017; 2018a; 2018b).

Table 2 Gaidai multivariate risks evaluation methodology benefits, NDOF = Number Degrees Of Freedom

	Gaidai multivariate risks evaluation methodology	Classic 1D/2D reliability/risk assessment methods
Potential to study complex nonlinear multivariate systems	NDOF=∞ D	NDOF $\leq$ 2D
Potential to fully account for system's non-linearities	Full	Partial/full
Potential to analyze systems with defect/degradation	Full	Partial

Discussion and results

Research on the SBS dynamics of the floating multi-objects system has been reported recently in a number of publications. Authors in Liu and Falzarano (2019) have investigated the coupling effects and hydrodynamic interaction of two floating platforms, and findings revealed considerable differences in roll and sway between exact and approximation solutions. Using the SIMO software tool, the authors of Zhao et al. (2014) examined the hydrodynamics for LNG carriers and found that the stiffness and hawser pretensions of the system had an impact on the entire hydrodynamic reliability of the dynamical SBS offloading system. Given the in situ environmental circumstances of the Caspian Sea, scholars in Tafazzoli et al. (2021) investigated the hydrodynamic interactions between the FPSO and its ST using the boundary-element approach. Employing potential flow theory-based techniques, the authors of Liu and Falzarano (2019) proposed a wall-damping approach for SBS offloading operational gap prediction. The damping lid technique was utilized in Yue et al. (2020) to study the hydrodynamic associations of the LNG SBS dynamic mooring system with the FSRU (i.e., Floating Storage and Regasification Unit), and the findings showed good agreement with existing experimental data. Potential flow theory was used by the researchers in Zhao et al. 2018a to evaluate gaps resonant. Authors examined LNG-FPSO parameter optimization in Tannuri et al. (2021) by combining neural network technology with optimization techniques. Using an improved Weibull approach, the authors of Gaidai et al. (2021) looked at the excessive hawser stresses of the FPSO along with ST. Research has shown that potential theory of flow is both feasible and useful for modelling the dynamic SBS offloading mechanism that operates between the FPSO along with its shuttle's carrier. Consequently, this research also used the potential flow theory-based programmed AQWA to investigate high hawser tensions that arise during SBS offloading procedures. In order to conduct a series of MC numerical models for the offloading operating process between the FPSO and its ST, this research made use of the potential flow-based software programmed AQWA for both the time and frequency domains; for additional information, consult the AQWA instructions, (AQWA theory manual 2013).

This Section offers an example of the above-mentioned procedure in action. Provided head wind-wave direction, 4 different most critical FPSO internal hawser tension forces (H_1,.., H_4, shown in Fig. 3) had been selected, as system's critical components X, Y, Z, W providing an illustration of a 4-dimensional dynamics vessel systems. FPSO numerical simulations had been performed with fine discrete time-step $dt = 0.2$ seconds, see Fig. 5. For other load cases with different wind-wave directions, critical hawser set, as

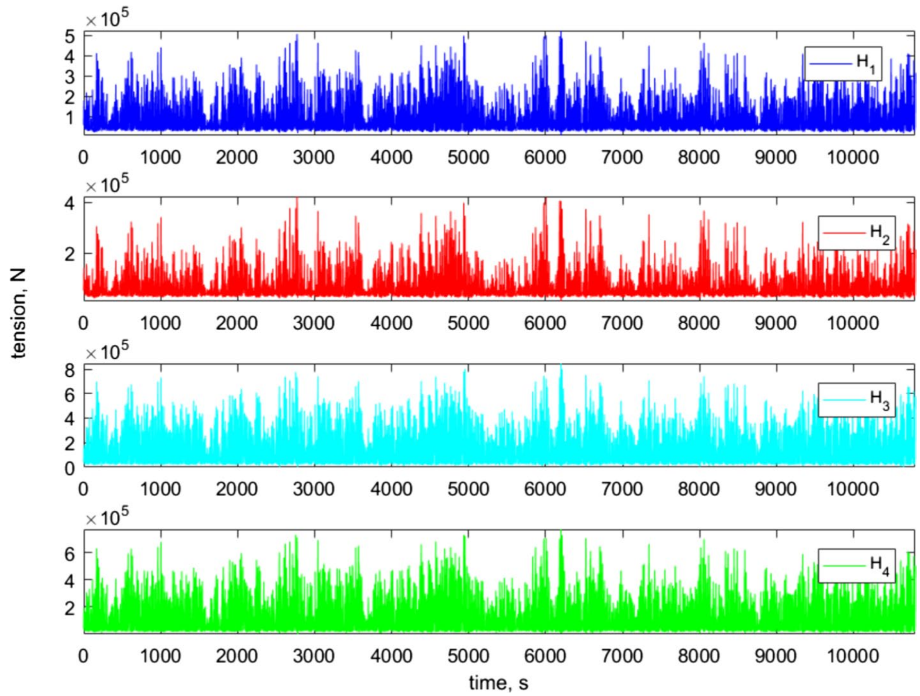


Fig. 5 $H_1, \ldots, H_4$ hawser tensions sample timeseries

well as number of critical hawsers will obviously vary—the latter however will not alter applicability of the suggested methodology. Note that this is methodological study—hence there was no objective to cover all possible load cases (including wind-wave directions), therefore only few head wind-wave direction had been studied.

For simplicity the global maxima of each hawser 1D tension force, had been taken as its critical/limit/risk thresholds, causing the whole FPSO hawser system to be damaged or fail. To bring all four measured underlying timeseries together X, Y, Z, W, following scaling has been carried out, following Eq. (6), making all 4 vessel system's critical components non-dimensional, having the same failure/hazard/risk limits, equal to 1. Next, all local maxima from 4 measured timeseries have been merged into 1D single timeseries, by keeping them in a temporally increasing order: $\vec{R} = (\{X_1, Y_1, Z_1, W_1\}, \ldots, \{X_N, Y_N, Z_N, W_N\})$ with the whole synthetic vector $\vec{R}$ being sorted, according to the non-decreasing times of occurrences of these assembled dynamic system component's local maxima, with NDOF $\equiv N = 4$, (Zhang et al. 2019, 2023, 2016b; Buchner et al. 2001; AQWA user's manual 2013; AQWA theory manual 2013; Naciri et al. 2007; Zhao et al. 2017, 2018a, 2014, 2018b; Vieira et al. 2018; Wang et al. 2012; Jin et al. 2019; Koo and Kim 2005; last accessed January 2024; OCIMF, Oil 1994, 2007; Lv et al. 2014; Yoo et al. 2022; DNV-RP, D. N. V. 2010; Veritas 2012, 2011; ABS 2011; Design 2005; Xu et al. 2019, 2023, 2018; Balakrishna et al. 2022; Fan et al. 2014; Gaidai et al. 2021, 2022a, 2022b, 2022c, 2022d, 2022e, 2023a, 2023b, 2022f, 2022g, 2023c, 2023d, 2023e, 2023df; Gaidai and Xing 2022; Gaidai et al. 2023g, 2023h, 2023i, 2023j, 2023k, 2023l, 2023m, 2023on 2023o, 2023p, 2023q, 2023r, 2023s, 2023t, 2023u, 2023v, 2024a, 2024b, 2024c, 2024d, 2024e, 2024f, 2024g, 2024h; Failed 2024; Gaidai 2024; Jian et al. 2018; Liu and Falzarano 2019; OCIMF, Oil Company International Marine

Form 2013; Qian et al. 2014; Tannuri et al. 2021; Tafazzoli et al. 2021; Stansberg et al. 2002; Sun et al. 2023, 2023a; Yakimov et al. 2023, 2023a; Yakimov et al. 2023b; Yan and Gu 2010; Yue et al. 2020).

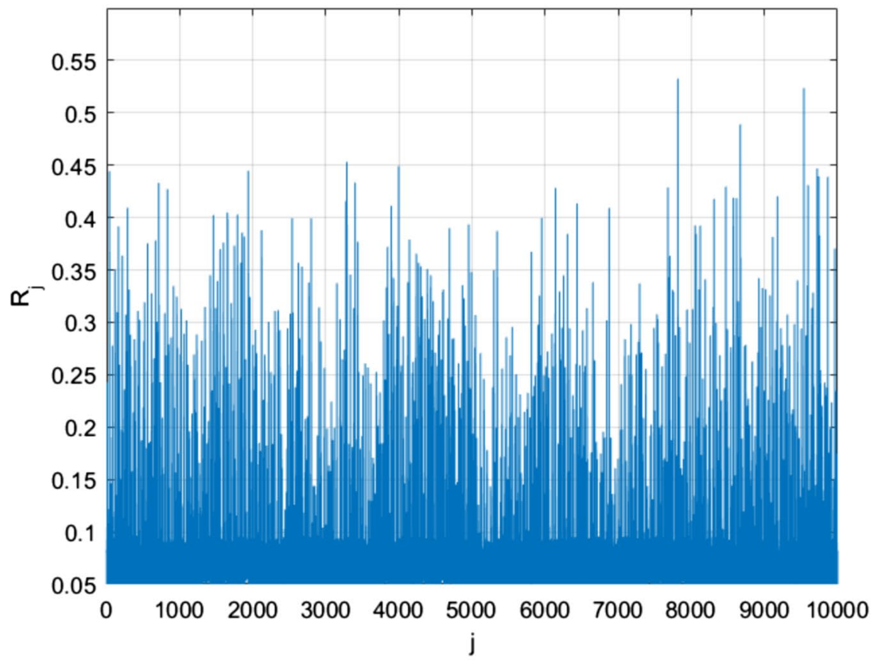
A non-dimensional constructed system's 1D vector $\overrightarrow{R}$, represented by the local maxima of the constructed system's critical components and determined FPSO hawser tension forces, is shown in Fig. 6a. The $\lambda > 0.05$ cut-on constrain has only been used as a demonstration because lower values $\lambda \geq 0$ are obviously not relevant for extrapolating the damage/failure/hazard PDF tail regarding the desired level $\lambda = 1$. Because 1D synthetic vectors $\overrightarrow{R}$ is made up of many important components of the system, it should be noted that it might not have any physical significance by itself. Just a running index of the local maxima from the dynamic system component observed in the expanding temporal sequence is represented by index j. The estimated 95% CI for the goal dynamic system survival probability $P(\lambda)$ is shown by dot-lines in Fig. 6b. Figure 6b exhibits quite narrow 95% CI, the latter being a clear advantage of the advocated approach. For the target hazard/failure/damage level $\lambda = 1$ mean-up-crossing-rate $P(\lambda) \approx \exp\left(-\nu^{+}(\lambda)\,T\right)$ have been extrapolated, one may conclude, that target dynamic system's LTD follows the homogeneous Poisson's distribution, having Poisson parameter $\nu^{+}(\lambda)\,T$, with $\nu^{+}(1)$ being mooring system's failure/hazard rate, measured in years^{-1}. Expected dynamic system's LTD being then $L_{\text{expected}} = \frac{1}{\nu^{+}(1)}$ following Eq. (9).

Extrapolation in Fig. 6b highlights CPU cost reduction, when using advocated methodology. It is seen that extrapolation in the PDF tail was done l orders of magnitude down on the decimal logarithmic scale, $l > 2$. Since N-dimensional MDOF system has been analyzed with $N = 4$, the total cost reduction will be $n \cdot l$ decimal orders of magnitude. Figure 6b visually illustrates 95% CI, uncertainty is roughly speaking inversely proportional to the dataset size and quality, thus it does not originate from the advocated method itself, as proposed method being exact.

To summarize results:

- Classical reliability methods mostly deal only with system's unidimensional components, which even being critical, do not fully reflect multi-dimensionality of the whole system. Moreover, only expected lifetime E[LTD] being given.
- Advocated Gaidai risk assessment methodology, on the contrary, tackles nonlinear multivariate dynamic system as a whole, accounting for complex inter-correlations between different systems' critical components. The latter approach will lead to a more conservative design estimate of the system's projected lifetime. Moreover, Gaidai risk assessment methodology supplies full LTD (i.e., Life Time Distribution), instead of only single expected lifetime value E[LTD].

Advocated methodology being designed for multi-dimensional nonlinear dynamic systems, when direct MC methods may become simply unaffordable. As mentioned above, the key novelty of Gaidai risk assessment methodology being its ability to treat complex nonstationary systems with practically unlimited number of critical components/dimensions. To author's knowledge there are no alternative multivariate risk assessment methods that can treat systems with number of dimensions higher than 2, hence the only validation that can be done is versus direct MC simulations. For the a)



b)

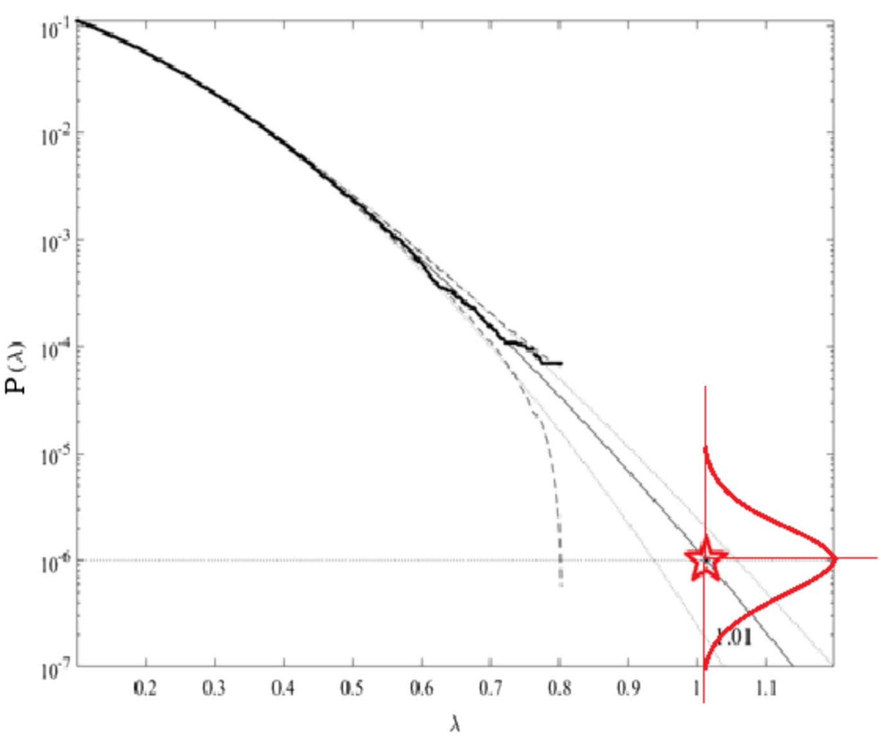


Fig. 6 **a** Example of dimensionless assembled system vector $\overrightarrow{\boldsymbol{R}}$. **b** Extrapolation of $\boldsymbol{P}(\boldsymbol{\lambda})$ towards the critical/hazard/damage level (red star). Extrapolated 95% CI marked with 2 dotted-lines. Rotated red plot illustrated LTD PDF

latter sake of method's validation, the original data sample size had been reduced 10 times, by keeping only each 10th datapoint, then predictions by Gaidai risk assessment method have been compared with the original raw/full dataset, and quite close estimates have been obtained. Regarding future work, nonstationary systems, especially systems with initial damage will be studied by applying Gaidai risk assessment methodology. Regarding proposed methods validation versus alternative reliability/risk assessment methods, to author's knowledge there are no available general purpose reliability methods, suitable for systems with dimensionality higher than 2, $N > 2$. Hence only extrapolation itself can be validated, but any extrapolation method can be plugged into by Gaidai risk assessment methodology.

Conclusions

Contemporary timeseries risk assessment approaches being often unable to take into account nonlinear cross-correlations between high-dimensional environmental and offshore energy system's critical components. Suggested methodology's key benefit lies within its robust capacity to assess complex dynamic system lifetime distribution, especially for high-dimensional nonlinear offshore engineering and environmental systems. This study examined FPSO mooring system dynamics, under realistic in-situ environmental loads. Brief note on experimental validation has been provided. Dynamic system service lifetime distribution, assessed throughout the whole course of intended design lifespan, has been accurately estimated, using novel Gaidai system's risk assessment approach. Theoretical underpinning of the advocated methodology has been briefly presented. Although direct measurements, as well as extensive MC simulations being attractive methods to assess complex dynamic systems risk assessment, high-dimensional dynamic systems necessitate development of novel, accurate, yet reliable risk assessment approaches, that can reduce necessary underlying dataset size, yet optimize its usage. Methodology, advocated in this study has previously shown quite effective, when employed for a large variety of simulation models, but only for one-dimensional dynamic system components. To summarize key findings:

- Main objective of this study was to provide a multi-dimensional, multi-purpose, spatiotemporal, yet user-friendly environmental and offshore energy system's risk assessment approach. As has been shown, the proposed Gaidai risk assessment methodology yielded reasonably narrow confidence intervals.
- Suggested methodology could be well useful for complex risk assessment evaluations of various nonlinear environmental and offshore dynamic systems. Provided offshore engineering example restricts in no way potential use of the novel methodology.
- Future studies will include more complex nonstationary dynamic systems, for example systems with initial manufacturing imperfections or with fatigue crack propagation. For that purpose, system component's limits within advocated methodology should be made slowly variable with time.

Primary limitation of the presented multivariate risk assessment methodology lies within assumption of system quasi-stationarity. In case of non-stationary systems, with strong underlying trend, e.g., system degradation, one has to identify trend first, before applying advocated methodology.

Abbreviations

CDF	Cumulative Distribution Function
CFD	Computational Fluid Dynamics
CI	Confidence Interval
FEM	Finite Element Method
FPSO	Floating Production Storage and Offloading
FSRU	Floating Storage and Regasification Unit
GEV	Generalized Extreme Value
LNG	Liquid Natural Gas
LTD	Life Time Distribution
MC	Monte Carlo
MDOF	Multi-Degree-Of-Freedom
PDF	Probability Density Function
SBS	Side-By-Side
ST	Shuttle Tanker

Author contributions

O. Gaidai—conceptualization, Y. Cao—data analysis, A. Ashraf—software, J. Sheng—visualization, Y. Zhu—validation, Z. Liu—project management.

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Data availability

Data will be available on request from the corresponding author.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publications

Not applicable.

Competing interests

Authors declare no competing interests.

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