AN INHERENTLY SAFER LAYOUT DESIGN FOR THE LIQUEFACTION PROCESS OF AN FLNG PLANT

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SUMMARY

Floating Liquefied Natural Gas (FLNG) facilities have limited space available and a high possibility of accidents occurring. The severity of consequences requires an inherently safer layout design. Scope of the liquefaction process requires to determine the size of utilities, operating costs, the deck area and the number of LNG trains. The layout of the liquefaction process plays a key role in defining operational and economical safety of the whole FLNG plant. The present study focuses on developing a novel methodology to design an inherently and optimally safer layout for the generic multi-deck liquefaction process of an FLNG plant. The integrated inherent safety principle is applied at the early phases of the layout design considering inherent safety and cost indices in three different layout options, and for the final design the most optimal option was selected. The proven indexing approach quantified the associated risks in all units. Safety measures were undertaken to eliminate or reduce the risk to an acceptable level. The results showed that the economic losses due to domino effects were limited by an improved layout design and passive control strategies. This study only dealt with evaluation and analysis of critical units of the plant due to a lack of detailed information at the early phase of the design. However, the proposed method plays a positive role in obtaining an inherently safer layout design of any multi-deck plants.

NOMENCLATURE

$a_{i,j}$	Hazard index for *j*th building or sensible target to be hit by *i*th unit
AA	Area affected by the potential accident (m^2)
A_j	Hazard index for *j*th building or sensible target
B*i*	Maximum damage distance of *i*th unit (m)
$D_{i,k}$	Geometric distance between *i*th unit and *k*th unit (m)
$DHS_{i,k}$	Maximum Domino Hazard Score for escalation from *i*th to *k*th unit
E_{lb}	Extent of applicability of the guideword limitation of the damage potential to target building
E_{le}	Extent of applicability of the guideword limitation of effects of domino escalation
E_{si}	Extent of applicability of guideword simplification
ISI_a	Inherent Safety Index for guideword attenuation
ISI_l	Inherent Safety Index for guideword limitation of effects
ISI_{la}	Inherent Safety Index for guideword limitation of the affected area
ISI_{lb}	Inherent Safety Index for guideword limitation of the damage potential to target buildings
ISI_{le}	Inherent Safety Index for guideword limitation of the effects of domino escalation
ISI_{si}	Inherent Safety Index for guideword simplification
H	Minimum value of ISI

1. INTRODUCTION

A Floating Liquefied Natural Gas (FLNG) facility is an emerging technology which predominately handles hydrocarbon gases with associated condensate liquids that can be processed, fractionated and stored as Liquefied Natural Gas (LNG), Liquefied Petroleum Gas (LPG) and condensate products. The key criteria that influence the process selection and plant optimization for an FLNG are efficiency, simplicity of operation and layout, flexibility, safety, vessel motion, refrigerant storage hazard, ease of start-up or shut down and capital cost [1]. In an FLNG facility, the main hazards are fire, explosion and cryogenic spill resulting from the loss of containment within the process, the storage and the offloading facilities. There are technical challenges involved in adopting onshore LNG processes and systems to offshore environments such as an FLNG. Some of these challenges are complexity and flexibility of the upstream gas treatment process and marinization of process equipment, selection of the appropriate liquefaction process that provide better efficiency with operational safety, reliability and availability requirements, minimization of equipment counts and sizes [8].

An FLNG plant has various critical components and-, the present study focuses on the most critical components only. The liquefaction module is one of the most critical and risky components due to technical and operational complexities [2]. Additionally, the liquefaction process accounts for 70% of the capital costs of the topside process system and 30-40% of the overall plant costs [11]. As the liquefaction process determines the rest of the utilities, operating costs, the deck area and the number of LNG trains, the liquefaction process is considered to be a key module of the FLNG process plant with respect to both safety and economical perspective.

Penteado and Ciric [10] determined optimal layout costs using mixed integer linear programming (MILP) in a multi-floor chemical process plant. Park et al. [9] performed an optimal equipment layout on a multi-floor process plant considering safety. Similarly, Ku et al. [5] performed an optimal equipment layout design of an LNG liquefaction process for LNG-FPSO, they considered safety by applying hybrid optimisation methods. In the conventional method proposed by Ku et. at [6], a mathematical model (an optimisation problem) was formulated considering 1652 design variables (unknowns), 1624 equality constraints and 1048 inequality constraints. The minimisation of the total layout cost was defined as an objective function. By then, by using a hybrid optimisation method consisting of the genetic algorithm (GA) and the sequential quadratic programing (SQP), the optimal module layout was obtained which satisfied the layout constraints and minimized the related costs and the deck area. Safety consideration was emphasised based on the minimum distance between equipment only and the hazards elimination or reduction strategies were not employed in the design. Therefore, the need for an inherent safety approach was felt necessary to improve and optimise the layout.

Landucci et al. [7] proposed a methodology to calculate key performance indicators quantifying both potential and inherent hazards in the early stage design of hydrogen storage plants. Tugnoli et al. [12] proposed a safety assessment in early plant layout design using an indexing approach based on an inherent safety perspective including safety cost analysis with indices for evaluation of various hazards related to potential of domino effects.

Layout design of the units of the liquefaction process plays a key role in defining operational efficiency and safety for the whole FLNG facility. While designing a layout, several issues should be considered such as process requirements, cost, safety, services and utilities availability, regulation and construction. At the final stage of the design cycle of a plant, a detail safety analysis can be done with little improvement; however, an application of inherent safety at the early phase of layout design helps to eliminate or reduce any associated risks throughout the operational life of a plant. This reduces high costs usually associated with the full plant lifecycle from hazard management to regulatory liabilities and safety system maintenance [12]. Additionally, it helps to reduce complexity, energy requirements, maintenance, waste and pollution. The reduction in inventories will help effect reduced size for the plant items such as reactors, distillation columns, heat exchangers and storage vessels. Additionally, there will be a corresponding reduction in the size of the pipework, structures and foundations suited for offshore operations as well as expenditure throughout the life of the plant.

The current study is focussed on designing an inherently safer layout of the liquefaction process of a floating LNG facility. This is based on the optimal module layout of a generic LNG liquefaction process proposed by Ku et al. [6] applying the Integrated Inherent Safety Index (I2SI) in layout analysis incorporated by Tugnoli et al. [12].

2. METHODOLOGY

An optimal module layout for a generic offshore LNG liquefaction cycle was derived from the module allocation of the generic LNG liquefaction cycle by formulating the optimisation problem, considering compactness, layout costs and safety [6]. The potential mixed refrigerant liquefaction cycle was placed separately on three modules, namely pre-cooling refrigerant (PMR) module 1, pre-cooling refrigerant (PMR) module 2 and mixed refrigerant (MR) module. The main components of the potential MR liquefaction cycle are compressors, heat exchangers, seawater (SW) coolers, an MR separator, Joule-Thomson (JT) valves, a compressor suction drum, dedicated compressor coolers, an overhead crane and a PMR receiver . The units with the same function were optimally placed within each module to minimise the available area of each module.

PMR module 1 is the first pre-cooling module consisting of a three-stage compression unit, an over head crane, a dedicated compressor cooler, three suction drums and three SW coolers. PMR module 2 is the second pre –cooling module consisting of a PMR receiver, three pre-cooling MR heat exchangers and three JT valves. The MR module plays a significant role in liquefaction and sub-cooling and consists of one compressor with two stage compression using two impellers, one overhead crane, one dedicated compressor cooler, one suction drum, three SW coolers, a Main Cryogenic Heat Exchanger (MCHE), three JT valves and two MR separators. Each module consists of multiple decks, each separated by 8 m of height. PMR module 2 and the MR module are available from deck A to deck E and the PMR module 1 from deck A to deck D. The minimum distance between equipment was taken to be 4 m and that between equipment and the deck boundary is taken to be 3 m.

An inherently safer layout design of the liquefaction process of an FLNG facility was proposed by employing an integrated inherent safety index based on key guidewords such as attenuation, simplification and limitation of effects [12]. The application of the inherent safety guidewords in the initial design stages of any modules of a plant allows an inherently safer design to be made, including areas such as design of process items, utilities location, and building locations, on site roads, accessways and maintenance. Thus, in the layout design of the liquefaction process of an FLNG, a specific value of the Inherent Safety Index (ISI), the Inherent Safety

Cost Index (ISCI) and the Loss Saving Index (LSI) were estimated for each guideword using the conceptual framework of I2SI as illustrated in Figure 1. As this method incorporates the use of proven and widely accepted tools of inherent safety principles, the obtained layout design will be assumed to be inherently safer.

As an inherently safer facility can be attained by the reduction or elimination of hazardous materials or processes through changes in chemistry, physics and physical design rather than by fully relying on layers of add-on protection, it would be cost effective to apply the Inherent Safety Principle (ISP) in the early stage of any project [12].

The risk reduction strategies aimed at reducing frequency or mitigating the consequences of potential accidents can be conventionally and hierarchically classified as inherent, passive (engineered), active (engineered) and procedural [3]. In this study, only inherent and passive measures were considered in investigating the ability to improve the safety performances of the layout design, as the active and procedural safety strategies do not belong to the first stages of layout design. The index approach quantified the effects of the inherent and the passive safety choices in three different layout options identifying the safer alternatives and highlighting critical units.

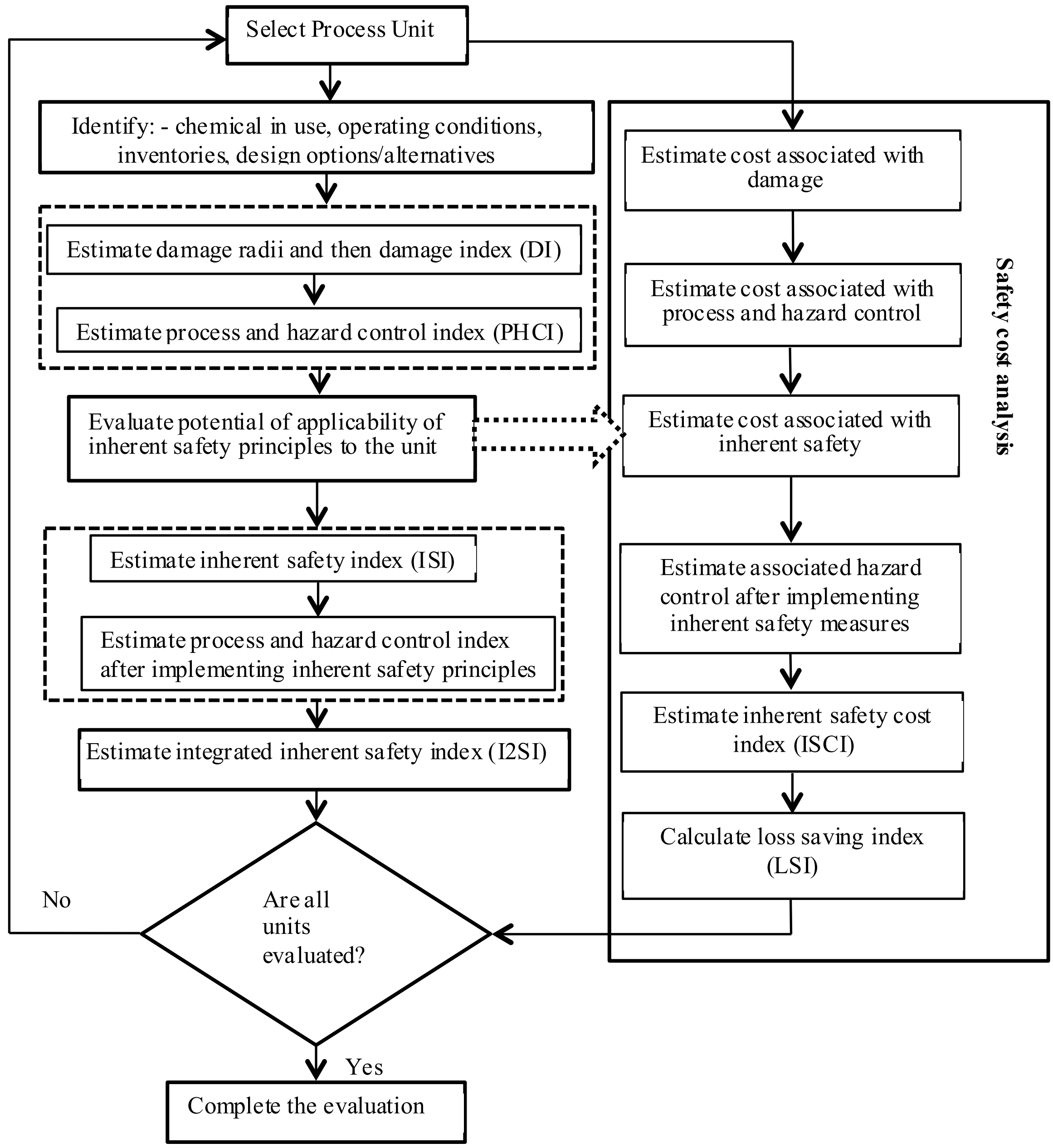

Figure 1 Conceptual framework of the I2SI and safety cost evaluation

2.1 THREE LAYOUT OPTIONS

The methodology is applied to all units in three different layout options namely Option 1, 2 and 3. Option 1 differs from Option 2 in the location of units and separation distances between units. Hazardous units of Option 3 are equipped with some passive protection and add on safety measures. These layout options are selected for the comparative analysis of I2SI, ISCI and LSI and to determine the most optimal option based on cost and safety perspectives.

2.1 (a) Option 1

The optimal layout design proposed by Ku et al. [6] was considered as Option 1 (base option). No passive protections are considered in this option because this is a starting option and other options were designed as possible inherent safety improvements with respect to it. However, the base case does not necessarily require the lack of passive safety measures.

2.1 (b) Option 2

This option presents an improved layout with increased separation distances among units. The deck E of PMR module 2 was removed as this deck was redundant. Thus, the PMR module 1 and PMR module 2 have four decks each. The MR module has five decks. All decks of three modules have the same dimensions (30 m × 20 m) and each deck is separated by a height of 8 m. The minimum distance between the equipment was assumed to be 4.50 m and that between the equipment and the deck boundary was assumed to be 2 m, as shown in Figure 2. The minimum distance between the maintenance area and the equipment was considered to be 2 m.

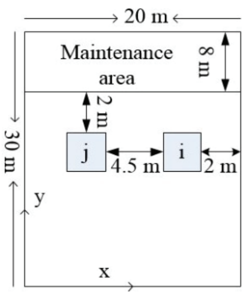

Figure 2 Plane view with minimum distance of ith unit and jth unit and deck boundary and maintenance area

2.1 (c) Option 3

This is a revised option of the previous options where separation distances were increased on decks B and D of PMR module 1, deck C of PMR module 2 and decks B, C, D and E of MR module. Some passive protection and add on safety measures were applied to hazardous units in the layout Option 2. Temperature controllers, pressure controllers, fire insulation and hydrants were added to hazardous units. A fire insulation wall and bunds were placed in between the two adjacent modules.

2.2 APPLICATION OF I2SI IN OPTION 1 (BASE OPTION)

Considering the layout proposed by Ku et al. [6] as Option 1 (base option), I2SI, the Conventional Safety Cost Index (CSCI) and associated loss costs were calculated employing the method proposed by Tugnoli et al. [12] and Tugnoli et al. [13].

According to Tugnoli et al. [12], the I2SI consists of two main sub-indices namely a Hazard Index (HI) and an Inherent Safety Potential Index (ISPI). The HI is a measure of the damage potential of the process after the application of the process and hazard control measures, ISPI is the measure of the applicability of the inherent safety principles (guidewords) to the process. The relationship between HI, ISPI and I2SI is given in Equation (1).

$$I2SI = \frac{ISPI}{HI} \tag{1}$$

The HI is comprised of two sub-indices namely a Damage Index (DI) and a Process and Hazard Control Index (PHCI) and their relationship is given by Equation (2).

$$HI = \frac{DI}{PHCI} \tag{2}$$

The damage indices estimated for each of these parameters; fire and explosion (*fe*), acute chronic (*ac*), chronic (*ch*) toxicity and environment (*en*) impairment) were combined to get total DI.

$$DI = Min\left\{200, [(DI_{fe})^2 + (DI_{ac})^2 + (DI_{ch})^2 + (DI_{en})^2]^{\frac{1}{2}}\right\} \tag{3}$$

Similarly, another sub-index PHCI was calculated for various add-on processes and hazard control measures that were required or were present in the system such as pressure (*p*), temperature (*t*), flow (*f*), level (*l*), concentration (*c*), blastwall (*b*), fire resistance (*fr*), sprinkler system (*s*), forced dilution (*d*) and inert venting (*iv*). The PHCI's of different control systems were combined to get a final PHCI.

$$PHCI = [PHCI_p + PHCI_t + PHCI_f + PHCI_l + PHCI_c + PHCI_{iv} + PHCI_b + PHCI_{fr} + PHCI_s + PHCI_d] \tag{4}$$

The numerator of Equation (1), ISPI comprised two sub-indices namely ISI and PHCI. In the safety assessment of layout plans only three guidewords were significant, namely simplification, attenuation and limitation of effects [12]. PHCI is redefined as Hazard Control Index (HCI) after the implementation of safety measures. The inherent safety index values for simplification and limitation of effects can be estimated from [3] for the base option. Attenuation depends on three main operating parameters such as temperature, pressure and toxicity /corrosiveness of the chemicals. According to the extent of applicability of the attenuation to these operating conditions, its index value was estimated from [3]. Thus, the final ISI for attenuation was estimated by Equation (5).

$$ISI_a = Min\left\{100, [(ISI_{temp})^3 + (ISI_{pres})^3 + (ISI_{toxi})^3]^{\frac{1}{3}}\right\} \quad (5)$$

The sum of ISI values estimated from different guidewords was given by Equation (6).

$$ISI = Min\left\{200, [(ISI_a)^2 + (ISI_{si})^2 + (ISI_l)^2]^{\frac{1}{2}}\right\} \quad (6)$$

Using Equation (3) and Equation (6), the Inherent Safety Potential Index was computed by Equation (7).

$$ISPI = \frac{ISI}{PHCI} \quad (7)$$

Using Equation (7) and Equation (2), the I2SI was computed. The HCI was calculated after considering the implementation of various add-on processes and hazard control measures (fire insulation, firewalls, and bunds). Thus, after identifying various hazards and their consequences layout design tools of inherently safer principles can be employed in different modules.

2.3 APPLICATION OF INTEGRATED INHERENT SAFETY INDEX IN THE PROPOSED LAYOUT DESIGN

In order to design an inherently safer and optimal layout plot of the liquefaction process, the I2SI method was applied considering two different options in addition to the base option.

2.3 (a) Option 2

The layouts of all units of PMR module 1, PMR module 2 and MR module in Option 2 are shown in Figure 3, Figure 4 and Figure 5 respectively.

On each deck, more than 50% empty space is kept for safety purposes and fire insulation was used in critical units such as the compressor, precool exchanger, separator, JT valves and MCHE. In this option, some passive protection and add on safety measures were applied on hazardous units and it was assumed that the structural integrity would not pose any risks.

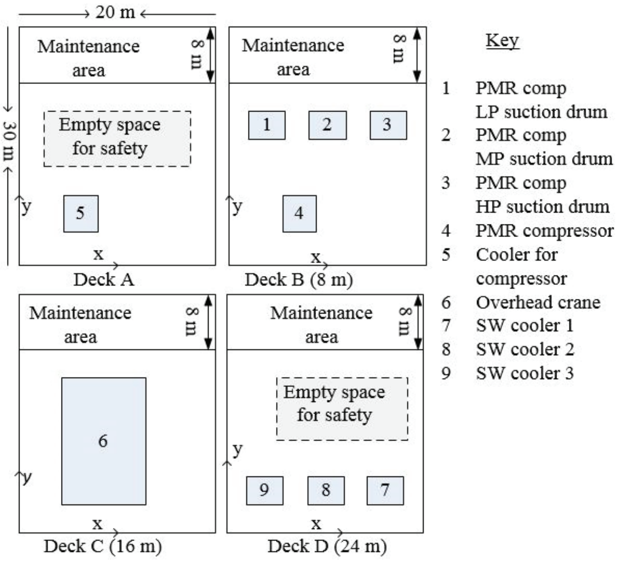

Figure 3 Layout of units of PMR module 1 on decks A, B, C and D in Option 2 with each number representing a specific unit on the particular deck.

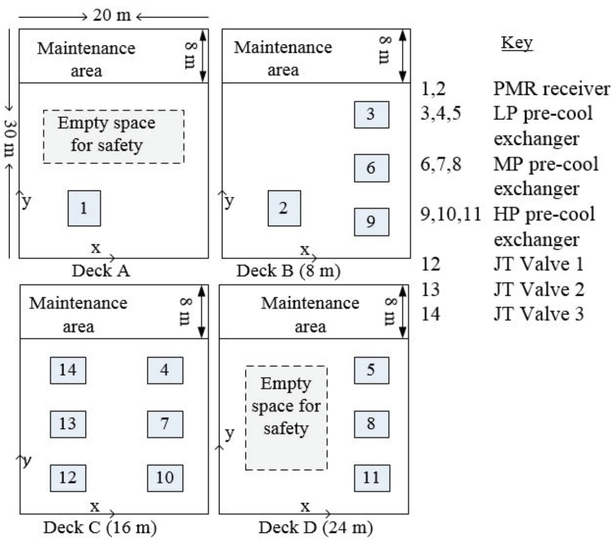

Figure 4 Layout of units of PMR module 2 on decks A, B, C and D in Option 2

2.3 (b) Option 3

In PMR module 1, units were placed along the y-axis such that separation distance was increased and easy access to the maintenance area was maintained as shown in Figure 6. Similarly, in PMR module 2 and MR module, the separation distances were increased as shown in Figures 7 and 8.

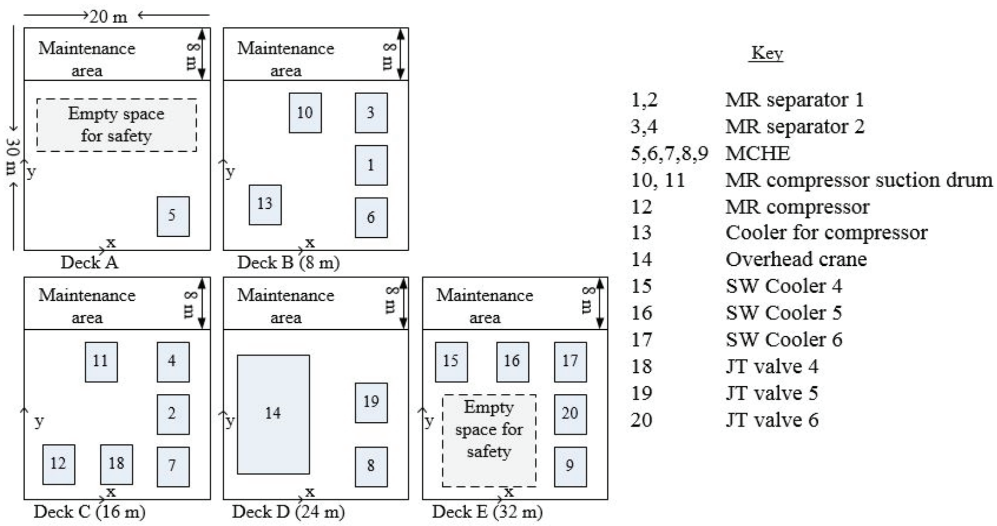

Figure 5 Layout of units of MR module on decks A, B, C, D and E in Option

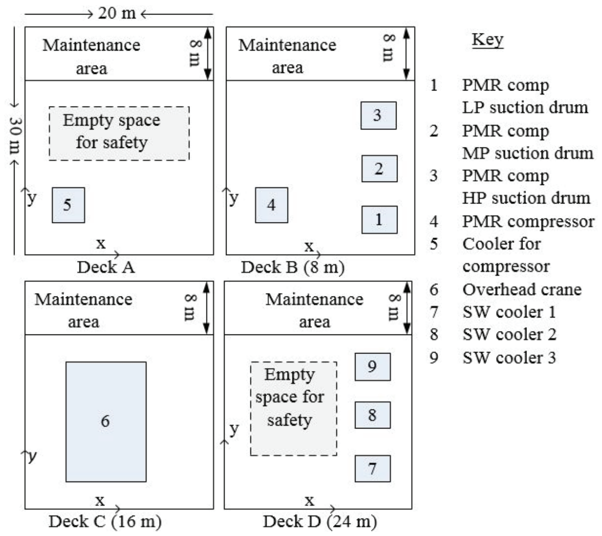

Figure 6 Layout of units of PMR module 1 in Option 3

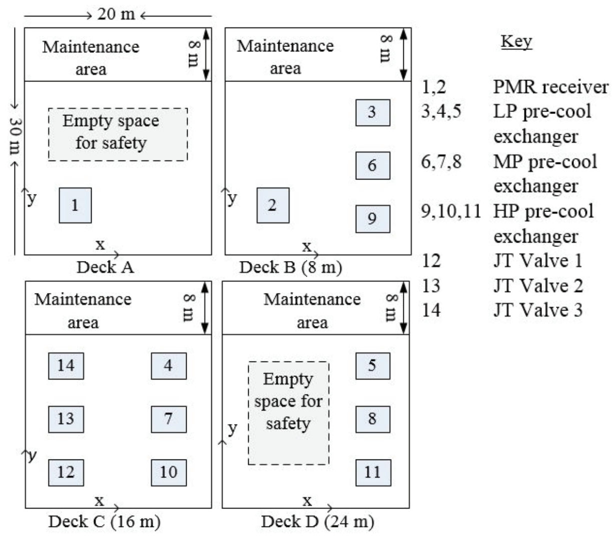

Figure 7 Layout of units of PMR module 2 in Option 3

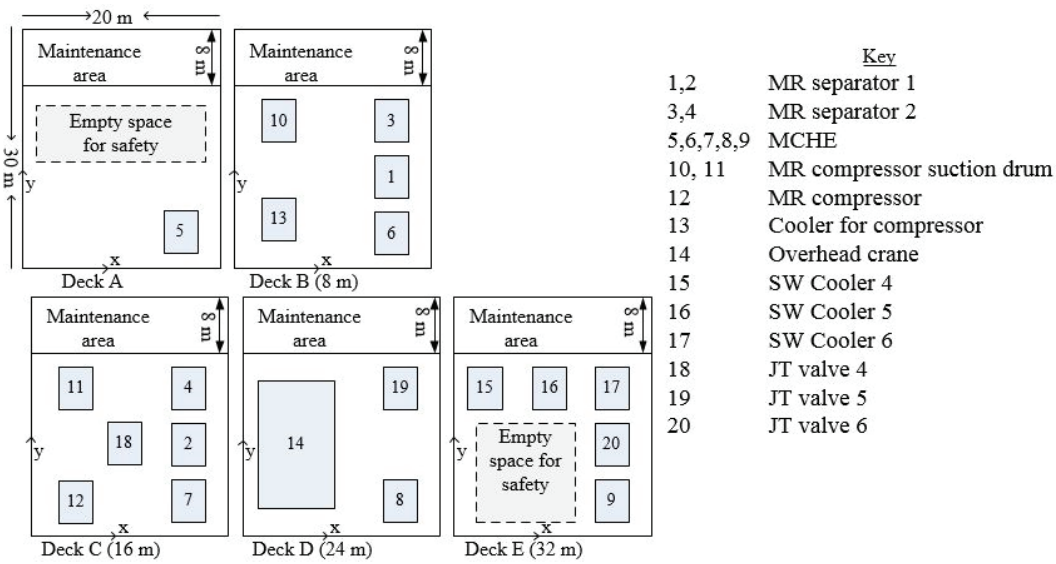

Figure 8 Layout of units of MR module in Option 3

The specific values of ISI for each guideword were combined to obtain the final ISI for the modified unit as given in Equation (8).

$$ISI = \left[Max\left(\eta^2, ISI_a^2 + ISI_{si} * \| ISI_{si} \| + ISI_l^2\right)\right]^{\frac{1}{2}} \tag{8}$$

Where the subscript '*a*' refer to attenuation, '*si*' refers to simplification and '*l*' refers to limitation of effects. The ISI for attenuation can be obtained from the monograph given in [12] after estimating its extent of applicability based on the Domino Hazard Index (DHI).

The estimation of the extent of applicability of attenuation based on DHI was carried out using Equation (9).

$$E_a = Max\left[0, \left(1 - \frac{DHI_{option}}{DHI_{baseoption}}\right) \times 10\right] \tag{9}$$

The DHI of each unit was estimated to assess the domino effect hazards caused by one unit to another in a specific layout design based on the method proposed by Tugnoli et al. [13]. It was estimated considering the potential hazards;- flame impingement or heat radiation, blast waves, fragment projection and toxic release. It considers the effects of both inherent and passive measures on the domino escalation potential. In order to calculate the DHI of each unit, the maximum Domino Hazard Score (DHS) for escalation from *i*th to *k*th unit ($DHS_{i,k}$) was estimated. For instance, the calculated DHI of various units of MR module (deck C) is given in Table 1. This shows that the MCHE has higher domino escalation hazards than the other units because it handles two phase fluids under low temperature.

Table 1 DHI on deck C of MR module in Option 3

Primary units	DHI of secondary units					
	2	4	7	11	12	18
2	−	2	3	1	2	2
4	2	−	2	3	1	1
7	2	1	−	1	2	1
11	1	2.5	1.5	−	3	2
12	2	1	3	2	−	1
18	2	1	1.5	2	1	−
Total	9	6.5	11	7	8	7

The extent of applicability of this guideword was assigned in terms of unit groups.The applicability of the limitation of effects to layout design involves three different elements namely (i) limitation of the effects of domino escalation (ISI_{le}), (ii) limitation of the damage potential to the target buildings (ISI_{lb}) and (iii) limitation of the affected area (ISI_{la}).

The ISI of the combined three elements was estimated using Equation (10).

$$ISI_l = Min\left\{100, \left[(ISI_{le})^3 + (ISI_{lb})^3 + (ISI_{la})^3\right]^{\frac{1}{3}}\right\} \tag{10}$$

The inherent safety indices of each element was calculated according to the extent of its applicability based on the method given by Tugnoli et al. [12]. Additionally, an assessment of the damage distances for each unit was carried out using Safety Weighted Hazard Index (SWeHI) methodology proposed by Khan et al. [4]. The geometric distance between two units plays a vital role in assessing the maximum Domino Hazard Score for escalation from *i*th to *k*th unit ($DHS_{i,k}$). The geometric distances of units on each deck were calculated in the form of a distance matrix; an example for Option 3 in deck C of MR module is given in Table 2. This shows that hazardous units were placed at an adequate distance from other units in order to limit domino escalation.

Table 2 Distances among units' geometric centres in deck C of MR module in Option 3

Units	2	4	7	11	12	18
2	−	9.1	8	11.9	12.5	7.6
4	9.1	−	17.3	7.7	13.5	14.2
7	8	17.3	−	18.4	14.2	7.4
11	11.9	7.7	18.4	−	11.5	13.1
12	12.5	13.5	14.2	11.5	−	10.2
18	7.6	14.2	7.4	13.1	10.2	−

3. COST INDEXING

In order to evaluate and assess the economic aspects of applied inherent safety, the cost indexing developed by Tugnoli et al. [12] was used according to the methodology given in Figure 1. The cost index is comprised of two sub-indices namely CSCI and ISCI. Additionally, an index specific to layout design analysis, the LSI was estimated to account for the cost savings on potential losses due to the reduction of possible domino escalation.

3.1 CONVENTIONAL SAFETY COST INDEX

According to Khan and Amyotte [3] the CSCI is calculated by Equation (11).

$$CSCI = \frac{C_{ConvSafety}}{C_{Loss}} \tag{11}$$

The $C_{convSafety}$ is the sum of the costs of process control measures and add-on safety measures. Similarly, C_{Loss} indicates the dollar value of expected losses caused by accidental events in a unit. It is the sum of five components as shown in Equation (12).

$$C_{Loss} = C_{PL} + C_{AL} + C_{HHL} + C_{ECC} + C_{DEC} \tag{12}$$

C_{PL} is the production loss cost, C_{AL} is the asset loss cost, C_{HHL} is the human health loss cost, C_{ECC} is the environmental cleanup cost and C_{DEC} is the domino escalation cost. The production loss cost, the asset loss cost, the environmental cleanup cost and the human health loss cost were estimated from [3]. C_{DEC} is the domino escalation cost due to possible chain accidents. It represents the sum of the loss related to the secondary units involved as given in Equation (13).

$$C_{DEC} = \sum_k S_k \left(C_{AL,k} + C_{HHL,k} + C_{ECC,k}\right) \quad (13)$$

$C_{AL,k}$, $C_{HHL,k}$, $C_{ECC,k}$ are the additional direct asset losses, human health loss and environmental cleanup costs for the failure of each kth secondary unit due to failure of primary unit. S_k is the credit factor for domino escalation toward the *k*th secondary target calculated against $DHS_{i,k}$.

3.2 INHERENT SAFETY COST INDEX (ISCI)

The ISCI was calculated from Equation (14).

$$ISCI = \frac{C_{InherentSafety}}{C_{Loss}} \quad (14)$$

The numerator, $C_{InherentSafety}$ is the sum of cost of inherent safety implementation, cost of process control and cost of add-on safety measures.

3.3 LOSS SAVING INDEX (LSI)

In order to find the economic effect of escalation reduction derived from inherently safer layout design, Tugnoli et al. [12] has proposed the LSI as given in Equation (15).

$$LSI_{option} = \frac{C_{InherentSafety,opt.} + \left(C_{Loss,opt.} - C_{Loss,baseopt.}\right)}{C_{Loss,baseopt.}} \quad (15)$$

The LSI compares inherent safety costs with a parameter that represents the savings from avoidable loss by domino escalation.

4. RESULTS AND DISCUSSIONS

Results of the current study are presented in three different sections 4.1, 4.2 and 4.3. Based on the results of I2SI and ISCI for three options, the safest and most cost optimal option was proposed for the layout design of the liquefaction process of the FLNG facility.

4.1 RESULTS FOR I2SI CALCULATION AND DISCUSSION

Results of the I2SI calculated for all three options are given in Tables 3 to 5. In Option 1, the I2SI indexing method was applied in the optimal layout design of the liquefaction process considering it as the base option, and revealing that the liquefaction process has low safety measures. The values of DI showed that all units have significant damage distances and hence significant potential to trigger escalation. As this is a base option, I2SI of all units were mainly influenced by hazard index values. Most of the units have I2SI values less than unity due to high HI and the absence of inherent safety measures as assumed in I2SI computation.

Table 3 I2SI values of units of PMR module 1 in three options

PMR Module 1	Option 1 (I2SI)	Option 2 (I2SI)	Option 3 (I2SI)
Cooler for compressor	0.63	1.13	2.48
PMR compressor LP Suction drum	0.70	1.69	2.60
PMR compressor MP Suction drum	0.37	0.89	2.42
PMR compressor HP Suction drum	0.31	0.70	2.05
PMR compressor	0.42	1.89	2.06
Overhead crane	0.98	1.94	2.63
SW cooler 1	1.03	2.29	2.40
SW cooler 2	1.00	2.25	2.40
SW cooler 3	1.00	2.21	2.28

In the PMR module 1 (given in Table 3), the PMR compressor HP suction drum on deck B seems to be the most hazardous unit due to its high pressure and high DHS. On the other hand, the SW cooler 1on deck D shows relatively safer performance because of a low DHI value, as it did not handle process fluids at high temperatures and pressure. Similarly, in the PMR module 2 (given in Table 4), the HP pre-cool exchanger on deck D requires a higher level of safety than the other units in the module because it handles two phase fluids at high pressure. In comparison, the PMR Receiver on deck A is relatively safer because it did not perform hazardous operations, and was the only unit lying on the deck. Thus, it has a low DHI. Similarly, as expected, the MCHE unit on deck C (given in Table 5) appears to be more critical in the MR module. This is because it is located on the deck with maximum units and it handled fluid at very low temperature and high pressure. The overhead crane on deck D did not pose any possibility of domino hazard due to its location on a sparsely populated deck.

In Option 2, I2SI values of all units were relatively higher than that of Option 1 (base case) due to decreased domino escalation hazards as a result of increased segregation. This leads to reduced values of DHI and increased values of ISI for the guidewords attenuation and limitation of effects. As there was no addition of units on any deck, and complexity of equipment layout did not occur, due to the addition of controllers to some units, there were relatively small negative impacts of the guideword simplification. In the PMR module 1 (given in Table 3), the HP pre-cool exchanger on deck B appears to be more hazardous than other units because of its poor inherent safety performance (lowest I2SI). However, it is safer than the base case because of increased segregation.

SW cooler 1 has the best safety performance due to the increased separation distances between units and passive safety measures. In PMR module 2 (given in Table 4), the HP pre-cool exchanger on deck D has the poorest safety level (lowest I2SI) because it handled the fluid in higher pressure than the other units. The PMR Receiver on deck A seems to be the safest unit in the module (highest I2SI) because it is the only unit located on the deck and did not have potential hazards from other units and it had low hazard index.

Table 4 I2SI values of units of PMR module 2 in three options

PMR Module 2	Option 1 (I2SI)	Option 2 (I2SI)	Option 3 (I2SI)
PMR Receiver on deck A	0.63	1.84	2.16
PMR Receiver on deck B	0.43	1.14	2.19
LP pre-cool exchanger on deck B	0.25	0.44	1.16
MP pre-cool exchanger deck B	0.23	0.42	1.08
HP pre-cool exchanger on deck B	0.23	0.39	1.06
LP pre-cool exchanger on deck C	0.25	0.46	1.22
MP pre-cool exchanger on deck C	0.24	0.42	1.38
HP pre-cool exchanger on deck C	0.22	0.40	1.26
JT valve 1	0.51	0.98	2.36
JT valve 2	0.48	0.92	2.28
JT valve 3	0.54	1.15	2.41
LP pre-cool exchanger on deck D	0.24	0.79	1.33
MP pre-cool exchanger on deck D	0.23	0.76	1.29
HP pre-cool exchanger on deck D	0.22	0.37	1.20

In the MR module (given in Table 5), the MCHE on deck B appears to be the least safe due to the cryogenic properties of fluids and the congested deck. The SW Cooler 4 has the highest safety level due to its low domino hazard escalation possibility.

Option 3 is a revised version of Option 2 and in this option, some control and safety measures were added to hazardous units in order to mitigate the hazards existing in Option 2. Units of all modules have I2SI greater than unity which indicates that the inherent safety feature of all units was enhanced. This was due to a significant decrease of potential hazards after the implementation of control measures. The applicability of the guideword limitation of effects obtained by increased segregation reduced the possibility of chain accidents.

Additionally, the high ISI value of attenuation yields high ISPI values and thus higher safety performance was obtained in this option. The increased segregation registers as negative on the guideword simplification due to increased piping networks. This can however be mitigated by safe pipe routing and passive safety measures. Among the various units of the three modules, the MCHE on deck C of MR module (given in Table 5) has the poorest safety performance due to hazardous operating conditions and domino effects. Similarly, the overhead crane of the PMR module 1 (given in Table 3) seems to be the safest unit in Option 3 due to its being a minimum hazard. In the overall analysis, all units have an I2SI greater than unity suggesting that of the three options, Option 3 is inherently the safest.

Table 5 I2SI of units of MR module in three options

MR module	Option 1 (I2SI)	Option 2 (I2SI)	Option 3 (I2SI)
MCHE on deck A	0.26	0.92	1.2
MR separator 1on deck B	0.24	0.53	1.24
MR separator 2 on deck B	0.22	0.48	1.17
MCHE on deck B	0.21	0.41	1.05
MR compressor suction drum	0.27	1.18	1.4
Cooler for compressor	0.30	0.63	1.46
MR separator 1on deck C	0.24	0.49	1.11
MR separator 2 on deck C	0.22	0.48	1.16
MCHE on deck C	0.20	0.83	1.02
MR compressor suction drum	0.27	0.61	1.36
MR compressor	0.22	0.44	1.06
JT valve 4	0.45	0.49	2.03
MCHE on deck D	0.23	0.84	1.05
Overhead crane	0.62	1.41	1.46
JT valve 5	0.43	0.46	1.82
MCHE on deck E	0.20	0.42	1.07
SW Cooler 4	0.71	1.71	1.89
SW Cooler 5	0.71	1.63	1.72
SW Cooler 6	0.69	1.52	1.6
JT valve 6	0.44	0.46	1.81

4.2 RESULTS FOR ISCI CALCULATION AND DISCUSSION

The results of the cost indexing of three modules in all options are reported in Tables 6 to 8.

In Option 1, no inherent safety measure was applied and each unit had identical conventional and inherent safety cost indices. It was observed that the costs of indices for all units were below unity and the costs of safety devices were lower than the expected losses. This is due to significant increase of the loss parameter values because of possibility of domino effects.

Table 6 Comparison of ISCI of units in three options of PMR module 2

	Option 1		Option 2			Option 3		
Unit	$C_{conve\ safety}$ (\$) [10^5]	ISCI [10^{-2}]	$C_{inherent\ safety}$ (\$) [10^5]	LSI Option 2	ISCI [10^{-2}]	$C_{inherent\ safety}$ (\$) [10^5]	LSI Option 3	ISCI [10^{-2}]
1	1.53	3.29	0.937	-0.1	2.01	0.736	-0.17	1.58
2	1.73	3.37	0.779	-0.15	1.52	0.76	-0.24	1.48
3	2.03	3.79	0.916	-0.15	1.71	0.932	-0.25	1.74
6	2.03	3.79	1.01	-0.16	1.89	1.03	-0.23	1.93
9	2.03	3.14	1.1	-0.22	1.7	1.03	-0.32	1.6
4	2.03	4.24	0.902	-0.12	1.88	0.943	-0.1	1.97
7	2.03	3.81	0.963	-0.16	1.81	0.996	-0.14	1.87
10	2.03	3.79	0.912	-0.14	1.7	0.972	-0.12	1.81
12	1.52	3.72	0.796	-0.09	1.96	0.754	-0.04	1.85
13	1.52	3.71	0.753	-0.11	1.84	0.744	-0.07	1.82
14	1.52	3.7	0.783	-0.1	1.91	0.712	-0.05	1.74
5	2.03	4.22	1.19	-0.1	2.47	0.955	-0.11	1.99
8	2.03	4.19	0.95	-0.1	1.96	0.964	-0.09	1.99
11	2.03	3.77	0.949	-0.14	1.76	0.973	-0.14	1.81

Table 7 Comparison of ISCI of units in three options of PMR module 1

	Option 1		Option 2			Option 3		
Unit	$C_{conve\ safety}$ (\$) [10^5]	ISCI [10^{-2}]	$C_{inherent\ safety}$ (\$) [10^5]	LSI Option 2	ISCI [10^{-2}]	$C_{inherent\ safety}$ (\$) [10^5]	LSI Option 3	ISCI [10^{-2}]
5	1.52	3.26	8.59	-0.11	1.85	9.45	-0.17	2.03
1	1.17	2.4	7.71	-0.11	1.59	7.56	-0.17	1.56
2	1.62	3.08	8.19	-0.13	1.56	7.93	-0.19	1.51
3	1.62	2.97	8.84	-0.11	1.62	8.04	-0.18	1.47
4	1.96	3.24	8.51	-0.14	1.41	8.77	-0.2	1.45
6	2.4	0.66	2	-0.1	0.55	2	-0.14	0.55
7	1.18	2.77	5.04	-0.11	1.18	5.23	-0.16	1.23
8	9.8	2.26	8.51	-0.11	1.97	5.1	-0.17	1.18
9	1.18	2.73	5.46	-0.11	1.26	5.62	-0.17	1.3

In Option 2, the increased segregation of units and the presence of passive safety measures reduced the domino hazard escalation possibility and the requirement of safety measures, and thus lowered the associated safety cost. The cost of applied safety devices such as pressure controllers, temperature controllers and fire insulation and space requirements were considered in the inherent safety cost evaluation. In most units, the ISCI values were comparatively lower than those of the base option which indicates that the application of inherent safety reduces the safety cost.

In Option 3, due to the application of inherent safety principles, the associated losses and costs of inherent safety were reduced in some units and the ISCI appears to be lower than those of Options 1 and 2. However, in some units due to increased separation distances among units, and the use of safety walls and bunds, the ISCI values were greater than that of Option 1and Option 2. This is due to the extra cost of the increased piping system and its safety control measures. While comparing the ISCI values in the three options, Option 3 shows better cost effectiveness due to a significant reduction of inherent safety cost requirements.

4.3 RESULTS FOR LSI CALCULATION AND DISCUSSION

The LSI of all units was calculated using Equation (15) and the results are given in Tables 6 to 8. In the base option, the LSI was the same as the ISCI due to identical $C_{Loss,option}$ and $C_{Loss,base\ option}$. Thus, the LSI values of all units were positive and below unity. The results revealed that Options 2 and 3 are more cost effective in limiting the expected loss from accidental events. This is due to the integrated effects of passive and inherent safety measures.

The presence of negative LSI values suggests that the costs of these safety measures are fully compensated for by the expected decrease in loss, in the event of an accident. Moreover, the reduction of DHI values reduces the requirement of safety measures and results in savings.

Table 8 Comparison of ISCI and LSI of units in three options of MR module

Unit	Option 1		Option 2			Option 3		
	$C_{conven\ safety}$ (\$) [10^5]	ISCI [10^{-2}]	$C_{inherent\ safety}$ (\$) [10^5]	LSI Option 2	ISCI [10^{-2}]	$C_{inherent\ safety}$ (\$) [10^5]	LSI Option 3	ISCI [10^{-2}]
5	1.05	1.47	0.78	-0.18	1.1	0.69	-0.19	1.0
1	0.98	1.73	0.91	-0.13	1.6	0.68	-0.14	1.2
3	0.98	1.72	0.85	-0.14	1.5	0.69	-0.15	1.2
6	1.05	1.59	0.74	-0.13	1.1	0.64	-0.14	1.0
10	0.85	1.52	0.61	-0.15	1.1	0.56	-0.14	1.0
13	1.39	2.61	0.79	-0.16	1.5	0.75	-0.16	1.4
2	0.94	1.65	0.83	-0.13	1.5	073	-0.14	1.3
4	0.94	1.65	0.72	-0.13	1.3	0.73	-0.14	1.3
7	1.05	1.56	0.76	-0.15	1.1	0.74	-0.18	1.1
11	1.06	1.94	0.78	-0.14	1.4	0.77	-0.13	1.4
12	2.00	3.42	0.96	-0.14	1.6	0.95	-0.16	1.6
18	1.06	2.43	0.89	-0.12	2.1	0.70	-0.12	1.6
8	1.14	1.70	0.80	-0.14	1.2	0.71	-0.15	1.1
14	0.480	1.17	0.19	-0.16	0.5	0.19	-0.06	0.5
19	1.19	2.53	0.64	-0.17	1.4	0..54	-0.09	1.1
9	1.14	1.66	0.83	-0.16	1.2	0.76	-0.15	1.1
15	0.95	2.18	0.44	-0.12	0.1	0.42	-0.10	1.0
16	0.95	2.18	0.45	-0.12	0.1	0.43	-0.10	1.0
17	0.95	2.18	0.45	-0.11	0.1	0.44	-0.074	1.0
20	0.95	2.24	0.48	-0.11	1.1	0.47	-0.07	1.1

Thus, for Option 3, the loss saving is higher than that of Options 1 and 2. From the results, it was found that Option 3 is considered the best option because most units have an I2SI of greater than unity and lower ISCI values than those of Options 1 and 2. An inherently safer plant can lead to a cost optimal option considering the lifetime costs of the plant [3]. Thus, the Option 3 layout design can be considered to be an inherently safer choice and the cost optimal option.

The study was based on the optimised layout (Option 1) obtained from the conventional method. It focussed on changing the process to eliminate or reduce hazards rather than accepting the hazards and developing add-on features to control them. Hazardous units were identified and were made less hazardous by eliminating or reducing the hazards. The separation distances between units were considered based on the possibility of domino escalation hazards associated with units.

The difference between the outcomes of the optimised layout obtained from the conventional method (Option 1) and Option 3 gives a comparison of the conventional method and the current study. According to the inherent safety perspective, Option 1 was not inherently safer and it was optimised further and made inherently and optimally safer using the conceptual framework of the I2SI methodology. Therefore, the layout Option 3 is the most economical and a safer layout in comparison to the conventional approach.

5. CONCLUSIONS

A preliminary and conceptual application of the Integrated Inherent Safer Index for the optimal layout module of a generic liquefaction process of an FLNG facility was carried out. The possibility of the various hazardous units interacting with other units during accidental events was kept at high priority in the layout design. The hazard of chain effects leading to catastrophic consequences by escalation was limited by proper design strategies using inherent safety principles. The application of the proposed safety index (I2SI and ISCI) methodology helped to identify critical and hazardous units in the layout design.

Additionally, it enabled a safer and cheaper layout design of the liquefaction process of a generic FLNG facility to be obtained. An assessment of the inherent safety performance was carried out for the three layout options and critical and hazardous units were made inherently safer.

General conclusions that can be drawn from the study include;

- Due to the application of I2SI, an empty deck kept on the PMR module 2 for safety measures had been removed and the capital cost for its construction was avoided.
- The optimal layout design of the generic liquefaction process was optimized in terms of

inherent safety and the inherent safety cost perspectives.

- The economic losses due to domino effects were limited by an improved layout design thereby yielding savings in terms of the avoidable costs of accidents.
- The I2SI methodology was implemented in layout design of a generic multi-deck liquefaction process and an inherently and optimally safer layout design was proposed.

This assessment lacks detailed evaluation and analysis of all equipment of the liquefaction process due to the unavailability of that information in the early phase of the design. However, the proposed method plays a positive role in implementing the inherent safety principles in layout design of any multi-deck plant.

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