Developments of a Synthesis Model for FLNG Design

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Abstract. The increasing demand for natural gas is encouraging the development of novel floating units' designs, capable of processing large quantities of hydrocarbon. These units called FLNG (Floating Liquefied Natural Gas) are facilities that produce, process and store liquefied natural gas (LNG) offshore. Once the topside and tanks of an FLNG are larger and more complex than the regular FPSO vessels, a design process considering these particularities must be used. Once just a few FLNG units are under construction and design and not yet in operation, the information on the design first stages is poor. It is difficult to obtain a first hull sizing without taking into account the complexity mentioned above. A previous work (Vieira et al. 2016) presented a set-based approach that works with sets of possible solutions that are analyzed and compared using a merit function to select the best and feasible solution. The initial modeling consists of a synthesis model that evaluates, based in a set of parameters, the FLNG topside general arrangement and weight estimative, the initial design of the midship vessel section, undamaged stability and seakeeping. This design approach is particularly useful to deal with project trade-offs and to optimize multiple characteristics. The present work shows the most recent developments of this modeling. New features were implemented as the consideration of three different loading conditions (30%, 60%, and 90%), evaluation of topside plants with a capacity between 2 and 4 MTPA, hull motions coupled with the dynamic of liquids inside the tanks. Furthermore, a more rational way of generating the set of cases to be analyzed was implemented as well as a user interface capable of providing more direct visualization of the vessel performance parameters. This paper aims to achieve a platform design capable of producing, storing, and offloading liquefied natural gas considering productions of 2, 3, and 4 MTPA. For motions purposes, environmental conditions of Santos Basin in São Paulo, Brazil was considered. In the same way, the design should guarantee the shortest downtime as well as keep costs, of acquisition and operation, as low as possible. Each of these characteristics must be quantified to allow a ranking of the generated solutions through an objective function.

Keywords: FLNG · Set-based design · Synthesis model

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1 Introduction

Natural gas is a fossil fuel and one of the few energy sources used in all sectors of the economy, including the domestic, commercial, industrial and transportation sectors. Other advantages of this energy source are that natural gas is the cleanest burning hydrocarbon and relatively abundant which attracts investments to this sector. Is expected that the global energy demand of natural gas to grow by 30% between 2015 and 2040, according to the International Energy Agency (IEA) New Policies Scenario.

Many of the reservoirs of hydrocarbon energy sources are in deep water. Brazilian oil reserves present a high gas-oil ratio (GOR) in pre-salt condition, thus representing a high possibility for natural gas monetization. And although its attractiveness, there are technological issues, particularly concerning the storage of the gas and due to restrictions imposed by the inexistence of export lines, most companies seek to reinject the associated gas into the reservoirs. Consequently, if the natural gas is monetized, the use of FLNG platforms with adequate processing and storage capacity seems to be one of the main feasible solutions to put natural gas on the market.

Due to its unique characteristics, the offshore exploration, the storage system and the transport of this energy source require a specialized platform named FLNG (Floating Liquefied Natural Gas) platform. The most suitable technology for storing large amounts of gas offshore is the liquefaction, which implies the need for a huge processing plant in the deck of an FLNG unit and large insulated tanks. These new challenges demand additional evaluation and analysis of the development of an FLNG platform design. Although several FPSO (Floating Production and Storage Units) have been designed and built for the last three decades, only recently the first platforms dedicated to process and store natural gas are being constructed as explained in Vieira et al. (2016). In addition to the increased difficulty to size and to install a LNG processing plant onto a floating unit, the FLNG design process also presents several challenges due to maritime requirements (stability and structural) and due to operational characteristics such as the loading and offloading process to a LNG carrier ship (LNGc), especially in a scenario that the LNGc is in side by side position with the FLNG platform, Zhao et al. (2011) summarized the main aspects in the FLNG side-by-side application problems in his recent studies. The result is a very complex problem with multiple parameters to evaluate by the designer in regards the wave performance, production and costs, Vieira et al. (2018).

Another considered as a major issue is the free surface effect inside the tanks, as shown in Rocha et al. (2015) and Vieira et al. (2016). Finally, the processing plant depends on low tilt angles and low acceleration levels to operate, Pettersen et al. 2013, making a careful seakeeping investigation necessary.

In 2016, extensive research undertaken at the Numerical Offshore Tank (TPN) laboratory of the University of Sao Paulo evaluated several factors and parameters of an FLNG floating unit design. The research experimentally and numerically investigated various inherent physical processes as LNG sloshing, side-by-side offloading, wind and current loadings, etc. Tests were performed both in the ocean and towing tanks; for further details, refer to Rocha et al. (2015) and Vieira et al. (2018).

The present work aims to present a computational tool capable of parametrically evaluate the performance of FLNG floating systems according to a previously defined merit function with production capacities ranging from 2 MTPA to 4 MTPA (Million Tonnes per annum). The routine uses the metocean conditions of Santos Basin in the Brazilian coast. The design should also guarantee the shortest downtime as well as keep costs, of acquisition and operation, as low as possible. Each of these characteristics must be quantified to allow a ranking of the generated solutions through an objective function.

This work presents a method to, given a set of basic parameters, design, evaluate and optimize a FLNG platform in agreement with the most established international rules considering topside layout, volume and weight distribution, cargo and ballast filled conditions, intact stability conditions, longitudinal and transversal structural specifications and seakeeping analysis in a unified synthesis model. Also, by compressing all the meaningful information in regards to the platform's performance with an automatic routine presenting it a graphic interface in an organized way to the client define which performance characteristic to optimize. Finally, the results are compared and analyzed for a typical production level and storage capacity, highlighting that the parametric model approach is usually applied to the conceptual design due to provide basic performance indicators on feasible solutions for the client's decision process.

2 Methodology

As mentioned in Vieira et al. (2016), the kernel of a parametric design routine is its synthesis model. The mathematical models, describing and evaluating each aspect of the design object, are assembled in a single continuous algorithm. Due to the FLNG system complexity, this methodology incorporates the integration of the areas of the process plant, stability, structure, and dynamics of the system in waves.

The amount of information required as input defines the sequence of numerical routine. Thus, each run of the software generates a topside configuration and evaluates the structure in three big blocks, respectively: stability, structure, dynamic of the system in waves, as shown in Fig. 1.

2.1 Stability

A package of numerical routines evaluates the parametrized hulls of FLNG floating systems. With the definition of the main dimensions, ship configuration and cargo loading as input parameters, the hydrostatic properties of the FLNG are calculated as the verification to IMO (International Maritime Organization) criteria. If the criteria are attended, the geometry is saved in the database; else, it is discarded. Figure 2 shows a flowchart of the main phases that make up the stability routines.

It is noteworthy that in this design phase, the standards of DNV-GL for maximum heel and trim were taken into consideration to determine the amount of ballast.

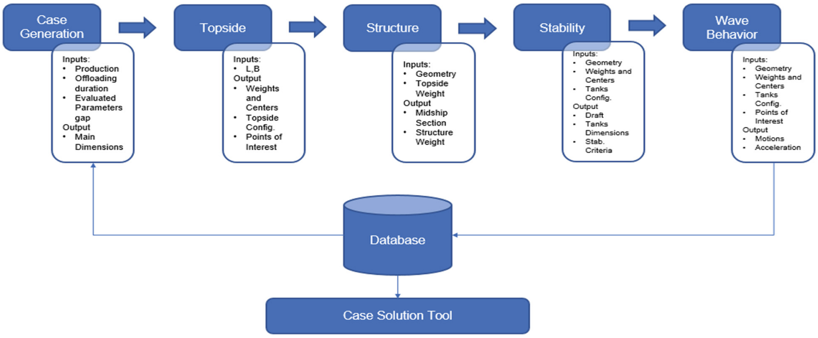


Fig. 1. Hull generation numerical routine flowchart

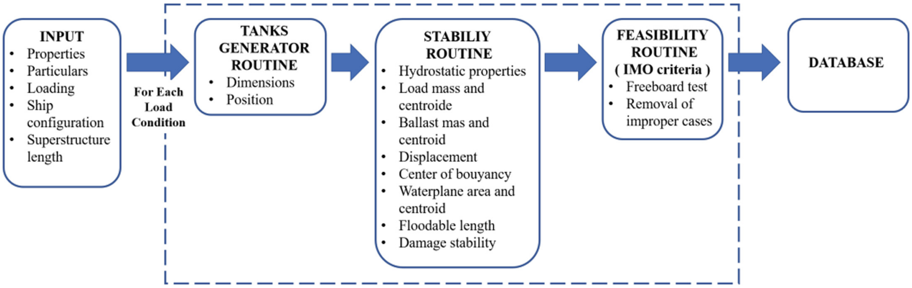


Fig. 2. Stability numerical routine flowchart

2.2 Structure

The structural arrangement evaluation is based on two main hypotheses. It was assumed that the tanks would be detached modules from the main structure, and they will be installed after the construction of the hull. This hypothesis is important since the hull structure can be designed independently of the tank structure. Thus, the primary DNV-GL (2012) requirements are completely achieved without regard to inertia provided by tank structure addition. Thus, using both the main dimensions L, B, and D as the hull geometry obtained from the previous phase, the structural midship section and the structural elements of the hull are determined. As in the previous phase, the results are verified with the DNV-GL criteria, and the database is updated.

Figure 3 illustrates the routine flowchart and consists basically of evaluating the central section arrangement, the cross-sectional arrangement, the steel weight of the hull and center of gravity using an iterative process.

As explained in Vieira et al. (2016), two main assumptions were made to evaluate the structure arrangement. First, it was assumed that tanks would be separated in modules which will be installed after the hull construction. An IMO Type B (SPB) prismatic tank will be used, which have the ideal characteristics to store LNG and LPG (IHI Offshore Group, 2019).

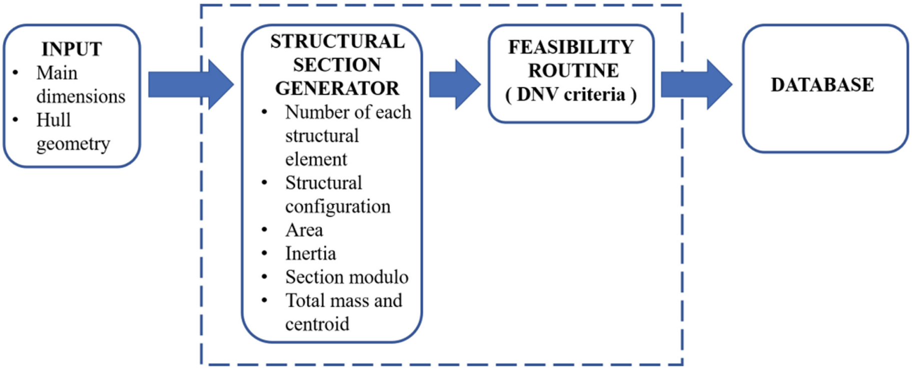


Fig. 3. Structure numerical routine flowchart

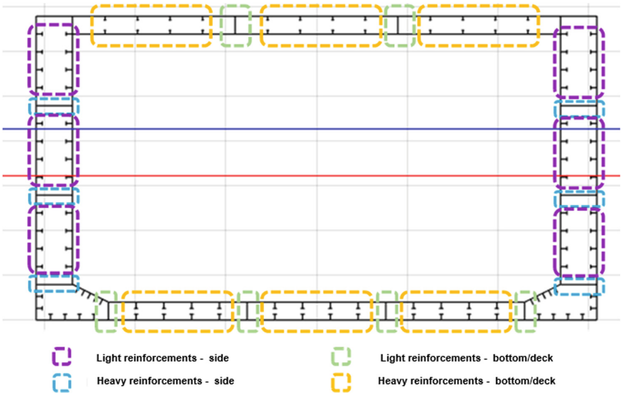


Fig. 4. Structural midship section in detail

This assumption is important once the hull structure can be designed independently of the tank structure. Thus, the DNV-GL primary requirements are fulfilled without considering the inertia due to the addition of the tank structure. It was considered a conservative approach once the tank structure presence will contribute to the increase of midship section properties.

The second assumption is that the other hull sections are, initially, considered equal to the midship section. It is also a conservative approach, once the main efforts are in the hull center. In future steps, a study can be made to evaluate the impact of this assumption in the hull weight.

Consider that a typical arrangement of the hull structure is composed by primary (single or double side; single or double bottom; single or double deck) and secondary (heavy reinforcements and light reinforcements) elements, as shown in Fig. 4.

2.3 Seakeeping

A frequency domain numerical model, performed by WAMIT software for wave analysis based on potential linear theory (Newman 1977), allowed the study of the ocean system under wave excitation. The main properties evaluated are wave forces, hydrodynamic coefficients (added mass, damping potential, and hydrostatic restoration) as well as the Response Amplitude Operator (RAO).

To evaluate the first order forces, the code standard method was used, as presented in Newman and Sclavounos (1988). First, the wet surface of each vessel was designed in a computational routine environment that created a geometrical data file (GDF) for each loading condition. Figure 5 shows a wet hull surface to 90% percent loaded ship that was used in the analysis.

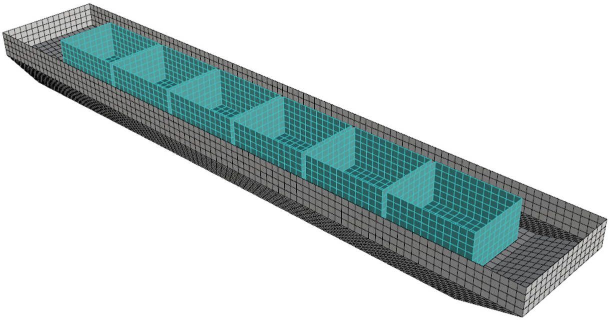


Fig. 5. 90% loaded ship wet surface: Hull (grey) and Tanks (blue).

The tanks wet surfaces were also provided to evaluate the influence of liquid cargo motion on ship motions (Newman 2005). The setup was made using WAMIT (2016) instructions. This influence has a significant impact on ship motions as larger tanks are used.

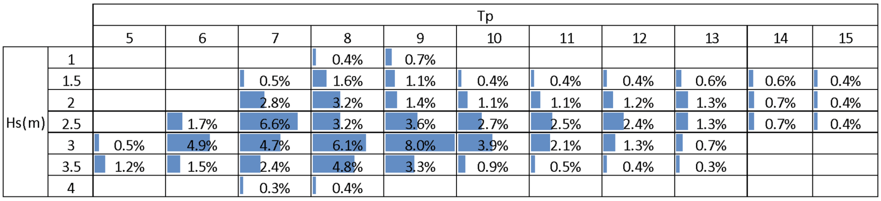
Figure 6 presents the processes and outputs involved in this stage of the numerical routine. First, the wet surface of each vessel was designed as a hull mesh in a computational routine environment using the database obtained in the previous phases that created a geometrical data file (GDF) for each loading condition. Each loading condition is then analyzed with WAMIT, and the wave behavior of the floating platform is characterized by the motions and accelerations of each loading condition being used to evaluate the downtime by classification societies.

Simulations were performed considering four-wave incidences angles (180°, 165°, 150°, and 135°, under equiprobable occurrence hypothesis as presented in Fig. 7) and fifty sea conditions (H_s, T_p) for incidence angle (Table 1).

Restrictions for the FLNG platform accelerations and motions were imposed to downtime analysis, as described in Table 2.

The downtime analysis was performed considering 30%. 60% and 90% load conditions, relative to LNG tanks total capacity. Each considered condition is associated with a fraction of total time of the operation, as shown in Table 3 and used to estimate the downtime.

Table 1. Sea condition occurrence probability



		Tp										
		5	6	7	8	9	10	11	12	13	14	15
Hs(m)	1				0.4%	0.7%						
	1.5			0.5%	1.6%	1.1%	0.4%	0.4%	0.4%	0.6%	0.6%	0.4%
	2			2.8%	3.2%	1.4%	1.1%	1.1%	1.2%	1.3%	0.7%	0.4%
	2.5		1.7%	6.6%	3.2%	3.6%	2.7%	2.5%	2.4%	1.3%	0.7%	0.4%
	3	0.5%	4.9%	4.7%	6.1%	8.0%	3.9%	2.1%	1.3%	0.7%		
	3.5	1.2%	1.5%	2.4%	4.8%	3.3%	0.9%	0.5%	0.4%	0.3%		
	4			0.3%	0.4%							

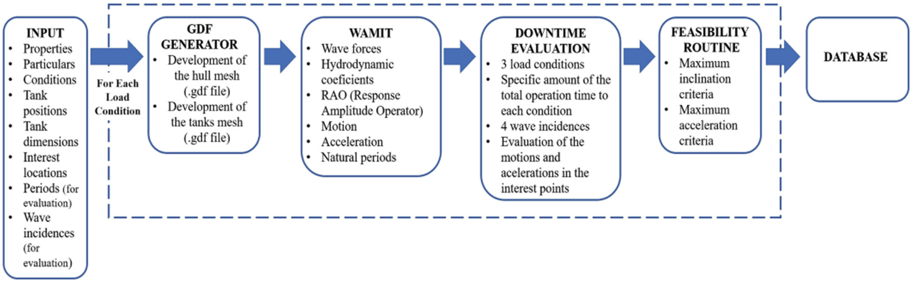


Fig. 6. Seakeeping numerical routine flowchart

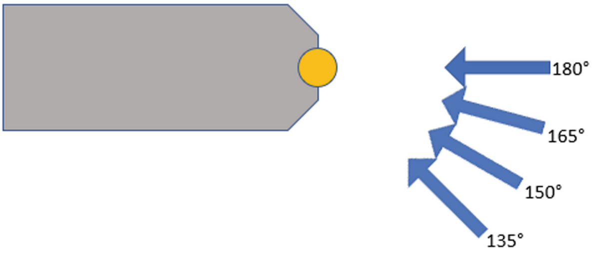


Fig. 7. Wave incidences angles considered in simulations

Table 2. FLNG downtime criteria for motions and accelerations

Criteria	Description
Motions (Angle)	The maximum angle of inclination of the vessel considering the coupled pitch and roll movement should not exceed 1°
Accelerations	The acceleration at the centers of gravity of the liquefaction modules shall not exceed 0.1 g

Table 3. FLNG loading conditions and operation time prevalence

Loading Condition	Operation Prevalence
30%	25%
60%	50%
90%	25%

The freeboard of the FLNG platform is a key parameter, used for feasibility system decision about stability analysis and loading/offloading operational conditions, especially in side-by-side operations. It is noteworthy that FLNG platforms usually have high depth dimensions comparing with the LNG ship's usual depth, which implies in maximizing the platform draft to minimize its freeboard. Thus, In the simulations, each platform model was initially considered fully ballasted, and its reduction was used to correct pitch and roll angles.

It is also noteworthy the importance of the liquid motions inside the LNG tanks to the analyses, since its direct influence on system stability and tanks configuration, besides affect the weight of the system and structural arrangement. A more extensive analysis is presented in Rocha et al. (2015) and Vieira et al. (2018).

At last, it is important to cite that the FLNG design software has a graphical interface in which it is possible to provide the input data for the merit function, which will be used to evaluate the generated cases. The interface also allows you to analyze and graphically observe all data obtained from simulated cases.

3 Application of the Algorithm to a Generic Case: Results and Analysis

The original numerical code, detailed in Vieira et al. (2016), was improved and is described in detail in this paper. The main advances regarding the original model are:

- Tank dimensions are no longer a data input, based on load capacity but output for the merit function;
- Consideration of three loading conditions (30%, 60%, and 90%) for stability and seakeeping analysis;
- Consideration of the dynamics of the liquid cargo inside the tanks;
- Improvement and optimization of the model and structural assessment processes;
- Update of the process plant database for estimation of weight, area, and volume;
- Implementation of a hierarchical algorithm to increase the sample resolution.

With the objective to implement a merit function that can be flexible to a chosen metocean condition, the algorithm was developed allowing the client to value each performance characteristic. To estimate a conceptual design FLNG, this work presented a merit function prioritizing the structural weight (S), load capacity (L), and downtime (D) as the following equation shows:

$$f(D, S, L) = 2D + 2S + L \tag{1}$$

Despite the scarce database, as emphasized by Vieira et al. (2016), an analysis of the similar system was adopted, which presents the main characteristics of the existing FLNGs in the world, either in operation or in the design phase. Thus, from the parameters related to production capacity, storage, main dimensions, and others, it was possible to perform parametric studies for the characteristic estimation of the platform or its upper and lower bounds.

Using the information obtained, an analysis of a similar system was performed due to apply the methodology previously explained by a hierarchical algorithm. The hierarchical algorithm consists of three phases explained below.

The first phase consisted of the definition of the parameters to study the initial performance of each case in a given environmental condition and respective production capacity. Since the present work seeks to optimize each design parameter and there are many variables to be evaluated given the system complexity, it was chosen a method to group each parameter, classified concerning its relevance to the global performance and about the remaining parameters. Therefore, three groups of parameters were established:

1. those related to the main dimensions: length L, beam B, and depth D;
2. three associated with the platform secondary dimensions: DD, DB, and DS (double deck, double bottom, and double side) width; and
3. the two last ones correlated to platform second-order effects: number of tanks, and tank arrangement.

Since the parameters L, B, and D have a significantly higher effect on the global FLNG performance; they were studied first and evaluated separately, with the remaining geometric features initially obtained from those main dimensions.

The first design case was generated from a study of similar FLNG platforms in CH-TPN (Sao Paulo, Brazil), by TPN and Frade Japão Petróleo Ltda teams. As described in Vieira et al. (2016), from this initial geometry, 300 random cases with similar geometries were developed by the Synthesis model (SM) to ensure an adequate sample space. The variation range of each dimension is presented in Table 4.

To avoid presenting a large amount of information and easy reader understanding, the study case of 4 MTPA liquid gas production was selected, and its partial design data is presented in Table 5.

Each case evaluation considered three main analysis variables: structural mass[1], the seakeeping/downtime[2] performance, and the maximum load capacity. After the initial calculation, a new iteration of the SM is performed to improve the parameters double deck (DD), double bottom (DB) and double side (DS) previously described

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[1] The structural mass is a variable directly related to the number of LNG tanks, the FLNG construction complexity and ultimately its total costs.

[2] Downtime is time lapse that the system is not operational, usually represented as a percentage of the total time available and is related to the ability to operate in adverse environmental conditions especially in rough seas.

Table 4. FLNG main dimensions per production

Production	Minimum length (m)	Maximum length (m)	Minimum breadth (m)	Minimum breadth (m)	Minimum depth (m)	Minimum depth (m)
2 MTPA	300	400	50	70	24	39
3 MTPA	350	470	60	80	28	43
4 MTPA	420	540	70	90	32	47

Table 5. Structure dimensions and performance characteristics of the best five FLNG systems evaluated – Phase 1

4 MTPA - Phase 1					
	1	2	3	4	5
ID	flng0004	flng0272	flng0001	flng0188	flng0148
L [m]	521	530	472	525	481
B [m]	74	73	74	73	74
D [m]	46	46	46	44	44
hDD [m]	4	4	4	4	4
wDS [m]	3	3	3	3	3
hDB [m]	3	3	3	3	3
Nº of tanks	6	6	6	6	6
Nº of tank rows	1	1	1	1	1
Structural mass [t]	168578	172996	153336	168603	151635
Downtime [%]	0.4	0.2	0.9	0.4	0.9
Load mass [t]	534755	536869	482849	503237	465938

Table 6. Dimension variation of double deck, double side and double bottom

Parameter variations										
hDD [m]	3.0	4.0	2.5	2.0	2.5	2.0	3.0	2.5	2.0	3.5
wDS [m]	2.0	3.0	4.0	3.5	3.0	4.0	2.0	4.0	2.0	3.5
hDB [m]	4.0	3.0	2.5	2.5	2.0	4.0	2.5	2.0	3.5	3.0

(Table 6 presents the considered range of these parameters). This hierarchical algorithm procedure guarantees a better sample resolution as described by Zitzler et al. (2000) (Fig. 8).

As pointed by Vieira et al. (2019), it is expected that increasing of the double side dimensions, and consequently filling the space between the LNG tanks and the hull structure with ballast, contributes significantly to reduce the vessel's freeboard as a consequence of displacement increasing. From the freeboard perspective, this assertion suggests that it is favorable to build narrower and higher tanks as well as the increase in ballast mass provided by larger double side width contributes to reducing the roll motion amplitudes of the FLNG, which is associated with the downtime in loading/offloading operations.

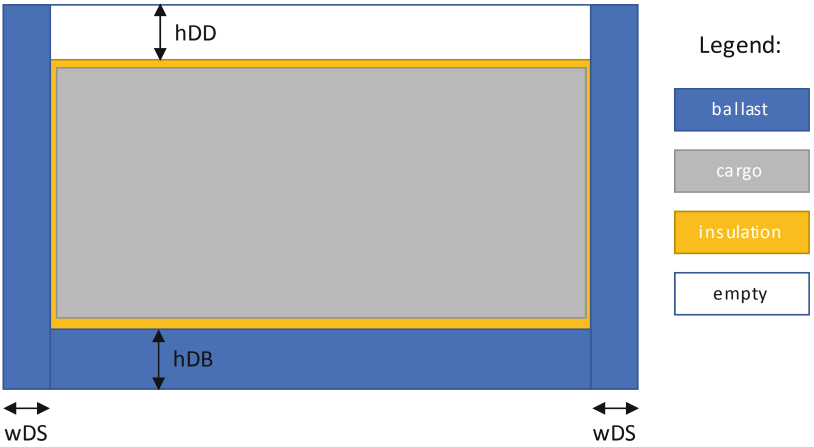

Fig. 8. Schematic of cargo and ballast tanks arrangement

Table 7. Structure dimensions and performance characteristics of the best five FLNG systems evaluated – Phase 2

4 MTPA - step 2					
	1	2	3	4	5
ID	flng0001_0009	flng0001_0001	flng0272	flng0004	flng0188
L [m]	472	472	530	521	525
B [m]	65	65	73	74	73
D [m]	40	40	46	46	44
hDD [m]	2	3	4	4	4
wDS [m]	2	2	3	3	3
hDB [m]	3.5	4	3	3	3
Nº of tanks	6	6	6	6	6
Nº of tank rows	1	1	1	1	1
Structural mass [t]	129492	129548	172996	168578	168603
Downtime [%]	0.4	0.4	0.2	0.4	0.4
Load mass [t]	378352	361094	536869	534755	503237

Table 7 presents the five best scenarios cases for the second phase of the algorithm.

The final phase of the synthesis model corresponds to the evaluation of the LNG tanks arrangement. Vieira et al. (2019) observed that configurations with smaller tanks have a reduction of sloshing effects, that is, movement of liquid (LNG) inside the tanks, which is associated with the platform downtime and its stability. Vieira et al. (2019) state that for smaller tanks, the downtime varies less than for large tanks. Besides that, tanks with high height/width ratio have less influence of the tank width than tanks with low height/width ratios. Table 8 presents the best design for all production capacity evaluated.

Table 8. Structure dimensions and performance characteristics of the best FLNG systems evaluated for each production capacity – Phase 3

BEST FLNG DESIGN			
ID	flng0058	flng0060_0009	flng0001_0009
Production [MTPA]	2	3	4
L [m]	414	467	472
B [m]	56	64	65
D [m]	36	40	40
hDD [m]	3	2	2
wDS [m]	2	2	2
hDB [m]	2	3.5	3.5
Nº of tanks	6	6	6
Nº of tank rows	1	1	1
Structural mass [t]	94426	125905	129492
Downtime [%]	2.7	0.4	0.4
Load mass [t]	252813	367280	378352

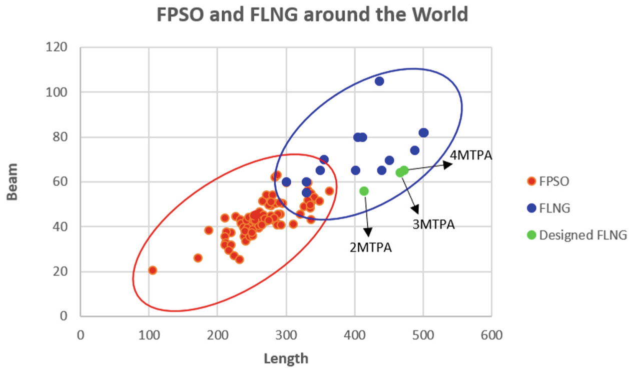

Fig. 9. FPSO and FLNG around the world

It is noteworthy that the third phase has a minor contribution, in that case, due to the number of tanks increasing leading to the total load volume decreasing and consequent negative effect regarding structural mass and corresponding total costs of the system. In that case, the changes in the configurations of the tanks owing to improve the dynamics of the liquid cargo resulted in adverse effects in the other parameters of the merit function.

Figure 9 presents a scatter distribution of existing or in design FPSO and FLNG around the world, together with the design model obtained by SM running. It is possible to notice that the three FLNGs designed are close to each other and have the beam range between 55 m and 70 m and length range about 400 m and 500 m.

Table 9. Dimensions and performance parameters comparison of the FLNG design with SM to the years 2013, 2018 and 2019 – 4 MTPA production capacity

	2013	2018	2019	Unit
Length	450.0	462.0	472	m
Beam	81.0	74.0	65	m
Depth	38.0	46.0	40	m
Maximum draft	17.1	28.9	25.9	m
Displacement	609731	953804	767953	t
Structural mass	192100	159459	129492	t
Topside mass	88007	98840	98778	t
Load capacity	240000	500735	378352	t
Number of tanks	20	10	6	units
Tank length	32.8	75.9	63.2	m
Tank beam	37.0	33.0	57	m
Tank height	19.7	40.0	35	m
Double deck	3.5	2.0	2	m
Double bottom	4.5	3.0	2	m
Double side	2.5	3.0	3.5	m

Table 9 presents the main characteristics and the performance parameters for three FLNG design process obtained with the newest version of SM (2019) and using 2013 and 2018 previous versions. It is important to mention that the new algorithm leads in an FLNG design with a higher length/beam ratio, as also with a smaller number of tanks.

4 Conclusion

For the study case, the first phase generates random cases to evaluate the effects of the main dimensions in the performance of the system. In this phase, it is perceptible the definition of a region of the best FLNG dimensions with beam between 55 and 70 m and length between 400 and 500 m.

The second phase evaluates the dimensions of double deck, double side, and double bottom, which directly affects the dimensions of the tank. The variation of these parameters is predefined, and the performance of the system is evaluated. The tank dimension is one of the major characteristics of the system as it can induce changes in the structural mass, the dynamics of the liquid cargo, and the total volume available to LNG.

It is noteworthy that the third phase has a modest contribution. Since the parameters of load capacity, structural mass and downtime are used to ponder the FLNG design performance, increasing the number of tanks affects negatively the total load capacity and the structural mass, decreasing the volume of cargo and increasing the structural mass and costs of the system.

It is also important to highlight that downtime has a slight variation in the third phase. The increase in the number of tanks highly affects the cargo capacity, which reduces the total mass of the system and turns the FLNG dynamics worst.

The designed vessel obtained in 2013 was a conceptual project using the same design software, which the main objective was only the improvement of the downtime factor.

Table 10. Comparison of the rank in the systems developed in the years 2013, 2018 and 2019

flng_2019	flng_2018	flng_2013
8.10	6.50	0.42

As observed in Table 10, this FLNG system has lower performance rank in comparison with the other solutions due to the storage capacity and the structural weight factors not being the main objective in the initial project. Even though the 2013 FLNG is still inside the optimum region defined by the third stage of the actual method, which shows the coherence of the design. As explained above, the 2018 FLNG has the inclusion of both the storage capacity and structural weight aspects in the merit function, beyond refinements in wave behavior and project criteria. These improvements ensure a higher rank than the 2013 solution.

The 2019 vessel, as the 2018 model, used the same merit function. But, differently, from the previous solution, it employed a three-phase evaluation defining suboptimum regions which the next solution is evaluated related to the previous one.

It is important to note the evolution in the final rank of each system, which shows significant improvements in the merit function employed. Besides that, all systems presented consider a theoretical mooring system called soft mooring, which does not influence the system's dynamic behavior significantly. A real mooring system should be employed in software design in future works.

5 Future Works

Future works intend to improve the software and implement new effects as:

- Simulations with different topside layouts;
- In the structural model, the analysis considering the transversal efforts must be implemented to carry out the classification society rules in the initial phases;
- Once a solution is obtained additional studies such as riser, mooring, and offloading analysis;
- Implementation of the effects of wind and current efforts;
- A more extensive simulation, considering a larger number of cases.

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