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REVIEW PAPER

Facility siting and plant layout optimization for chemical process safety

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Abstract−Designing the process layout in a chemical plant is a complex and multidisciplinary task requiring input from experts in fields such as chemical, civil, mechanical, and instrument engineering. Plant layout entails the allocation of a given number of facilities on a given piece of land. Determining the optimal distribution of facilities in a plant requires an optimization calculation, including a variety of distance constraints, one of which is related to process safety. A few approaches have been taken to transform consequence analysis, such as toxic gas dispersion and its mitigation as well as the risks of fire and explosions, into mathematical equations as constraints of an optimization problem. An optimization problem with constraints related to safety is not easy to solve given limitations such as nonlinearity, uncertainty, and ethical difficulties in converting human life to costs for calculation purposes. However, safety concerns have increased to the point that developing this type of approach is necessary. The objective of this study was to review the current methodologies for plant layout optimization and to resolve facility siting issues. Process safety concepts are considered with a view to identifying gaps and issues with current methods in order to develop better methodologies for designing safer layouts.

Keywords: Consequence Modeling, Optimization, Plant Layout, Facility Siting, Quantitative Risk Analysis (QRA)

INTRODUCTION

The arrangement of process equipment and buildings has a significant impact on plant economics. To maximize plant efficiency, the plant layout should be designed to facilitate the production process by, for example, minimizing material handling and operating costs and promoting labor utilization. Moreover, the layout should take into account safety considerations, as well as the possible need for additional space for future expansion and installations.

In a general plant layout, process units that perform similar functions are usually grouped within a particular block on the site, with each group typically referred to as a facility. In addition, a facility can refer to any human-occupied building near a process unit, such as a control room or a portable trailer in which people may be exposed to an unsafe situation. In general, constructing a plant over a large area increases process safety by preventing one accident from triggering others; however, this approach may increase the construction, land and operation costs. Therefore, cost and safety need to be integrated into the optimization of a plant layout.

The Texas City refinery explosion in March 2005 highlighted concerns related to the siting issue. Inadequate space between the trailers and the isomerization process unit was identified as a contributing factor in the fatalities [1]. Similarly, insufficient distance between process equipment and occupied buildings (control rooms) was cited as one of the major causes of accidents in Flixborough, England (1974), and in Pasadena, Texas (1989) [2]. Moreover, disasters such as those in Seveso, Italy (1976) and Bhopal, India (1984) demonstrate that positioning a hazardous plant near a densely populated area can have fatal results [3]. The abovementioned fatal disasters demonstrate that facility layout and siting are crucial factors in ensuring process safety. Previous accidents affecting offsite people, such as that in Bhopal, stress the need to consider offsite civilians during the early stages of design and risk assessment. Indeed, during the early stages of layout and siting development, preliminary identification of the various hazards impacting offsite people may substantially reduce the severity of damage in the event of an accident.

Ideally, plant layout designers must strike a balance between risks and costs [4]. Previous efforts in this area have used heuristics approaches [5] or have focused on optimizing the economics to provide a decision making tool for minimizing construction costs [6-8]. However, few researchers have handled the integration of layout configurations and risk assessments. Only a few studies have sought to integrate safety into plant layout optimization, and almost no papers were published on this topic before 1996. Penteado et al. [9] developed a layout model to account for financial risk and protection devices, and assumed that the land occupied by each unit or facility had a circular footprint [9].

This paper reviews approaches to the inclusion of risk assessments into calculations for determining the optimal layout of chemical plants. Decision makers require such approaches to determine whether a proposed plant can be safely operated and economically installed. Consideration of the literature highlights the need for a better model that more closely reflects reality, and indicates that more realistic consequence analysis as part of a quantitative risk analysis (QRA) would help achieve the goal of achieving well-arranged

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‡This paper is dedicated to Professor Hwayong Kim of Seoul National University, S. Korea, on his retirement. The author, Seungho Jung, earned his Master's degree under Professor Kim's direction in 2006.

facility layout based on safety and optimization.

PLANT LAYOUT OPTIMIZATION

Plant layout optimization (often referred to as facility layout optimization) deals with the placement of facilities in a plant area, and is usually considered important to work in progress, manufacturing costs, lead times, and productivity. From the viewpoint of manufacturing engineering, Drira et al. [10] classify the layout problems as follows: 1) workshop characteristics impacting the layout; 2) static vs. dynamic layout problems; 3) formulation of layout problems such as discrete, continual, fuzzy, and multi-objective formulations, as well as the simultaneous solving of different problems. In addition, designers may be required to solve multi-floor problems, instead of those of a single floor, since more integration is necessary to reduce costs; in fact, many plants are built on multiple floors. Studies on multi-floor plants have examined various processes and areas [11-14]. Furthermore, in association with layout optimization, 3D computer-aided plant design (CAPD) can assist in multi-floor design [15,16].

The present review considers the problem of determining the optimal chemical plant layout while taking into account safety risk, and places emphasis on including consequence analysis in the optimization problem.

1. Plant Layout Optimization without Considering Safety

In the past, the distribution of process units was set according to simple rules, such as following the order of the process and separating adjacent units by sufficient distances to allow all operations to occur without wasting space [17]. This design problem has inherent difficulties arising from the large number of possible combinations that exist, even in plants with a small number of facilities [18]. To overcome these difficulties, the complete problem is frequently divided into easier-to-solve modules that can be solved sequentially [19].

In general, a heuristics based approach to plant design does not yield optimal solutions but can be improved by using its results as an initial assignment (i.e., a starting distribution). Thus, the initial layout can evolve to eventually obtain a lower objective value. This strategy has been combined with graph theory to generate a two-stage heuristic approach. The first stage consists of generating a hexagonal and maximum-weight planar adjacency sub-graph, where a tight upper bound is derived using integer programming [20]. During the second stage, the graph is then converted into a rectangular block layout. In addition, graph theory has been used to formulate algorithms for multi-floor facility layouts [21]. Several studies have used a graph-theoretic approach to explore different algorithms and models [22-24]. To analyze manufacturing firms, fuzzy set techniques have been added to this approach [25]. Moreover, the use of stochastic techniques has also been shown to be effective in obtaining practical solutions for plant layouts.

The use of early genetic algorithms in layout design has been reviewed [26], but these methods do not guarantee identifying the global optimum; rather, they are only able to solve optimization problems containing nondifferentiable objective functions [27]. The sample average approximation method was used in a Monte Carlo simulation to solve the routing problem by considering it as a stochastic problem [28]. Genetic algorithms have been developed to solve layout problems in the fashion industry [29] and in manufacturing systems [30] in an acceptable amount of time. This approach has also been used to solve the packing problem, which is similar to the layout case [31]. A heuristic method in which another local heuristic search procedure is used at each step—regarded as a meta-heuristic approach—has been applied in the layout of manufacturing systems through simulated annealing [32-34]. Moreover, the genetic algorithms and simulated annealing of both approaches have been compared when solving multi-period planning for the dynamic layout problem [35].

Programming techniques have also been applied to solve the layout problem. During an analysis of the arrangement of departments under conditions of a certain traffic intensity, the linear ordering problem was shown to be strongly NP-hard [36]. This issue clearly reflects the degree of difficulty that the layout problem represents. Originally, the facility layout problem was formulated as a quadratic assignment problem (QAP) [37]. Several algorithms have been proposed using the QAP to specifically solve challenging layout problems [38,39]. The equivalence of the QAP to a linear assignment with certain additional constraints has been demonstrated [40]. Furthermore, the contour line procedure, developed to optimally place a new facility near the existing facilities, has been extended to consider rectangular shaped facilities and rectilinear distances. [41-43]. Mixed integer programming has received significant attention for modeling the layout problem. Several models were produced using a linear extension of the QAP to generate a mixed integer program (MIP) [44-46]. A new formulation was proposed for the fixed orientation and rectangular shape of facilities; in this method, the big-M was first applied to improve the numerical calculation [47]. In addition, a two-step approach was proposed to solve the problem of the dynamic facility layout of unequal areas [48,49]. A study on pipeless batch plants sought to combine design, layout, and scheduling in a mixed integer linear program (MILP) [50]. In that work, the plot plan problem (i.e., allocation of process units) was formulated as a mixed integer nonlinear program (MINLP), but it was converted to an MILP to ensure a numerical solution. Several MILP models have been developed to solve different particularities of the layout problem, using an ad hoc method or commercial package, with a common part that uses the big-M method to model disjunctions [51-56]. Furthermore, improvements to the big-M formulation for the layout problem have been obtained using the convex-hull approach [57]. An iterative solution approach was proposed to solve large-scale, single-floor layout problems with computational savings [58,59]. Geographic information systems were used for chemical plant layout problems with a geographic dimension and finally for decision making [60].

Recently, the particle swarm optimization (PSO) technique has been suggested to find the optimal solution under various constraints, and the applicability of the method was illustrated by applying it to an ethylene oxide (EO) plant [61]. PSO is, along with genetic algorithms, one of the representative sampling approaches that does not need the derivatives of equations.

2. Plant Layout Optimization Including Process Safety

None of the studies mentioned in the previous section, except for that of Penteado et al. [9], considered safety beyond the typical minimum separation distance constraints. Indeed, only a small fraction of research papers published on plant layout optimization have included higher level safety constraints. The first such work developed a model that included the financial risk associated with protection barrier costs, and assumed circular process unit footprints. This model was extended to include a rectangular shape in the footprint as well as the Dow Fire and Explosion Index [62]. Risk analyses of particular layout designs have also been conducted without using a programming formulation. After Penteado's paper was published, other researchers used models that were disjunctively formulated and converted into an MINLP.

Some work on the issue of incorporating safety into plant design has been done by the research group that includes Richard Vazquez and M. Sam Mannan. This group performed several studies aimed at solving the problem of toxic gas dispersion affecting humans in control rooms [63-66]. The papers had the following titles:

- A Comparison of Deterministic and Stochastic Approaches to Solve the Facility Layout Problem with Toxic Releases (2009)
- An Approach to Solve the Facility Layout Problem Based on the Worst-Case Scenario (2010)
- An Approach for Risk Reduction (Methodology) Based on Optimizing the Facility Layout and Siting in Toxic Gas Release Scenarios (2010)
- Optimal Facility Layout under Toxic Release in Process Facilities: A Stochastic Approach (2010)

These studies were based on approaches using GAMS (General Algebraic Modeling System), to solve MINLP problems in a continuous plane rather than a grid-based plane, using either a stochastic or a deterministic approach. The stochastic approach in the papers considered random effects of meteorological parameters such as wind speed, direction, air stability and air temperature, which are very significant for toxic dispersion. A toxic downwind distance was first simulated under each scenario (8760 scenarios per year based on weather station's hourly record), and the resulting toxic dispersion distances were used to generate 36 directional risk functions by 10 degrees to reduce uncertainties. In these studies, toxic gas release scenarios were assumed to have a fixed incident frequency per year. Later, mitigation systems in the form of water spray curtains or barriers were assumed to exist to mitigate the consequences of toxic gases. The following studies sought to solve the optimization problems including such mitigation systems [67,68]:

- A Simplified Steady-State Model for Air, Water and Steam Curtains (2012)
- A Model to Optimize Facility Layouts with Toxic Releases and Mitigation Systems (2013)

However, a more significant plant layout/facility siting issue is that of how to properly include fire and explosion risks in layout problems. Vazquez et al. attempted to include fire and explosions in the MINLP approach in the following studies [69-71]:

- New Approach to Optimizing the Facility Siting and Layout for Fire and Explosion Scenarios (2011)
- A MINLP Approach for Layout Designs Based on the Domino Hazard Index (2014)
- A Stochastic Approach for Risk Analysis in Vapor Cloud Explosion (2014)

Another recent study sought to include fire and explosion risks using a bowtie analysis developed for hazardous units instead of predetermined worst-case scenarios [72]. Again, all of these studies used GAMS to solve their MINLP optimization problems. Given the difficulty of solving nonlinear problems, the MILP approach has been used for plant layout optimization considering process safety.

Yoon et al. researched solutions to the optimization of plant layouts using MILP [73]. They used MILP to solve the optimization problem, with linearizing overpressure consequences from the TNT equivalency method. Overpressure values can be translated into the probability of structural damage or human vulnerability risk using probit functions. The equation with a probit function is highly nonlinear, but Yoon et al. modified the consequences from the TNT equivalency model to allow incorporation into a MILP solution.

In another paper, Mannan et al. used the MILP approach by addressing the risk index, to provide a method for designing a safe layout, with various safety distance measures including equipment-equipment, equipment-workplace, and equipment-public distances. Moreover, the authors suggested using a modified individual risk index for the direct personnel risk associated with being near dangerous equipment [74].

Another suggestion made was to divide the plant area into a grid so as to reproduce the problem to the MILP format [75]; this approach is examined in the following section.

3. New Methodology for Using MILP by Mapping Risks onto Grids

This section draws heavily on the paper, "A New Approach to Optimizing the Facility Siting and Layout for Fire and Explosion Scenarios" [75], which introduced a new approach to plant layout optimization by considering consequence analysis. The work focuses on developing a methodology to find the optimal placement of a hazardous process unit and other facilities using optimization theory and a risk map of the plant area divided into square grids. Risk scores were estimated for each grid. The overall cost was a function of the cost of probable property damage attributable to fires or explosions and interconnection costs. A case study was presented in which a hexane-heptane separation plant was designed taking into consideration meteorological data for vapor cloud explosions (VCEs). The solution, shown in Fig. 1, included the locations of seven facilities and a process unit in the center. The facilities in green represent occupied buildings, which were assigned with a weighted factor to reflect additional protection for the occupants.

This work considered non-overlapping separation distance constraints, as shown in the following equations:

$$\sum_{k=1}^{K} B_{ik}=1,\ \forall i \in \text{Facilities},\ \forall k \in \text{all grids on the plane} \tag{1}$$

$$\sum_{i=1}^{n} B_{ik} \le 1 \tag{2}$$

where:

$$B_{ik}=0 \text{ or } 1 \begin{cases} k=1, 2, 3, \ldots, K \\ i=1, 2, n \end{cases}$$

$$B_{ik}=\begin{cases} 1 \text{ if unit i is allocated to site area} \\ 0 \text{ otherwise} \end{cases}$$

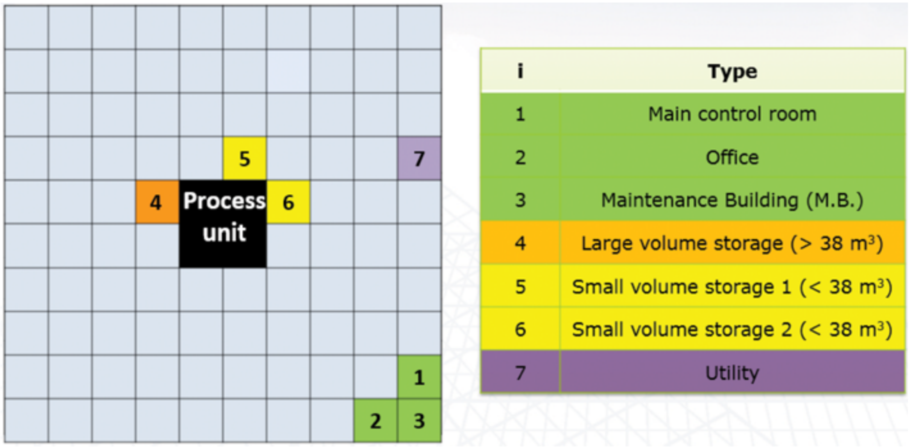

Fig. 1. Location results from the paper [75].

In addition to the proper process units, certain facilities, such as storage facilities and occupied buildings, should not be placed too close together. Recommendations exist for the separation distance between storage tanks and other buildings. Therefore, separation distance constraints that take the following form are needed:

$$|x_i - x_j| + |y_i - y_j| \geq D_{i,j} \quad (3)$$

This equation can be modeled in a mixed-integer linear form by using "big-M" constraints, as follows:

$$\{x(i) - x(j)\} + \{y(i) - y(j)\} \geq D_{i,j} \times sepB_{i,j}1 - M(1 - sepB_{i,j}1) \quad (4)$$

$$\{x(i) - x(j)\} - \{y(i) - y(j)\} \geq D_{i,j} \times sepB_{i,j}2 - M(1 - sepB_{i,j}2) \quad (5)$$

$$-\{x(i) - x(j)\} + \{y(i) - y(j)\} \geq D_{i,j} \times sepB_{i,j}3 - M(1 - sepB_{i,j}3) \quad (6)$$

$$-\{x(i) - x(j)\} - \{y(i) - y(j)\} \geq D_{i,j} \times sepB_{i,j}4 - M(1 - sepB_{i,j}4) \quad (7)$$

$$sepB_{i,j}1 + sepB_{i,j}2 + sepB_{i,j}3 + sepB_{i,j}4 = 1 \quad (8)$$

where:
$i \in$ occupied buildings, $j \in$ hazardous facilities such as storage tanks
x_i: x coordinate of facility i
y_i: y coordinate of facility j
$D_{i,j}$ is the minimum separation distance between i and j
$sepB_{i,j}$ 1, 2, 3, 4 are binary variables used to decide the location of i and j
M is an appropriate upper bound distance

In contrast, similar types of facilities need to be near one another for better management. For instance, gathering storage tanks in a certain part of the plant area is more cost effective; Eq. (9) is formulated to achieve this purpose.

$$|x_i - x_j| + |y_i - y_j| \leq m_{i,j} \quad (9)$$

Eq. (10) is modeled in linear form as follows, and all of the equations should be satisfied.

$$x_i - x_j + y_i - y_j \leq m_{i,j} \quad (10)$$

$$x_i - x_j - y_i + y_j \leq m_{i,j} \quad (11)$$

$$-x_i + x_j + y_i - y_j \leq m_{i,j} \quad (12)$$

$$-x_i + x_j - y_i + y_j \leq m_{i,j} \quad (13)$$

where:
$m_{i,j}$ is the limitation distance among similar facilities
$i, j \in$ occupied buildings or $i, j \in$ storage tanks

The objective function to be minimized includes the piping cost and the probable property damage cost.

$$\text{Min} \quad \Sigma_{i=1}^{n} \Sigma_{k=1}^{K} \{RS_k \times FC^i + RD_k \times UP^i\} \times B_{ik} \quad (14)$$

where:
RS_k=risk score of grid k caused by the center facility (process unit)
RD_k=rectilinear distance of grid k calculated from the center facility (process unit)
FC^i=facility building cost of facility i
UP^i=unit piping (relationship) cost between facility i and the center facility (process unit)
(Subject to non-overlapping, minimum-maximum separation distance constraints)

In this case study, the total cost associated with interconnection costs and safety costs on the grids is 53,522. The most hazardous facility in the case study is the process unit, centered on the plant area to provide the maximum separation from the boundary, which may be near residential areas.

If no residential area exists outside the plant area, the problem can be recast to determine the optimal layout with the process unit at any of the 81 possible locations within grid; the problem is then to solve the minimization of 81 different optimizations.

$$\text{Min Min } (\Sigma_{i=1}^{n} \Sigma_{k=1}^{K} \{RS_k \times FC^i + RD_k \times UP^i\} \times B_{ik})_{map\,1}^{map81} \quad (15)$$

Fig. 2 shows the result, which has a total cost of 29,208. This result is superior to the result obtained with the process unit fixed at the center because it allows the process unit to move throughout a larger area.

LIMITATIONS AND SUGGESTIONS

The literature review on current methods for plant layout optimization highlighted several limitations that should be addressed. Possible directions for future work on these limitations include:

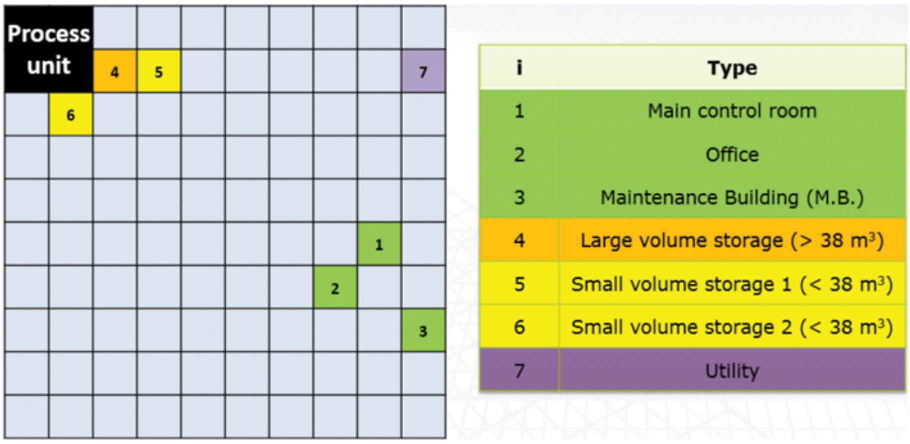

Fig. 2. Optimal layout obtained in calculations with 81 possible locations of process unit.

1. Nonlinear problems that can cause mathematical difficulties in achieving a global optimum;

2. Obtaining reliable incident frequencies to decrease uncertainties; and

3. Properly quantifying consequences from better consequence modeling analysis.

To address problems related to nonlinearity, particularly those encountered with MINLPs, methods to achieve global optimums may be developed using various techniques such as addressing rectilinear distance instead of Euclidean distance for interconnection costs, separating intervals of nonlinear. As shown in the example given above, such nonlinearity issues can be avoided by reducing the problem to an MILP rather than an MINLP using grids. However, this grid-based approach with an MILP has the drawback that it is difficult to use various sizes and shapes of facilities in the formulation because the units must be allocated [76].

The second and third limitations listed above are related to obtaining more realistic and accurate quantitative risk analysis (QRA) results. In many areas of the chemical industry, QRA combining frequency analysis and consequence modeling has been widely used to enhance safety [77,78], but simplified approaches have frequently been used due to the large calculations involved. One problem involves including VCEs. In VCE modeling, confinement and congestion have taken on increased importance, whereas use of an unconfined explosion approach has declined. For example, API RP 752 recommends not using TNT-equivalency modeling when determining the occupied building layout to minimize damage due to VCEs' [79]. As an alternative, a flame acceleration simulator (FLACS) may be used to provide risk scores in each grid on the map, or at least to evaluate the program. Therefore, an integrated method, as shown in the schematic diagram in Fig. 3, is recommended.

The proposed methodology has three steps. First, QRA is used to obtain the risk score for each grid on the plane. Second, an optimization program (MILP) is run to select the locations for the facilities around the hazardous unit. The final step is to evaluate the locations obtained from the second step using computation fluid dynamics (CFD) simulation, such as a commercial program (FLACS), to better understand geometric effects on explosions.

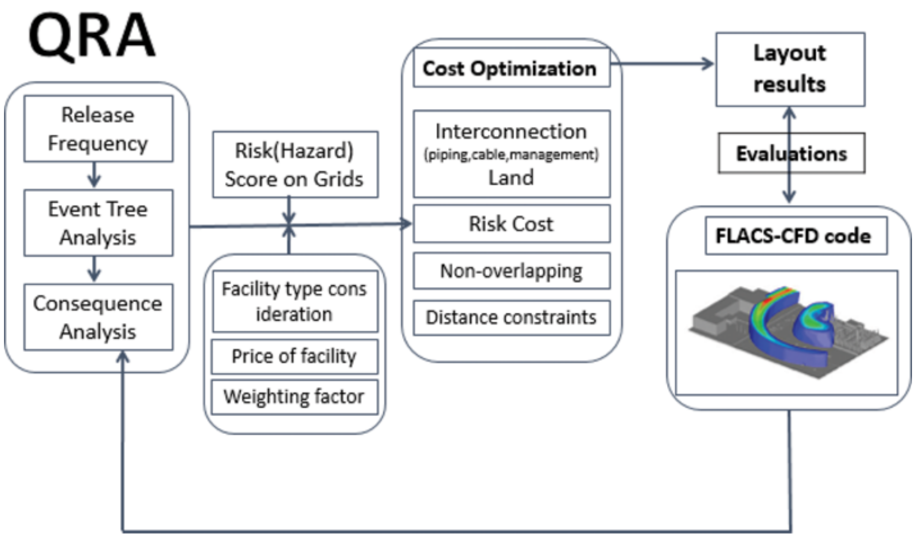

Fig. 3. Flowchart for the proposed methodology.

CONCLUSIONS

This review has explored the methods available for designing chemical plants with better and safer layouts. Researchers have sought to incorporate process safety and QRA approaches into the models used to solve plant layout problems. Those studies have overcome some of the difficulties associated with nonlinearity, uncertainties, and accuracy for consequence modeling. However, future work should seek to develop layout optimization technologies suitable especially for sites with extremely limited areas such as offshore platforms and FPSOs (Floating production storage and offloading), where a multi-deck layout is required though there have been trials of such systems including safety concepts [13], Current approaches, including the research on FPSO, could be further improved by more rigorous consequence analysis. In addition, a 3D explosion simulator could be used to include a more realistic explosion overpressure load, which is important in situations with congestion. Computer-aided plant design can also contribute to a better layout when used in conjunction with optimization and consequence analysis, as well as a dispersion, fire, and explosion study that uses 3D simulation programs. This approach would enhance the speed of comparing and computing different layouts, since 3D consequence simulators need geometries from CAD.

The approaches to plant layout optimization discussed in the present work can be used by decision makers to create low-risk layouts, and to determine whether a proposed plant can be safer and more economic.

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