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RESEARCH ARTICLE

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Floating production storage and offloading systems' cost and motion performance: A systems thinking application

Abstract Floating production storage and offloading (FPSO) units increasingly represent a practical and economic means for deep-water oil extraction and production. Systems thinking gives a unique opportunity to seek a balance between FPSO technical performance(s), with whole-cost; stakeholder decision-making is charged to align different fit-for-use design specification options' that address technical-motion(s), with respective life-cycle cost analyses (LCCA). Soft system methodology allows situation based analyses over set periods-of-time by diagnosing the problem-at-hand; namely, assessing the antecedents of life-cycle cost relative to FPSO sub-component design alternatives. Alternative mooring-component comparisons for either new-build hulls or refurbished hulls represent an initial necessary consideration to facilitate extraction, production and storage of deep-water oil reserves. Coupled dynamic analysis has been performed to generate FPSO motion in six degrees of freedom using SESAM DeepC, while life-cycle cost analysis (LCAA) studies give net-present-value comparisons reflective of market conditions. A parametric study has been conducted by varying wave heights from 4 – 8 m to understand FPSO motion behavior in the presence of wind and current, as well as comparing the motions of turreted versus spread mooring design alternatives. LCCA data has been generated to compare the cost of such different mooring options/hull conditions over 10 and 25-year periods. Systems thinking has been used to explain the interaction of problem variables; resultantly this paper is able to identify explicit factors affecting the choice of FPSO configurations in terms of motion *and* whole-cost, toward assisting significantly with the front-end engineering design (FEED) phase of fit-for-purpose configured FPSOs, in waters off Malaysia and Australia.

Keywords FPSO, LCCA, spread/turret-mooring, DeepC, cost, motion, soft-systems

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1 Introduction

Floating production storage and offloading (FPSO) units are increasingly the oil and gas industry's preferred deep-water oil-extraction platforms. Feasibility studies for a FPSO project must necessarily involve motion performance analyses, as well as, ideally, cost-comparisons of such hull condition and mooring system alternatives. Currently there is a lack of communication between design and costing departments, and resultantly a mismatch of problem-variable identification and unaligned solutions at the important decision-making stage. Design engineers are uncertain of the extent to which whole-cost knowledge applications might influence respective fit-for-use options' comparisons. This confusion lends itself to a soft-systems methodology which can be argued as able to help stakeholders toward a holistic approach that combines a philosophical-*what* with a technical-*how* (Checkland, 1981).

Problem analyses here must embrace both a cost effective and a best-performing FPSO design. Typically, confusion arises over (weighted) interdependence considerations; in this case, coupled dynamic analyses of six FPSO motions (yaw/heave/pitch/sway/roll/surge, as shown in Fig. 1) require examination alongside, FPSOs LCCA comparisons of new-build/converted hull(s) and

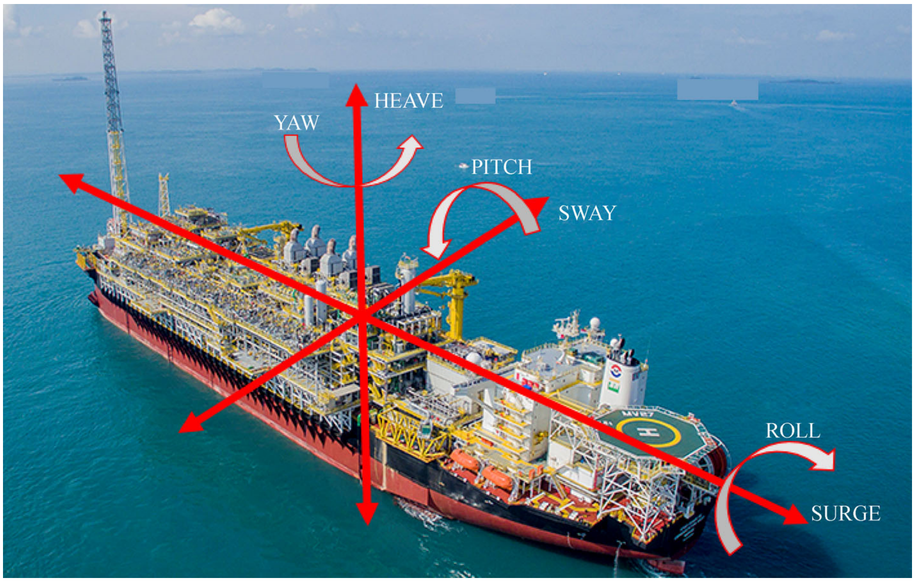

Fig. 1 Six motions (yaw, heave, pitch, sway, roll and surge) of FPSO
(Motion superimposed upon FPSO Image sources from MODEC)

different respective turret-mooring and spread-mooring design-specification options. Addressing these problems goes toward an identification of the relationship between cost and motion responses of FPSOs, to assist in deciding optimum facilities for oil-exploitation off the waters of Australia and Malaysia. The need for this study stems from the mounting number of converted FPSOs in these regions, notably either external-turret, internal-turret or riser-turret mooring, and stakeholder confusions regarding an objective optimum solution.

In coastal Australia, out of the 10 operating FPSOs, 7 are converted tankers, whist off Malaysia, all the operating FPSOs (5 FPSOs) are converted tankers (Barton et al., 2017); choice between options (relative to motion and cost) is argued as largely subjective. This study addresses this gap through systems thinking.

During the conversion of FPSOs, retention of existing hulls are complemented by commonplace replacement of elements (Mattos and Mastrangelo, 2000); after conversion, replacement of mooring-systems, usually turret-mooring, is typical toward increased resistance to environmental loads. Anecdotally, mooring-system multiple periodic replacements can be costlier when compared to manufacturing new purpose-built vessels. Since the CAPEX of the mooring system is high when compared to that of the hull, a life-cycle cost study for the various FPSO hull-mooring combinations (also addressing yaw/heave/pitch/sway/roll/surge off Australia/Malaysia) were conducted.

One of the major barriers in doing a life-cycle cost study is the absence of sufficient data (Al-Hajj, 1991), especially in the oil and gas industry where commercial confidentiality is particularly high (Ahiaga-Dagbui et al., 2017). Sometimes ‘unreal’ variables can put the findings generated through LCCA in doubt (Ferry and Flanagan, 1991), hence, proper care should be taken to reduce the uncertainty in results (Ashworth, 1996). The data gathered in this study seeks to alleviate such concerns by addressing explicit metocean conditions, specifically for FPSOs component/subcomponent specifications.

The current knowledge gap is filled here by doing a motion response study to evaluate FPSO performance (alongside addressing whole-cost criteria within a soft-system approach). Technical assessment below addresses (a currently incomplete) understanding of the nonlinearities associated with the effect of random waves on FPSOs; these are complex, as FPSOs have a ship-like form with one axis of symmetry and sometimes the waves, winds and current can be non-parallel, with high wave-heights subjecting vessels to quartering or beam-seas that can significantly influence the response of a ship-shaped vessel, with related knock-on life-cycle operation and maintenance cost considerations.

Hence the primary objective of this study is to establish the factors affecting the choice of efficient FPSO options by correlating their cost and motion via systems thinking. In this study Australian and Malaysian offshore locations are identified as areas of interest, and respective site-specific motion response calculations and life-cycle cost analyses are presented.

Results below justify LCCA input along with motion response studies, as essential to the front-end engineering-design *FEED*-phase of sustainable design and future decommissioning.

The paper describes explicit technical problem-solving, alongside assistance for managers in using a systems thinking view to identify the factors contributing to the problem-at-hand, establish respective interrelationships, and recognize underlying patterns over time to ease the decision-making process.

2 Literature review: LCCA/SSM

2.1 Life-cycle cost analysis (LCCA)

Life-cycle costing analysis of offshore structures is an increasing requirement. Gratsos et al. (2009) investigated ship design, through cost/benefit analysis related to the average annual cost of ship transport variance, with (progressive) corrosion. The results of this study indicated that ships built with corrosion allowances, dictated by experience of the ship's design life when all factors have been considered, have a lower life-cycle cost per annum related to respective maintenance of the integrity of offshore structures.

Howell et al. (2006) discussed the various factors affecting the CAPEX and OPEX of turret moored and spread moored FPSOs and the technical issues related to the design of a mooring system. They sought the NPV for a spread moored FPSO and a turret moored FPSO in Brazil with 10.5% discount rate. However, a detailed whole-cost estimate was not given. They affirmed that in addition to the CAPEX of both specification systems, differences exist in terms of motion and offloading performance.

Kayrbekova (2011) performed LCCA to compare maintenance cost of an oil and gas production facility in the sensitive environment of Arctic, implementing different technical solutions; however of the whole life-cycle, only the maintenance phase was considered. Nam et al. (2011) developed a new life-cycle cost methodology with risk expenditure taken in to account for comparative evaluation of offshore process options at a conceptual design stage. The risk expenditure consisted of the failure risk and accident risk expenditures. The former accounted for production loss with maintenance expense deemed due to equipment failures, while the latter reflected asset damage and the fatality worth caused by disastrous accidents such as fire and explosion. This work demonstrated that LCCA methodology can begin to assist with process selection toward choice of best (in this case liquefaction) process options, for power generation systems for floating LNG (Liquefied natural gas) production facilities.

Thalji et al. (2012) conducted a case study on innovative vertical axis wind turbine concepts to generate a scalable and customer oriented life-cycle costing model. Their cost analysis of wind turbine concepts covered the whole life process, manufacturing, installation, operating and maintenance. Santos et al. (2013) developed a theoretical methodology to study the life-cycle cost of floating offshore wind farms. Six life-cycle phases, needed to install a floating offshore wind farm, were defined: Conception and definition; design and development; manufacturing; installation; exploitation; and, dismantling. They suggested such a methodology could be used to calculate the 'real' cost of constructing floating offshore wind farms.

Recently, Kurniawati et al. (2016) evaluated the long-term charter rate in volatile or uncertain conditions for FPSOs, by a capital budgeting principal where NPV was an evaluation criterion. Miranda et al. (2018) derived a target reliability index for FPSOs for ultimate limit state designs of turret mooring lines for hypothetical tanker dimensions; a life-cycle cost model was used to optimise disconnection criteria by counting failure instances due to green water, hull and mooring-lines, to advise design criteria. However, results couldn't be generalized as cuts to life-cycle expenditures occurred when optimisation criteria were implemented (Miranda et al., 2018).

Research into LCCA of FPSOs is somewhat piecemeal and limited at present, with no work found to report NPV variation when different types of turret mooring are used across different, converted versus new-built, FPSO hulls. Industry's current need to compare such technical variables in terms of whole-cost represents a gap, which lends itself to a more holistic problem analysis, through soft system thinking.

2.2 Soft systems methodology (SSM): Applications in (construction) management

The systems thinking concept seeks to provide clarity in situations where management situations become complex (Checkland, 2000), and is a methodology which allows the user to take situation based decisions (Watson, 2012).

There is no strict rule in systems thinking applications (Checkland and Scholes, 1990). The very nature of systems thinking, makes it useful where management (problem-identification and decision-making) difficulties are prevalent. Systems thinking concepts have been previously applied in construction projects where uncertainties prevail (Li and Love, 1998). Recent applications include developing conceptual frameworks for construction process protocols (Farag et al., 2016). FPSO SSM applications are not known, and to this end this work is somewhat uniquely exploratory.

Choice of FPSO specifications, based on motion and whole-cost can be given clarity through an application of systems thinking, since management must balance, on the one-hand technical solutions for motion response analyses (solvable through detailed technical examination of site specific metocean data and structural details), with on the other-hand the respective whole-cost(s) of FPSO options effectiveness.

FPSO systems thinking is applied here to facilitate problem clarification and design consideration relative to human judgement, experience, knowledge gap identification and decision-making skill-sets.

3 Methodology

Systems thinking is applied here toward amplification of the problem at-hand in balancing whole-cost with motion-performance of FPSOs; the seven steps of soft systems methodology (Fig. 2 below) are embraced.

The systems thinking concept does not require strict compliance with procedures or rules and encourages a situation to be examined from different viewpoints; effectively, this cost/motion relationship is explored through extending available literature/data sets toward deeper understanding and observations answering FPSO performances' 'what, why and how' (Checkland and Scholes, 1990).

The advantage of embracing a soft systems methodology lies mainly in its flexible, unstructured approach, since whole-cost information is currently largely unaligned with specification context; the confidential nature of cost/whole-cost data (if at all available) compounds solutions development and any final decision-making process, where silo-mentality can separate technical-design and cost expertise.

SSM allows engineers to advise final specification selection for FPSO design that provides fit-for-use performance, within whole-cost expectations at the FEED phase of a project.

Figure 2 below lists the steps; initially expressing the problematical situation regarding the choice of efficient FPSO options in terms of cost and motion and collection of (foundation literature review) data pertaining to the problem. The second step is to give a structure to the problem through a research proposal or summary to define the problematical situation. Thirdly, root definitions allow adoption of a research methodology. The fourth step involves building a conceptual model based on a single worldview, extending the research methodology of step-3. The fifth step assesses whether the conceptual model developed is based on the summary developed in step-2. Step 6 is used to rectify and to execute changes in the conceptual model and finally the seventh step (in Fig. 2 below) is the implementation stage where action is taken to solve the problematical situation of the extent to which coupled dynamic analysis alongside LCCA for FPSOs, off Malaysia and Australia, can identify best FPSO options in terms of cost and motion.

With an ultimate goal of an FPSO Front-End-Engineering-Design, a system thinking methodology to problem-antecedent interaction and decision-making, is presented in Fig. 3.

Incorporated within this SSM format scheme is an example of how an informed designer may align information generated in a more humanistic and flexible framework (adapted from Checkland and Scholes (1990) and Checkland (2000)).

3.1 Coupled dynamic analysis of FPSOs

To re-structure the problem, develop root definitions and go toward conceptual (FEED) modeling (defined within Fig. 2 and Fig. 3 below), a coupled dynamic analysis was performed to obtain an analysis of motion; namely, the 6 FPSO motions (of yaw/heave/pitch/sway/roll/surge, as shown in Fig. 1 above), under varying wave heights in the presence of wind and current, to understand the behavior of spread-moored FPSO and turret-moored FPSO motions. Relevant stages that develop SESAM programs and are given in Fig. 4.

SESAM programs were used to perform the numerical investigation of FPSO motion responses. Ship lines were generated in Rhinoceros 5 3D software and then imported to SESAM Genie V5.3-10 for, modifications and finite element mesh generation.

Response-amplitude-operations (RAOs) were obtained by performing a hydrodynamic analysis in SESAM HydroD V4.5-08 by giving finite element mesh from SESAM Genie V5.3-10 (Tn.FEM) as input. The RAOs generated were stored in the Hydrodynamic results interface file and eventually used for the time domain analysis in SESAM DeepC V5.0-06 along with the mesh generated in Genie. The time series plot for 6 DOF FPSO motions was obtained from the fully coupled dynamic analysis program SESAM Deep C V5. 0-06.

The SESAM simulation parametric study varied wave heights from 4 to 8 m on a case-study calibrated/validated Malaysian-waters FPSO (labeled here as BT FPSO with full-name withheld to ensure anonymity) using a verified modeling/simulation procedure (Nishanth et al., 2016),

Step-1: An un-structuring of the situation
Step-2: Re-structuring the problem at hand
Step-3: Developing root definitions
Step-4: Building conceptual models
Step-5: Comparing structures problems in step-2 to the conceptual model in step-4
Step-6: Defining changes after appropriate re-review
Step-7: Implementing action towards balancing FPSO coupled dynamic analysis & LCCA

Fig. 2 Seven steps of soft systems methodology

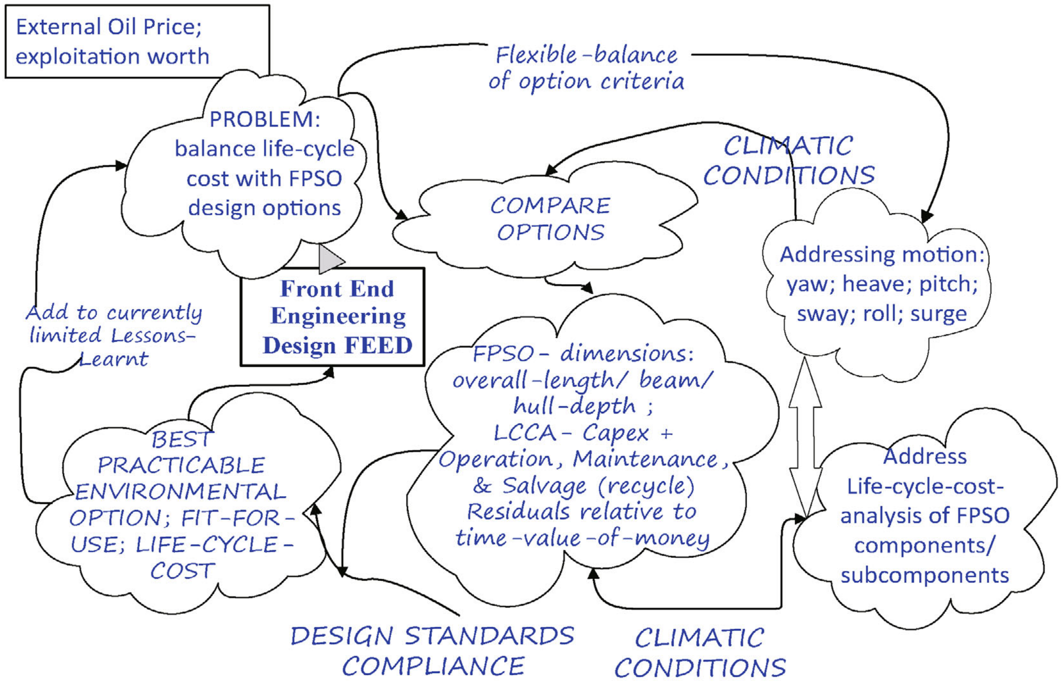

Fig. 3 FPSO Front-End-Engineering-Design FEED-phase: SSM flow-chart/framework (adapted from Checkland and Scholes (1990) and Checkland (2000)).

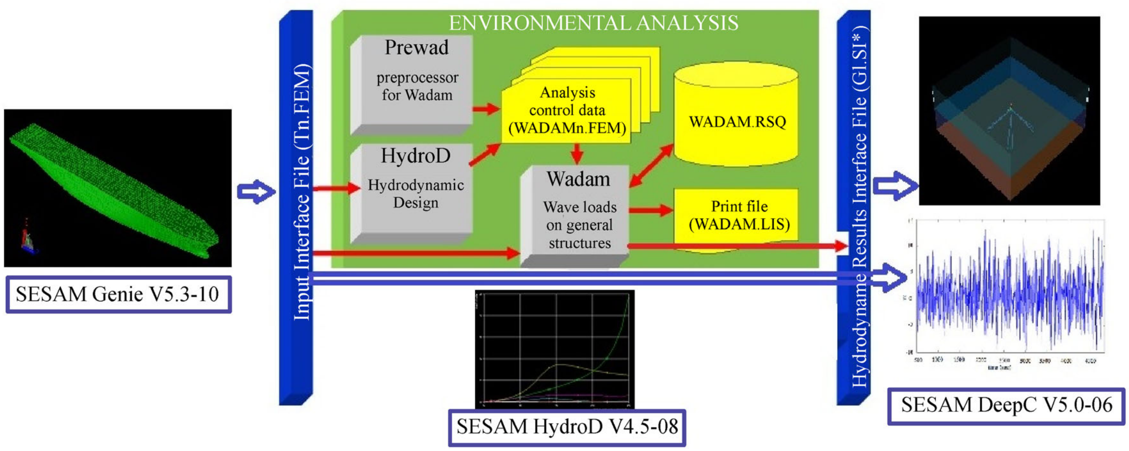

Fig. 4 Coupled dynamic analysis using SESAM Suit of programs

noting: dead-weight-tonnage of 58000 T; draft vertical waterline to hull-bottom distance 12.6 m; and, dimensions mentioned in Table 1.

Mooring-line details were chosen such that FPSO natural (rolling) periods were typical after free decay

Table 1 Case-study BT-FPSO dimensions

Dimension	Measurement	Unit
Overall length	207.4	m
Beam	32.2	m
Depth of hull	17	m

analysis in SESAM DeepC V5.0-06.

To study the effect of wave height on turret-moored and spread-moored FPSO configurations in crossing sea conditions under the influence of wind, unidirectional random waves and current, wave height was (as mentioned) varied from 4 to 8 m, while peak period(s) ranged from 5 to 25 s.

Wave height was not increased beyond 8 m as wave breaks at height$\leqslant$8 m for low wave periods (Chakrabarti, 1987; Muzathik et al., 2010); current-velocity was 4.38 m/s acting at 210°, wind-velocity was 36.91 m/s acting at 225° and the wave was directed at 225°.

3.2 Life-cycle cost analysis – LCCA of FPSOs

Embracing the soft-systems approach and to further restructure the problem, develop root definitions and go toward conceptual FEED modeling (as Fig. 2 and Fig. 3 above), a cost analysis was performed. Cost data in Australia and Malaysia was collated from reputable sources (Royal Institution of Chartered Surveyors, 2013; Wessex, 2013; Cordell, 2014; Petronas, 2014; Rawlinson, 2014; Wood-Mackenzie, 2014; Langdon and Seah, 2015; AECOM, 2017) to allow cost breakdown, extrapolation and comparisons of life-cycle costs of FPSOs with different mooring configurations and hull conditions, where the cost data generated is argued to allow region-specific indicative estimates.

The capital cost for project assets, operation and maintenance costs, and the residual scrap-value of hull steel were calculated necessarily to input into the life-cycle cost analyses; however, accidents, shut-downs, mooring-line breakages and (profit) benefits from oil production were excluded from this LCCA scope at this time.

The procedure adopted to calculate LCCA for FPSOs is shown in Fig. 5 below, albeit it is noted that the rigid graphical structure (of Fig. 5) for an identification of cost variables, sits somewhat at odds with soft-system expectations for humanistic soft-curved connections (Checkland, 2000) developed and described in Fig. 3 above to describe this particular problem's antecedent interactions.

The following equations are assessed where the Australian economy's inflation rate in 2017 can be taken as 1.3% from the Reserve Bank of Australia. Based on a reasonable 10-year yield, the treasury bond rate of return can be taken as 4.75%, with 13.6% as the average equity return rate from investment. Following the method specified by Royal Institution of Chartered Surveyors (Whyte, 2015) as shown in Eq. (1), the discount rate was calculated as 7.8%.

$$\begin{aligned} &\textit{Discount rate} \\ &= \textit{No risk return} + 0.5 \\ &\quad \times \textit{Average risk premium discount rate}, \end{aligned} \tag{1}$$

$$\begin{aligned} &\textit{No risk return} \\ &= \textit{Treasury bond rate of return} - \textit{Inflation}, \end{aligned} \tag{2}$$

$$\begin{aligned} &\textit{Average risk return} \\ &= \textit{Treasury bond rate of return} - \textit{Inflation}. \end{aligned} \tag{3}$$

Capital cost is counted in the zeroth (initial) year, while annual operation and maintenance cost is counted from the 1st year through-to *N*th year and finally the residual/(scrap) value is counted at the end-of-life *N*th year.

A discount-rate is essential to aid an understanding of the time-value-of-money such that, a dollar now is worth more than a dollar in the future. An empirical formula gives the discount rate based on the relevant input data as

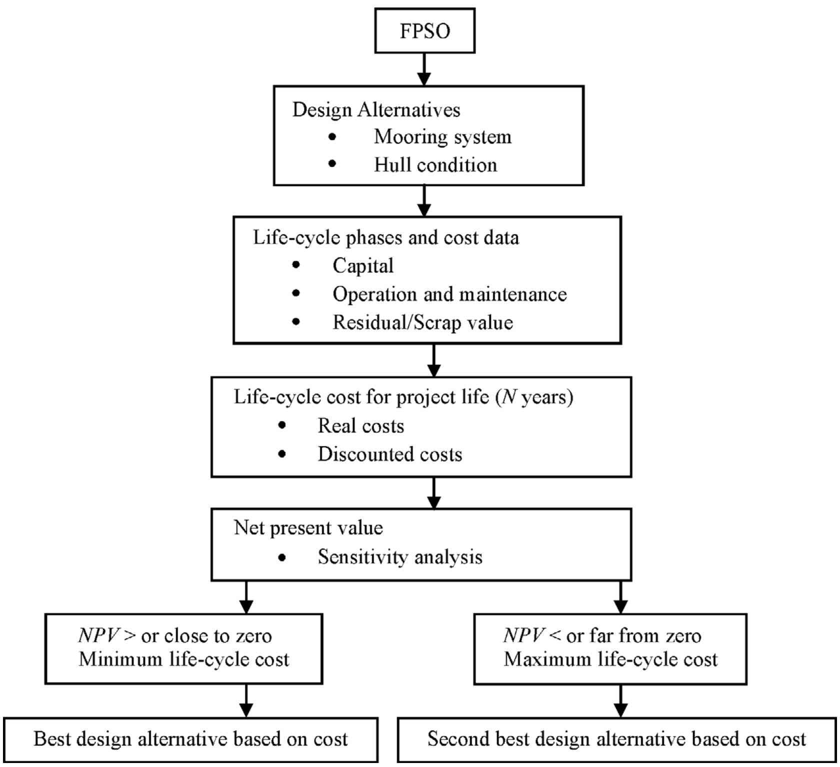

Fig. 5 LCCA procedure for FPSO

shown in Eq. (1), Eq. (2) and Eq. (3) above; Equations provide a means to calculate: No risk return; average risk premium discount rate from inflation rate; treasury bond rate of return; and, average equity return.

Hull-condition (new-build versus converted hulls) alongside mooring-system (spread/ ET/ IT/ RTM/ STP mooring-line options) represent design alternatives for life-cycle cost consideration across capital cost, operation and maintenance cost and residual scrap value.

While new-build FPSOs are generally designed for 20 to 30-year fatigue life, converted-vessels are usually used for a shorter period of 10 years. Hence, two life-cycle periods were chosen for this study: 10 years and 25 years.

A range of individual location oil field dependent resources have been identified toward FPSO mooring-line performance analyses, as shown in Table 2 below (where two-letter abbreviations for FPSO locations are used here to provide a degree of anonymity).

3.2.1 Life-cycle cost calculation for FPSO

Taking all outgoing cash flow as a positive value and residual cash flow as a negative value, the life-cycle cost (LCC) of a FPSO is given by Eq. (4),

$$LCC_{\text{FPSO}} = O_1 + O_2 + O_3 - I_1, \tag{4}$$

where O_1 is the capital cost, O_2 is the Operation and Maintenance cost over the life-cycle period, O_3 is the lease rate for a FPSO over the life-cycle period and I_1 is the residual scrap value of hull steel. O_2 is calculated as the sum of operation and maintenance cost from the 1st year to the *N*th year, while O_3 is calculated as the sum of a lease rate of FPSOs from the 1st year to the *N*th year.

3.2.2 Net present value (NPV) calculation for FPSO

Real costs incurred per year (R_n) are calculated once capital costs, annual operation and maintenance costs and residual scrap values are calculated. In the zeroth year, capital cost is counted as a negative value, then for every year annual operation and maintenance is counted as a negative value and finally in the *N*th year the incorporation of a residual/ scrap value is a positive value. To the real costs for every year, a discount factor as shown in Eq. (5) is multiplied. For year *n*, a discount factor is calculated as,

$$Discount\ Factor_n = \frac{1}{(1 + discount\ rate)^n}. \tag{5}$$

The discount factor will be 1 for the zeroth year, which gradually reduces as the life of the FPSO expires, considering a time-value-of-money then, the discounted present value (PV_n) of the FPSO for each year is the product of real costs incurred in that year (R_n) and Discount Factor for that year (*Discount Factor*) as shown in Eq. (6).

$$PV_n = R_n \times Discount\ Factor_n. \tag{6}$$

Finally, the sum of discounted present values from year zero to year *N* gives *NPV* as shown in Eq. (7)

$$NPV = \sum_{n=0}^{N} PV_n. \tag{7}$$

Calculation by detailed spreadsheet analysis was used to compute life-cycle costs and *NPV* for the range of FPSO design specification options across all respective cost data input; all *NPV*s are negative as project-profits (as a factor of external-oil-price/exploitation-worth) are excluded from the scope (as Fig. 2 above). A design with minimum life-cycle cost and *NPV* close to zero was identified as a cost effective FPSO alternative.

4 Results and discussion

Toward a soft-system assessment of updated problems' analysis (Fig. 3), defining changes after appropriate re-review, and implementing action toward balancing FPSO motion and cost performance (Fig. 2), factors to consider in choosing an efficient FPSO design required a parametric

Table 2 FPSO LCCA study

FPSO location	Country location	Converted or new-build hull	Mooring type
PK	Malaysia	Converted	External turret
KK	Malaysia	Converted	External turret
CD	Malaysia	Converted	Spread-moored
BT	Malaysia	Converted	Spread-moored
NV	Australia	Converted	Spread-moored
GD	Australia	New-build	Internal turret
MV	Australia	Converted	Internal turret
SB	Australia	New-build	Internal turret
PV	Australia	Converted	Internal turret
OH	Australia	Converted	Riser turret-moored
NH	Australia	New-build	Riser turret-moored

study by varying wave heights in the presence of wind and current and, LCCA to calculate the life-cycle cost and net present values of FPSO options. The sections below detail the results.

4.1 Wave height parametric study

As the wave height was increased from 4 to 8 m, the surge, sway and yaw motions (horizontal plane motions) for the (case-study) BT-FPSO decreases when turret-mooring is used, while it increases when spread-mooring is used.

The same was observed when a FPSO of another dimension was tested (Nishanth et al., 2016). Figure 6 below shows the behavior of the BT FPSO to varied wave heights in the presence of wind and current.

The mooring system allows the turret-moored FPSO to weathervane and hence resists the combined effects of wind, wave and current.

The horizontal plane motions of turret-moored FPSOs are relatively higher when compared to that of spread-moored FPSOs due to drift forces in the presence of wind, wave and current. However, if a spread-moored FPSO is adopted in an adverse climate, the motions escalate which can lead to mooring-line damage and a resultant increase in overall life-cycle cost. This suggests the option of a turret-moored FPSO to be a safe alternative design in adverse climates.

To complement motion assessments (in Fig. 6) that identify a turret-moored specification as preferable, FPSO cost comparisons are presented in section 4.2.

4.2 Cost data for FPSOs

Table 3 gives the cost data of selected FPSOs in Australia and Malaysia. The KK-FPSO with external turret-mooring has the sample's maximum capital cost of 7,195M USD. FPSOs with riser turret-mooring have comparatively high capital costs when compared to other moored FPSOs with the NH-FPSO costing 5,234M USD. Out of the spread-moored FPSOs under study, NV-FPSO has the highest capital cost of 1,391M USD, while CD and BT have capital costs of or under 800M USD.

4.3 Life-cycle cost for FPSOs

Figure 7 gives the total life-cycle costs calculated (Eq. (4)) for a life-cycle period of 10 years, and 25 years. It can be seen (Fig. 7) that the total life-cycle cost reaches a maximum for the NH-FPSO location with its riser turret-mooring of 75334M USD for the 25-year life-cycle period.

Even though the capital cost was higher for KK-FPSO, the life-cycle cost of FPSOs in the location of MV, SB, PV, NV, and NH is higher when compared to the life-cycle costs of the KK-FPSO, with an average difference in life-cycle costs of 16766M USD for the 25-year life-cycle period; particularly SB and NH which have new-build hulls.

The average life-cycle cost of internal turret-moored FPSOs is around 13,000M USD for a 25-year life-cycle period and 6,180M USD for the 10-year life-cycle period.

When compared to the average life-cycle cost of riser

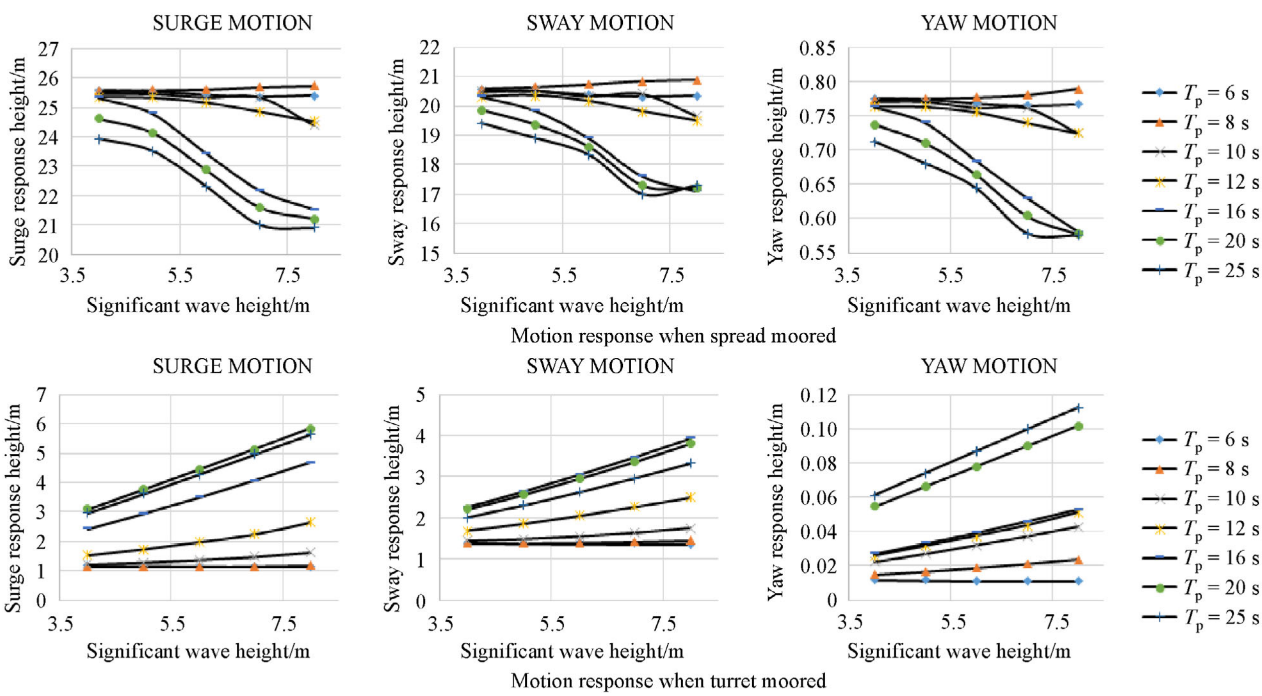

Fig. 6 Motion response of BT FPSO with spread-mooring and turret-mooring

Table 3 Cost data of FPSOs

FPSO location	Capital cost (USD)	Annual operation and maintenance Cost (USD)	Annual bare boat charter rate (USD)	Scrap value of metal (USD)
PK	272100000	6750000	45000000	42241248
KK	7195000000	7837500	59418700	90417600
CD	660000000	14726250	98175000	33126624
BT	800000000	7700000	49500000	18327614
NV	1391000000	63454545	423030300	33726758
GD	175100000	3000000	20000000	34776000
MV	624000000	52700000	351333333	49576003
SB	1125000000	61071429	407142857	46368000
PV	3359000000	63333333	422222222	47590128
OH	4214000000	55600000	N/A	52329600
NH	5234000000	2806000000	N/A	49680000

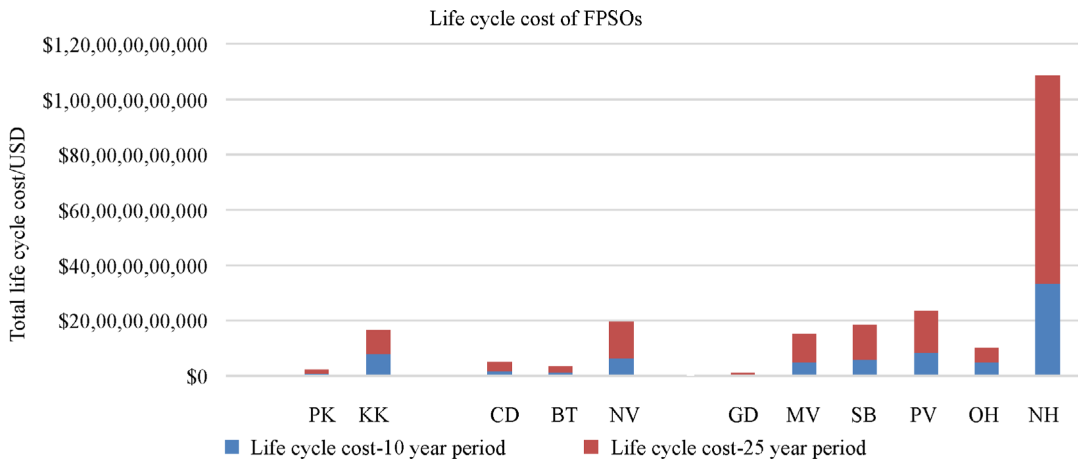

Fig. 7 Total life-cycle cost of FPSOs for 10-year and 25-year life-cycle period

turret-moored FPSOs, a spread-moored FPSO's average life-cycle costs are 12%, external turret-moored FPSO's average life-cycle costs are 15%, and internal turret-moored FPSO's average life-cycle costs are 25%.

Hence ranking the costliest FPSO and associated mooring system in terms of its life-cycle cost, the costliest option is the riser turret-moored FPSOs, followed by the internal turret-moored FPSOs, then external turret-moored FPSOs and, finally the spread-moored FPSOs, based on the available FPSO cost data from different reliable sources.

4.4 Net present value of FPSOs

The Net present value for FPSOs are calculated as per section 3.2.2 for different mooring configurations at a (calculated built-up) discount rate of 7.8% and are shown in Fig. 8.

A maximum number of FPSO configurations have capital costs less than 2000M USD and NPVs greater than −10000M USD as seen from Fig. 8; capital costs are minimum and NPVs are closer to zero for these FPSOs. The PV-FPSO location with its internal-turret, locations OH and NH with their riser-turret-mooring and the KK-located field with its external-turret, do not fall into this category.

The NPV of all the FPSOs except OH, is greater than −10000M USD even though their capital costs are higher. Clearly where the revenue obtained by the oil production is known, the profitability of these FPSOs can be more accurately presented and this can be considered within a future scope of work, noting this to be currently to be outside the current soft-system-methodology (as Fig. 3).

With values greater than −1000M USD and capital costs less than 300M USD, the GD and PK located FPSOs have the next highest NPV and it is noted that these are turret-moored FPSOs.

The NPV falls between −1414M USD to 6634M USD with capital cost less than 1,391M USD for spread-moored FPSOs; thus when life-cycle worth is considered, it cannot

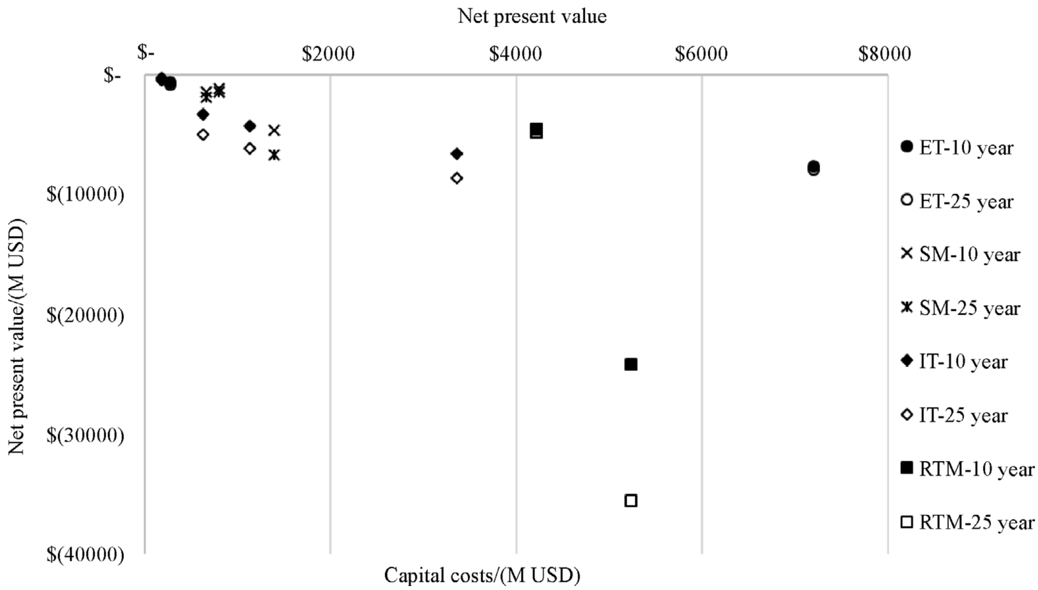

Fig. 8 NPV of FPSOs plotted against their capital cost

be generalized that all the turret-moored FPSOs are costlier than their spread-moored alternatives. Figure 8 shows that as the life-cycle period increases, the NPV decreases.

4.5 Cost and motion of FPSOs

Extreme motion of FPSOs can result in production down time leading to loss of profit from the project. As a result, a basic dynamic response study is required while choosing a whole-cost effective FPSO option (suitable to a particular oil field) signifying that the relationship between FPSO motion and cost is skewed; cost related decisions are (currently) taken without considering the (motion) performance of the FPSO. As seen in section 4.4, even though the capital costs are higher for FPSOs with new-build hull and turret-mooring system, their net present values are higher than their counterparts for converted hull(s) and spread-moorings.

As seen from section 4.1, turret-moored FPSOs have weathervaning capabilities and are preferred mostly in environments with extreme weather conditions, while spread-moored FPSOs are preferred in calm weather conditions due to their comparatively lower CAPEX (section 4.2). It was shown in section 4.1 that the horizontal motions decrease for higher wave heights in the presence of wind and current when turret-moored FPSOs are used, and increase when spread-moored FPSOs are used.

Following from the life-cycle cost analyses above, it was seen that the average life-cycle cost is minimum for spread-moored FPSOs; whereas, the NPV of these spread-moored FPSOs are lower than some of the external turret-moored and internal turret-moored FPSOs (as Fig. 8). Even though, the capital cost is minimum, when comparing FPSOs with similar dimensions and dead-weight-tonnages, spread-moored FPSOs with converted hulls are shown to have higher OPEX (as Fig. 9) resulting in much lower NPV than the turret-moored FPSO with new-build hull(s).

Figure 9 compares the CD-located FPSO with spread-mooring and converted hull, to the GD-located FPSO with internal turret-mooring and new-build hull for a 10-year analysis period. Even though a converted hull is used for

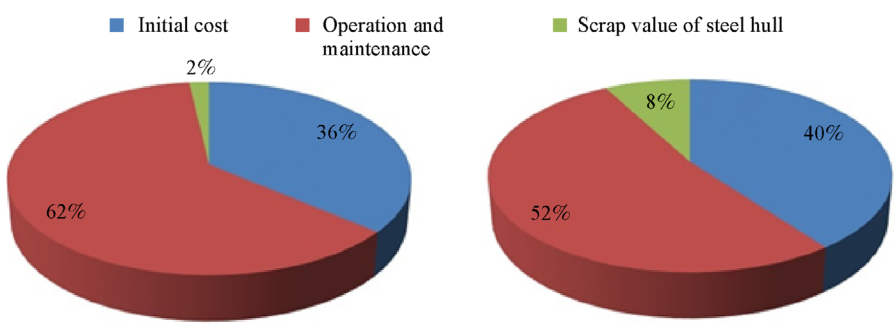

Fig. 9 Cost proportions of CD (on the left) and GD (on the right)

the CD-location, the difference in initial cost of the two FPSOs is only 4%; GD costing is more with its new-build hull. The operation and maintenance cost of FPSO with a converted hull and spread-mooring, i.e., CD-located FPSO, is higher by 10%.

It is to be noted that, the NPV of the GD-field asset is more with a value of −314M USD for a 10-year life period. The NPV of location-CD is −1406M USD. So, even though the capital investment was higher for the GD-located FPSO with internal turret and new-build hull, over the whole life period, it proves to be the better option, due to the use of converted hulls which are not specifically designed for the metocean conditions.

This emphasizes the need for a site specific dynamic motion response study of the converted hull to be used to minimise the future operational down time and cost.

As most of the oil companies use converted tankers for small projects, detailed study to provide guidance for the use of an appropriate tanker can lead to huge profit increases in terms of respective life-cycle cash flows.

5 Conclusions

The primary objective of this paper sought to clarify the antecedents of front end engineering design (FEED) factors contributing to the selection of an efficient FPSO based on whole-cost and motion.

With regard to the motion of FPSOs, it was seen that in the presence of wind, wave and current, the amplitude of horizontal plane motions of turret-moored FPSOs are relatively higher due to the drifting force when compared to spread moored FPSOs. When a spread-moored system is used, sway and yaw motions are significantly reduced; however, the horizontal FPSO motions for turret-moored FPSOs decreases as wave height increases. Thus, FEED factors must be cognisant that spread-moored configuration(s) in adverse climates can escalate motions resulting in mooring-line damage.

Among the FPSOs off coastal Malaysia and Australia, the total life-cycle cost is maximum for the NH-located FPSO with its riser turret-mooring, albeit the KK-located FPSO with its external-turret has the highest CAPEX.

FPSOs with riser turret-moorings have a comparatively high capital cost when compared to other FPSOs. Compared to the average life-cycle cost of riser-turret-moored FPSOs, the average life-cycle cost of spread-moored FPSOs are 12%, external-turret-moored FPSOs are 15%, and internal-turret-moored FPSOs are 25%. Hence, ranking the costliest FPSO and associated mooring system in terms of life-cycle costs, it is found that: the riser-turret-moored FPSOs are costliest, followed by internal-turret-moored lines, then external-turret-moored FPSOs, and finally spread-moored FPSO design options.

It can be concluded that for short-lived oil fields in calm weather, spread moored FPSOs are an effective option both in terms of whole-cost and motion, but for hostile weather conditions, turret-moored FPSOs turn-out to be the go-to option based on the motion response data and LCCA studies, ordered from a systems thinking perspective.

The conclusions made here are based on definite FPSOs, respective sub-components and explicit locations' climatic conditions, in Malaysian and Australian waters' oil fields. While noting the limitations in the applicability of the (location-specific) results presented, the findings of this work are argued to greatly assist with the decision-making process for initial FPSO configuration at the FEED phase by adopting a systems thinking methodology.

Abbreviations

FPSO – Floating Production Storage and Offloading System
LCCA – Life-Cycle Cost Analysis
FEED – Front End Engineering Design
ET/IT – External turret mooring system/Internal turret mooring system
RTM/SM – Riser turret-moored/Spread-moored system
SSM – Soft Systems Methodology
NPV – Net Present Value

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