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Inherently safe and economically optimal design using multi-objective optimization: the case of a refrigeration cycle

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Abstract

The Economic viability of industrial processes strongly depends on their safe and reliable operation. The method of inherent safe process design enables systematic consideration of safety measures in order to ensure process safe operation at the early stages of process design. The challenge is that the economic measures that are often considered for the design of industrial processes are often incommensurable with the safety measures. In the present research, a novel framework is proposed in which the safety criteria are quantified based on consequence modeling and aggregated with the economic performance using multi-objective optimization programming. The developed methodology was applied to the design of a simple refrigeration cycle. The optimization algorithm was NSGA-II. The results suggested a strong trade-off between the competing economic and safety objectives in terms of Pareto frontiers that clearly quantified the required compromise. It was observed that only with a minor increase in the capital investment, it is possible to significantly improve the safety. While the case of the LNG refrigeration cycle was selected as a demonstrating case, the research methodology is to large extend general and deemed to be acceptable to design and operation of other industrial processes.

Keywords

Inherent safety, Consequence Modeling, Multi-objective Optimization, Layout Optimization, Simple refrigeration cycle

1. Introduction

The modern approach to chemical process safety is to apply risk management systems theory. This includes identification of the hazards, and assess the associated risks, in order to reduce

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them to an "as low as reasonably practicable" (ALARP) level, while balancing other business objectives (CCPS, 2009). In general, the risk reduction policy, whether directed toward reducing the occurrence or the severity of potential accidents, falls into one of the inherent, passive, active, and procedural categories. The ideal way of dealing with a hazard is to remove it completely if possible. This principle has been incorporated in the systematic application of inherent safety (Mannan, 2013). The provision of the means to control the risk associated with a hazard is very much the second best solution.

There are four basic principles to design an inherently safer process (Kletz, 1991): (1) Minimize: use smaller quantities of hazardous substances (also called intensification); (2) Substitute: replace a material with a less hazardous substance; (3) Moderate: use less hazardous conditions, a less hazardous form of a material, or facilities that minimize the impact of a release of hazardous material or energy (also called attenuation or limitation); (4) Simplify: design facilities which eliminate unnecessary complexity and make operating errors less likely.

An inherently safer design (ISD) can either reduce the magnitude of a potential incident, or make the occurrence of the accident highly unlikely, or perhaps impossible. Consequently, a process that is inherently safer will require fewer and less robust, layers of protection (Mannan, 2013).

Although this strategic ideally should be implemented at an early stage in the process design phase (CCPS, 2009), it may become necessary to implement the concepts of inherent safe design and required major enhancements for existing plants at various phases of the process life cycle (Khan and Amyotte, 2002, 2003; Mannan, 2013). As the process moves through its life cycle and enters the operational phases, it becomes more difficult to change the basic process (CCPS, 2009). At the conceptual design stage, the process configuration and equipment design are developed, their implications are explored, and potential problems are identified. In most cases, the conceptual design stage may be quite short and associated with many uncertainties in the involved physical and chemical phenomena and the process model parameters. However, if the safety measures are neglected during the process design phase, it may have costly implications during operational phases in terms of hazardous accidents and production interruptions. Therefore, at the earliest phases of process design, the designers are encouraged to incorporate ISD concepts. In order to do so, one can integrate these design concepts into the process design by using optimization-based techniques (Mannan, 2013).

The inherent safety level can be evaluated either using (1) consequence modeling (calculation of accidents' consequences) or (2) scoring the process features in terms of safety indices. The majority of the research in the field has focused on developing safety indices in order to evaluate the inherent safety level, for which extensive literature reviews are provided by Khan and Amyotte (2003, 2005), Kletz and Amyotte (2010), and Khan et al. (2015). However, there are little studies on the application of consequence modeling for designing inherently safer processes. In the following, firstly, a brief survey of the methods which apply safety indices is presented. Then the discussion continues with further elaboration of the methods which apply consequence modeling for designing inherently safer processes. The aim is to identify the research gaps and put the present research in the context.

The inherent safer design of heat exchanger network (HEN) has been the focus of researchers. Chan et al. (2014) and Hafizan et al. (2016) integrated the STEP (stream temperature vs. enthalpy plot) graphical approach and the inherent safety index (ISI) which had been developed by Heikkilä (1999). In addition to the inherent safety concepts, Hafizan et al. (2016) considers process operability of the HENs as well.

Ng et al. (2014a) proposed a framework in which various index-based methods can be selected based on the availability of process data during process development and design. One of the shortcomings of the index-based methods is scaling in which the physical or chemical properties are divided into various ranges, in which each range has a score. The scaling procedure may result in subjective measures and discontinuities at the sub-range boundaries. Ahmad et al. (2014) proposed a new measure called Logistic function. Logistic function is a continuous function that relates a score (as the dependent variable) to a safety parameter (as the independent variable) in order to prevent discontinuity issues.

Ahmad et al. (2015) proposed a methodology in which the inherent safety of a separation process is assessed during the design stage. In this approach, four parameters (volatility, toxicity, flammability, and explosiveness) were used to find the total score in order to rank the alternative designs. A systematic framework was proposed by Ng and Hassim (2015) to assist process designers and engineers in assessing and reducing inherent occupational health hazards or the potential risks based on process information availability. Pandian et al. (2015) proposed a systematic methodology for designing an inherently healthier process during the R&D stage using ISD principles.

Groos-Gerardin et al. (2015) presented a framework by combining product engineering and inherent safety to improve the powder impregnation process. They have used minimum ignition energy as a measure of inherent safety. A combined approach for inherent safety and environmental (CAISEN) assessment was presented by Ee et al. (2015). They integrated a life cycle assessment (LCA) and the Inherent Safety Index (ISI) scoring system.

Several researchers have focused on developing inherently safer and healthier bioprocesses using index-based approaches. Ng et al. (2013, 2014b) and Liew et al. (2014, 2015) utilized fuzzy optimization approach in order to analyze inherent safety, health, environment, and economic performance of biorefinaries. With respect to the same objectives, Liew et al. (2016) proposed a sustainability assessment framework for a biorefinery including uncertainty in some parameters (feed flow rate and price).

Ramadhan et al. (2014) developed a multi-objective fuzzy-based optimization model in order to minimize work-related casualties within a palm-based bioprocess during its life cycle, while simultaneously minimizing the operating costs. Due to the stochastic nature of workplace accidents, realistic statistical data has been used for estimating the best possible pathway for the desired process. Ng et al. (2015) presented a process-graph (P-graph) methodology for the planning of bioenergy supply chains. The methodology was developed in order to take into account both total cost minimization and supply chain risk reduction. The p-graph approach enables embedded algorithms for solution structure generation and optimization to be used for planning the supply chain. Ling et al. (2015) reviewed the sustainability assessment methodologies which were used during the process synthesis of an integrated biorefinery system. Ahmad et al. (2016) discussed the inherent safety assessment of biodiesel production pathways from the flammability parameter. The numerical descriptive inherent safety technique (NuDIST) for flammability score calculation was used in this research. Scarponi et al. (2016) proposed a methodology for the selection of inherently safer biogas technology during early design stages. In this method, Monte Carlo sensitivity analysis was applied for the uncertainty of the input parameters and addressing the robustness of the ranked solutions.

The application of inherent safety indices is a simple approach to quantify the level of safety that a process features. However, these methods only provide a relative evaluation of the level of risk between different design options and do not consider vulnerable elements in the surrounding environment that are the true hazard receptors. More importantly, these indices do not demonstrate the potential economic benefits of implementing inherent safety strategies. Quantification of the opportunities for ISD based on consequence modeling approach provides a clearer understanding of the risk (Eini et al., 2015).

Several researchers have focused on developing computing tools based on consequence modeling. Mohd Shariff et al. (2006) developed a tool called integrated risk estimation tool (iRET) that applies the TNT equivalence method and the TNO correlation method to study explosion consequences. Later, Shariff and Zaini (2010) developed toxic release consequence analysis tool (TORCAT) in order to analyze the consequence of a toxic release. A model known as inherent fire consequence estimation tool (IFCET) was developed by Shariff et al. (2016) to assess process plant for the potential boiling liquid expanding vapor explosion (BLEVE).

Patel et al. (2010) integrated consequence modeling and regulatory guidance from "environmental protection agency risk management program" (EPA RMP) in order to select inherently safer solvents.

Jha et al., 2016 developed a hybrid methodology using both index-based and consequence modeling-based methods in order to select the inherently safer design. In this framework, the best process route and the inherent safety level of all process streams are estimated using different indices. Finally, a risk assessment approach (based on consequence modeling) is applied to the worst stream in order to evaluate the acceptability of the design. Methyl methacrylate (MMA) routes were selected for demonstrating the methodology.

Unlike the abovementioned works which have not considered the plant economic during incorporation of ISD concepts, Medina et al. (2009) have proposed an optimization methodology in which both cost and risk were taken into account. They studied the optimum number of storage tanks in a chemical plant. Bernechea and Arnaldos Viger (2013) have used a probabilistic approach to assess risk and to optimize the design of storage plants and for minimizing the risk. None of these studies has considered inherent safety measures in their optimization procedure.

Medina-Herrera et al. (2014) developed a methodology that can be applied in order to design inherently safer distillation systems. They used the principles of quantitative risk analysis combined with economic objectives for the design of two types of distillation arrangements, namely conventional distillation and multi-effect distillation. However, they didn't present an optimization framework for systematic selection of the optimum design.

Since making the processes inherently safer seem to be conflicting with the plant economics in some cases (Medina-Herrera et al., 2014), an optimization framework is required to find an economically inherently safer design.

Nowadays, inherent safety has gained acceptance, with law initiatives and is included in codes. Although considering the costs of hazardous accidents an ISD is necessarily the cost-optimal option (CCPS, 2000; Edwards and Lawrence, 1993; Hendershot, 2000; Khan and Amyotte, 2002), it requires quantification of safety risks and consequences, in addition to bridging between the incommensurable economic and safety objectives (Medina-Herrera et al., 2014; Eini et al., 2015). In addition, a holistic method is needed that systematically generates alternative solutions and screen the candidate decisions in order to find the optimal solution. Such a framework conforms to optimization programming.

Eini et al. (2015) proposed an optimization procedure which integrates both plant economics and accident costs based consequence modeling for different design schemes. They applied the sum of accident costs and processing costs all through the plant lifespan, as the objective function.

They applied consequence modeling and "Probit" function for assessing the costs of the accidents. However, they didn't consider the probability of the accidents. To assess the risk of any accident scenario, it is necessary that the probability of that event and associated consequences be quantified (Javidi et al., 2015).

Due to the uncertain nature of accidents, incorporation of accidents costs directly in optimization problems do not necessarily represent the real risk level. The implication is that ISD concepts should be based on a probabilistic approach. Even if the accident risks are fully quantified by a cost function, the probabilistic nature of the frequency and the intensity of the potential accidents makes the economic function highly uncertain. Therefore, in order to underpin a design solution which is inherently safer and economically optimum, the optimization program should minimize risk levels and plant costs simultaneously. In the present research, multi-objective optimization programming is applied in order to quantify the trade-off between the production economy and the costs of accidents. The solution of a multi-objective optimization is not unique but a set of solutions that form a Pareto front. At one extreme, more weight is given to the economic objective. Here, the risks of potential accidents are assumed to be relatively low. On the other extreme, the safety objective is dominant and the risk of accidents is considered to be likely in order to achieve an inherently safer design. Such a Pareto front can quantify the trade-off between the costs of inherently safe design strategies and process profitability and enable decision-maker to underpin a practical compromise.

In this paper, a multi-objective optimization (MOO) framework is proposed to optimize simultaneously inherent safety level and plant economic. The applicability of the framework is shown using a case study. To evaluate inherent safety level probabilistic risk analysis is considered which combines accidents costs with the likelihood of accidents occurrence. The inherent safety strategies are incorporated into the optimization algorithm by considering decision parameters associated with each strategy. The novelties of the present study in comparison to the previous research (Eini et al., 2015) are as follows:

- Multi-objective optimization programming is applied in order to simultaneously optimize economics as well as inherent safety measures
- Detailed quantitative risk assessment is applied in order to measure inherent safety considering incidents frequencies and consequences
- The combination nature of accident scenarios is formulated in the optimization program.
- Layout optimization considering land cost in the economic analysis as well as safe distances in the case study

Accidents frequencies have not been considered in the procedure presented by Eini et al. (2015). Their defined objective function comprised of summing plant processing costs and accident costs. Consequently, the optimization procedure concerned finding the optimum design using a single-objective function.

Due to the probabilistic nature of the accidents, the consequence modeling results should be corrected by accidents frequencies and accidents occurrence combination to show more realistic risk calculation. Therefore in addition to the plant costs (considering both operating and capital costs) as an objective function, risk can be introduced to the optimization problem as another objective function. According to the different nature of these two objective functions (plant costs and risk), a multi-objective optimization (MOO) problem should be implemented.

The outline of the paper is as follows. The present section explored the research background and justified the necessity of the research. Section two discusses the research methodology and presents the formulation of the multi-objective optimization (MOO). In Section three, the case study is described and the details of risk analysis, as well as the economic objective function, are presented. The results are reported and discussed in Section four. Finally, Section five summarizes the research and concludes the paper.

2. Methodology: Multi-objective optimization for inherently safer design

To Design a process it is required to consider and to compare all feasible alternatives. These alternatives may differ either in their structure, or operation, or both. Different structural and operational decision variables result in different design alternatives. The final selected design scheme should be economically feasible and be consistent with environmental regulations. Nevertheless, the safety level of a design should be of high standards. Considering risk management strategies in the process design provides the opportunity to enhance the process reliability and reduces the losses associated with potential accidents. Therefore, the aim of the present research is to propose a computational algorithm in which inherent safety criteria are systematically considered in the early design stages. The main parts of the proposed algorithm are shown in Figure 1. They are (I) superstructure constriction and objective function evaluations, (II) multi-objective optimization (MOO), and (III) decision-making. Once a superstructure is developed, the MOO algorithm proposes different values for the decision variables. The fitness of the candidate solution is benchmarked against economic and safety criteria. The output of the MOO algorithm is a set of optimal solutions that forms a Pareto front. Finally, using decision-making tools a single solution that established the trade-off between competing objectives is selected as the optimal design. The details of each of these three calculation steps are discussed in the following.

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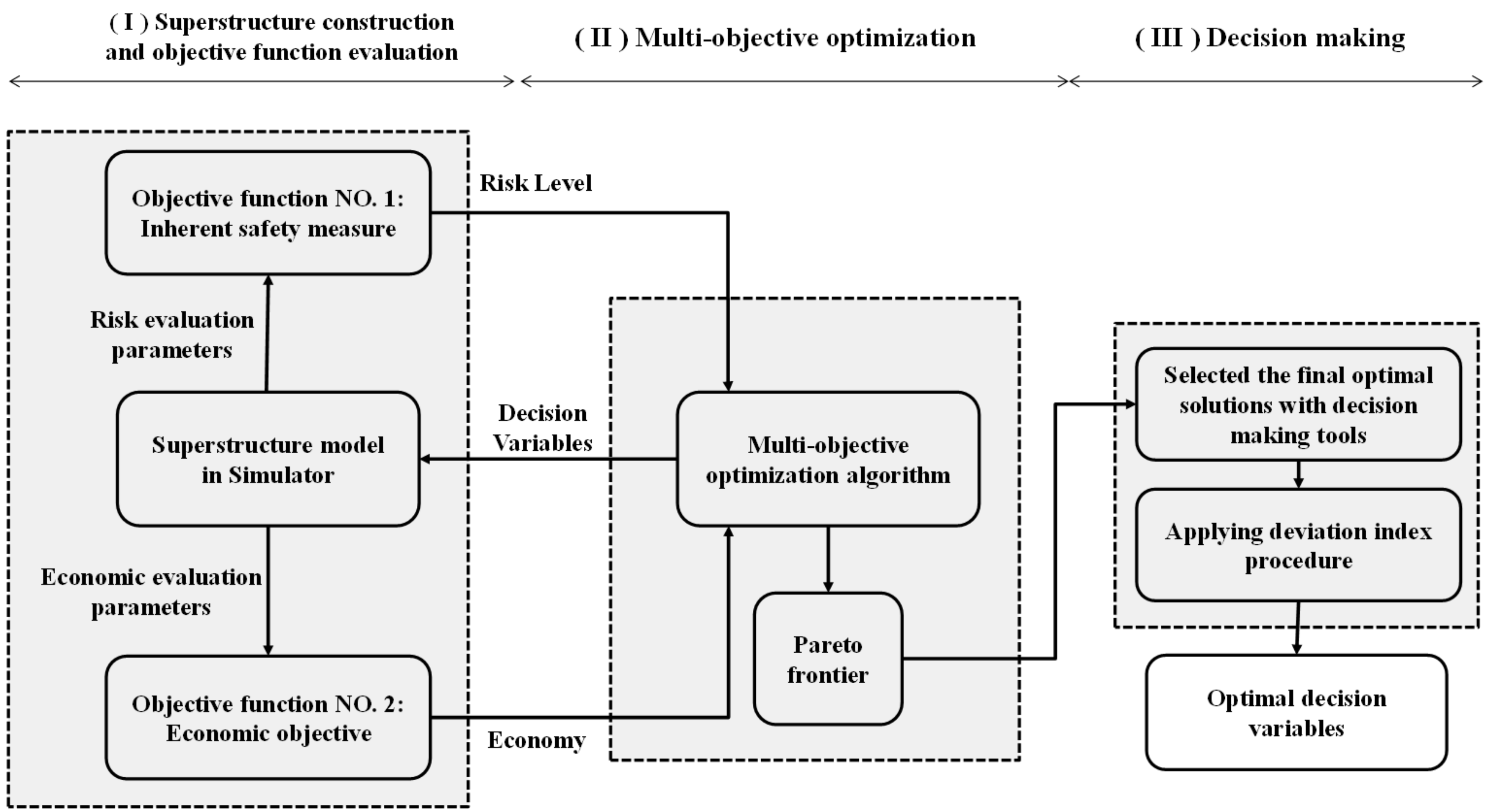

Figure 1 - The general algorithm to select an inherently safer and economically optimal design using multi-objective approach

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2.1. Superstructure construction and objective function evaluation

The ideal treatment for potential hazards in the first place is to completely remove them. However, there is often a very low chance to make a process absolutely "safe" and the goal of safe process design is to find a configuration that is rather inherently "safer" and more reliable compared to other alternatives. Therefore, the provision of means to control the risk associated with a hazard is very much the second best solution (Mannan, 2013). Inherent safety strategies reduce or permanently eliminate the hazards and guarantee lower risk levels by changing the nature of the process. In order to make a process inherently safe, it is necessary to generate alternative solutions systematically. Afterward, the solutions should be screened based on the desired performance criteria. In the following subsection, the required methods for superstructure construction and evaluation of the objective functions are discussed.

2.1.1. Superstructure construction

To take into account all feasible options, a superstructure should be created which embeds all alternative process configurations, processing technologies and their feasible interconnections (Smith, 2005). Such a superstructure should also include various strategies for enhancing the inherent safety of the process, including substitution, simplification, and minimization, moderation. Examples of such strategies are:

- Selection of safer reaction pathways;
- Substitution of hazardous energy transfer mediums, solvents, and adsorbents;
- Selection of alternative safer process equipment (e.g. reactor type, separation technology);
- Moderating processing conditions such as temperature and pressure, or reducing concentration of hazardous materials using inert;

- Reducing the inventory of hazardous materials

The general algorithm to select an inherently safer and economically optimal design (ISEOD) using multi-objective approach is shown in Figure 1.

2.1.2. Objective functions

The two objective functions that should be considered in order to develop an ISEOD are inherent safety measure as well as an economic objective. The economic objectives can be expressed using one of the common methods: total annualized cost, capitalized cost, net present value, and so on. In addition, layout optimization considering land cost as well as safe distances between plant elements may be required. Besides, in order to measure the inherent safety level of a process plant, risk level calculated using quantitative risk assessment (QRA) can be utilized. Nowadays, QRA has become an efficient tool in decision-making to evaluate the risk level. QRA procedure is carried out in several stages: (i) Hazardous scenario selection, (ii) Frequency estimation, (iii) Consequence modeling, and (iv) Risk level calculation. These stages are discussed in the following.

(i) Hazardous scenario selection:

The first stage of the QRA procedure is hazardous scenario selection. For this purpose, all necessary data such as environmental conditions, physical and chemical specification, and process specifications must be collected. Afterward, the potential sources of the hazards which can lead to an accident in the plant are selected as the accident scenarios.

(ii) Frequency estimation:

When the accident scenarios are selected, the second stage of QRA procedure is scenarios frequency estimation. A method for estimating the accident frequencies is event tree analysis (ETA) (Casal, 2008). Having the frequency of a release (as the initial event in each accident scenario), Event Tree is applied for calculating the frequency of final possible outcomes. For example, upon a flammable chemical release, the potential outcomes can be a pool fire, a jet fire, vapor cloud explosion (VCE), vapor cloud fire (VCF) and boiling liquid expanding vapor explosion (BLEVE). Two ways can be applied in order to estimate the frequency of an initial event. They are fault tree analysis (FTA) or using failure frequency databanks (Casal, 2008). Failure frequency databanks are constructed based on past accident records. There are several databanks available such as API (2008), OGP (2010), and Handbook of failure frequencies (LNE, 2009).

(iii) Consequence modeling:

Consequence modeling is the third step in the QRA approach. The outputs of this stage are the effects associated with accidents on people, equipment, environment, and so on. Consequence modeling is supposed to be carried out in several steps to model the effects of various scenarios. First, source modeling is performed that provides discharge rate and the total discharged volume over a time horizon. Dispersion modeling is subsequently used in order to describe how the hazardous material is dispersed to certain concentration levels. Then, fire and explosion models convert the dispersion model information into hazard potentials such as thermal radiation and blast overpressure. Consequently, using appropriate effect modeling, the number of individuals affected and the property damage can be calculated. Finally, using of individuals affected and the property damage, and associated costs, the total imposed costs of any accident scenario can be obtained.

(iv) Risk level calculation:

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The final stage of the QRA is risk level calculation. The general expression to calculate the risk level associated with an accident scenario (R_i) imposed to a risk receptor can be shown as follows (CCPS, 2000).

$$R_{(x,y)_i} = f_i \times C_{(x.y)_i} \tag{1}$$

Where i refers to the accident scenario, f is the scenario frequency, C is the scenario consequence, and (x, y) represents the risk receptor location.

Based on Equation (1), the risk level associated with all scenarios in the (x, y) location can be represented as Equation (2).

$$R_{(x,y)} = \sum_{i} f_i \times C_{(x.y)_i} \tag{2}$$

Finally, the risk level imposed to all risk receptors can be calculated using Equation (3).

$$Risk\ level = \sum_{(x,y)} R_{(x,y)} \tag{3}$$

2.2. Multi-objective optimization procedure

Simultaneous consideration of process economy and the level of inherent safety using mathematical programming conforms to multi-objective optimization. A multi-objective optimization program consisted of several competing objectives as follows:

$$\begin{aligned} &Optimize\ \{f_1(\vec{x}), \dots, f_k(\vec{x})\} \\ &Subject\ to\ x \in S \end{aligned} \tag{4}$$

Here, the instances of the economic objectives are the capital investment required for purchasing process equipment, operating costs, raw material costs. Often capital and operating costs are aggregated based on the plant lifespan for example in terms of total annualized costs. The quantification of the level of inherent process safety was discussed in subsection 2.1.2. In the

Optimization problem (Equation (4)), x is a vector of decision variables. Examples of decision variables include process configuration, equipment design, process inventory, and process operating conditions. The decision variable can be decided within a range of feasible candidates $S \subset R^n$ which include alternative process configurations, practical size of equipment, and the safe operating conditions.

In multi-objective optimization problems, the optimal solution is not unique, but compromises a Pareto front or Pareto set. For a given solution on the Pareto front, it is not possible to improve an objective function without compromising other objective functions. For the case of simultaneous optimization of economic and inherent safety, such a Pareto front represent the best comprise that can be reached among these competing objectives. In other words, if further improvement is desired in the level of process safety, more investment is required. Conversely, if further economic saving is needed, the designer should make sure that the safety will not be compromised. The ideal solution vector F^{ideal} and a non-ideal solution vector $F^{non-ideal}$represent the upper and lower bounds for the objective function values of the Pareto optimal solutions, respectively (Gebreslassie et al., 2009; Konak et al., 2006; Madetoja et al., 2008). Figure 2 displays Pareto front, ideal and non-ideal solutions for four possible combinations of the minimization and maximization procedures. The solid curve marks the Pareto optimal solution set. In the algorithm proposed in this paper (Figure 1), there are two objective functions:$f_1(\vec{x})$: Total annualized costs and $f_2(\vec{x})$: Plant risk level which both should be minimized. Therefore it is expected that the Pareto front matches the figure shown in case (a). With respect to this case, the ideal solution is the point in which the risk level, as well as the total annualized costs, have their minimal values. However, this ideal solution cannot be reached in reality.

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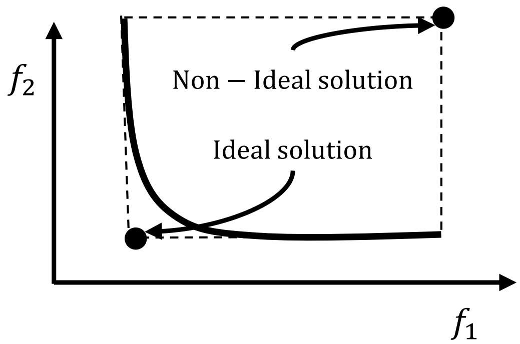
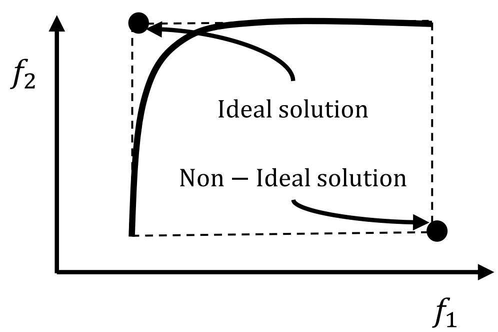
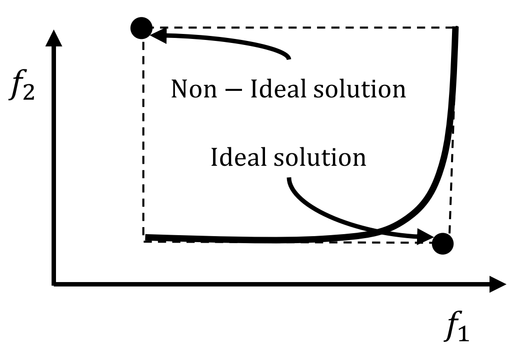
Subsection 2.2.1 describes the multi-objective optimization algorithm used in this paper in order to generate the Pareto front.



Case (a): Minimize f_1, Minimize f_2



Case (b): Minimize f_1, Maximize f_2



Case (c): Maximize f_1, Minimize f_2

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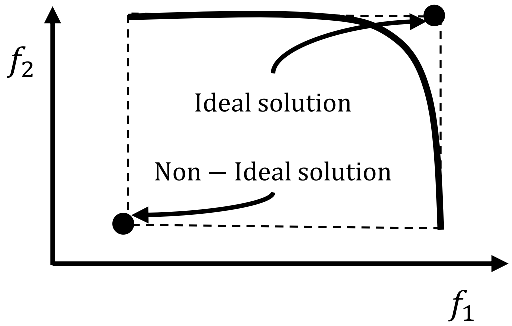

Case (d): Maximize f_1, Maximizef_2

Figure 2 - Pareto set for four combinations of two types of objectives

2.2.1. Visualizing the Pareto furniture, Non-dominated sorting genetic algorithm (NSGA-II)

In this study, NSGA-II algorithm which was introduced by Deb (Deb, 2005) is utilized as a multi-objective optimization method in order to find the optimal Pareto set and the corresponding Pareto front. Deb investigated the simulation outcomes from a number of difficult problems and concluded that NSGA-II outperforms two other contemporary multi-objectives evolutionary algorithms (EAs) (Pareto-archived evolution strategy (PAEs) and strength Pareto EA (SPEA)) (Knowles and Corne, 1999) in terms of finding a diverse set of solutions and in converging near the appropriate Pareto optimal set. According to Figure 3, NSGA-II as an Elite-preserving technic and an explicit diversity-preserving structure can be depicted through the seven steps (Li et al., 2015).

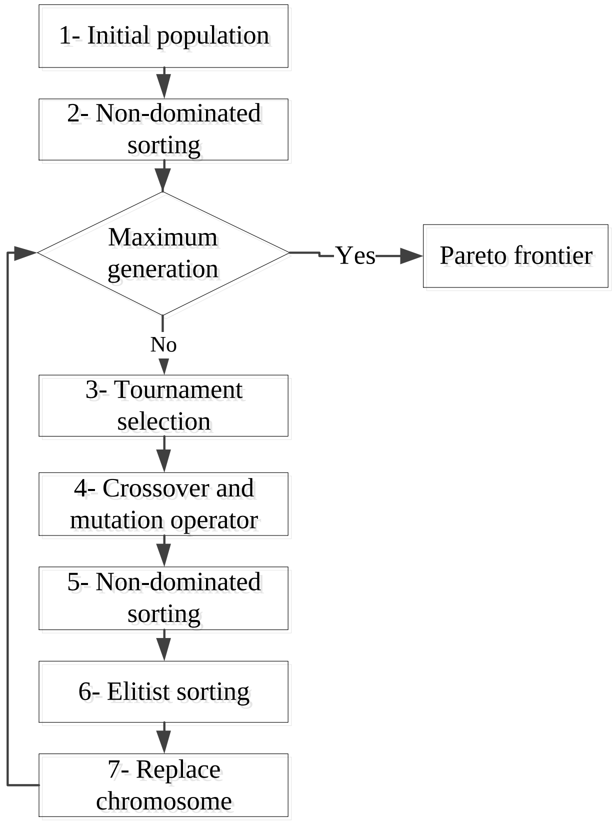

Figure 3 - Flow chart of NSGA-II algorithm

In an evolutionary cycle of NSGA-II, initially, a random parent population is generated. The population is sorted based on the non-domination procedure (rank and crowding distance). Parent selection for crossover and mutation operation is performed based on the tournament selection. In the next step, crossover and mutation are used to generate the child populations. Then all previous and current population members are integrated together to create a combined population, then the population is sorted according to non-domination. Since all previous and current population members are included in combined population, the elitism is insured. It means that solutions with better fitness are chosen by elitist sorting and these become the parent individuals. These steps are repeated until the maximum generation number is reached and Pareto front developed.

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All of the point on the Pareto front can be a candidate for the optimal solution. Therefore, to select a single point on the Pareto front, a decision-making tool is needed. Subsection 2.3 presents the basic concepts of two well-known decision-making methodologies.

2.3.Decision-making on multi-objective optimization

In multi-objective optimization problems, all the points on the Pareto set are optimal solution with different weights to various objective values. However, in the practical point of view, only one optimal solution should be chosen. In this paper most well-known and the common type of decision-making processes including the LINMAP and TOPSIS methods are applied in parallel in order to specify the final optimal solution. TOPSIS estimates the alternatives adoptability according to their distance with the ideal and the non-ideal points. Meanwhile, LINMAP method follows the nearest alternative to the ideal point. The following sections are presented here in order to describe these decision-making algorithms.

2.3.1. LINMAP decision-making (Linear Programming Technique for Multidimensional Analysis of Preference) (Yu, 2013)

The distance of every solution on the Pareto front from the ideal solution marked by d_{i+} is defined as:

$$d_{i+} = \sum_{j=1}^{m} (F_{ij} - F_j^{ideal})^2 \quad i = 1, \dots, n \tag{5}$$

Where F_j^{ideal} is the ideal solution of the jth objective in a single-objective optimization. In the LINMAP decision-making, the solution with minimum distance from the ideal point is selected as a final desired optimal solution.

2.3.2. TOPSIS decision-making (Technique for Order Preference by Similarity to an Ideal Solution) (Yue, 2011)

Besides the ideal solution, the non-ideal solution is considered in TOPSIS decision-making. Therefore, besides the distance of each solution from ideal solution d_{i+}, the distance of each solution from the non-ideal solution denoted d_{i-} is implemented as a criterion for the selection of final optimal solution:

$$d_{i-} = \sum_{j=1}^{m} (F_{ij} - F_j^{non-ideal})^2 \quad i = 1, \dots, n \tag{6}$$

A new assessment parameter is defined as follows:

$$Y_i = \frac{d_{i-}}{d_{i+} + d_{i-}} \tag{7}$$

In TOPSIS decision-making, a solution with maximum Y_i is selected as a desired final solution. In order to explore the reasonable status of various solutions obtained using above-mentioned tools, the deviation index of each solution from the ideal solution is calculated as Equation (8).

$$d = \frac{\sqrt{\sum_{j=1}^{m} (F_j - F_j^{ideal})^2}}{\sqrt{\sum_{j=1}^{m} (F_j - F_j^{ideal})^2} + \sqrt{\sum_{j=1}^{m} (F_j - F_j^{non-ideal})^2}} \tag{8}$$

3. Case Study

Vapor-compression refrigeration systems are used in the many types of the industrial plants for separation purposes or chemical storage at low temperatures. It is very common to use hydrocarbons as the refrigerant in gas and petroleum processing plants with respect to the availability of hydrocarbons. However, hydrocarbons have a great flammability hazard potential. Nevertheless, due to the usually high power demand of the compressors (Sharifzadeh et al.,

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2011), refrigeration cycle shares great costs in a plant. Therefore, the optimal design of this particular unit, in terms of both economic and safety, is very important.

In the present study, the case of a pre-cooling natural gas using single refrigerant propane cycle is considered, (Manning and Thompson, 1991). Figure 4 shows the process flow diagram. The cycle consists of two compressions stages and aims at cooling dry natural gas down to −13.2 °C.

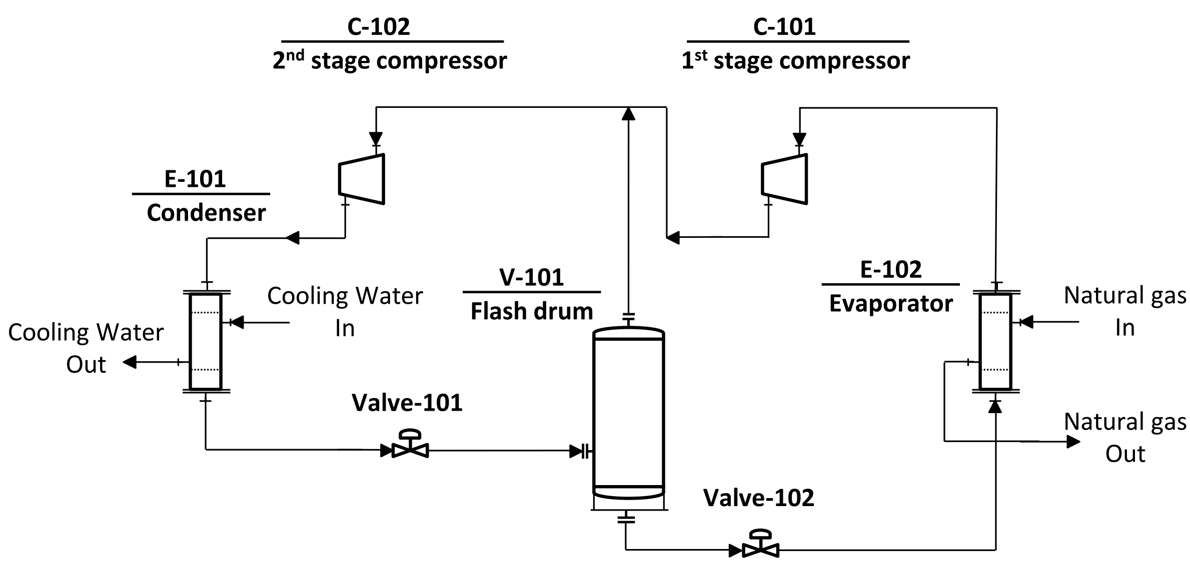

Figure 4 – Simple Refrigeration Cycle

The optimal operating pressure of the flash drum in the propane refrigeration cycle can be estimated as following (Manning and Thompson, 1991):

$$P_{econ} = P_{ch} \, (P_{cond} \, / \, P_{ch})^{0.614} \tag{9}$$

Where: $\mathrm{P_{econ}}$ = optimum drum operating pressure, kPa

$\mathrm{P_{ch}}$ = chiller (evaporator) pressure, kPa

$\mathrm{P_{cond}}$ = condenser pressure, kPa

For the cycle under study, cooling water (entering and leaving the condenser at 25°C and 30°C, respectively) is used as the coolant in the condenser. A typical approach temperature of 5 °C is used for both the condenser and the evaporator (Smith, 2005). Consequently, the temperature of the propane in the condenser and evaporator is 35 ˚C and -18.2 ˚C, respectively. The saturation pressure of propane in these temperature levels is 1234 kPa for the condenser and 260 kPa for the evaporator. Using Equation (9) the optimal operating pressure of the drum is equal to 676 kPa.

The cycle with above-mentioned specification is considered as a base-case in this paper. The optimum pressure calculated by Equation (9) may not be the optimal value if one considers both economic and safety aspects. Therefore, drum operating pressure is one of the decision variables. One of the principal ways to make a process inherently safer is to limit the inventory of hazardous material. It is better to have only a small inventory of hazardous material rather than a large one which needs highly engineered safety systems. Thus, according to the minimization strategy of inherent safety, the number of parallel paths (NPPs) of pressure drop, shown in Figure 5, also can be a decision variable. Because increasing the NPP reduces the refrigerant rate in each path and consequently, the size of the drum and the refrigerant inventory of the drum will be smaller. The NPP as a structural variable is determined in the superstructure. The superstructure which is used in the present study is shown schematically in Figure 5 (Eini et al., 2015). The lower and upper bound values of drum operating pressure are considered to be 300 kPa and 1200 kPa, respectively. These ranges of operating pressures are selected according to the saturation temperature of the propane refrigerant in the condenser and evaporator. Also, it is assumed that NPP can have the values in the range of 1 to 20.

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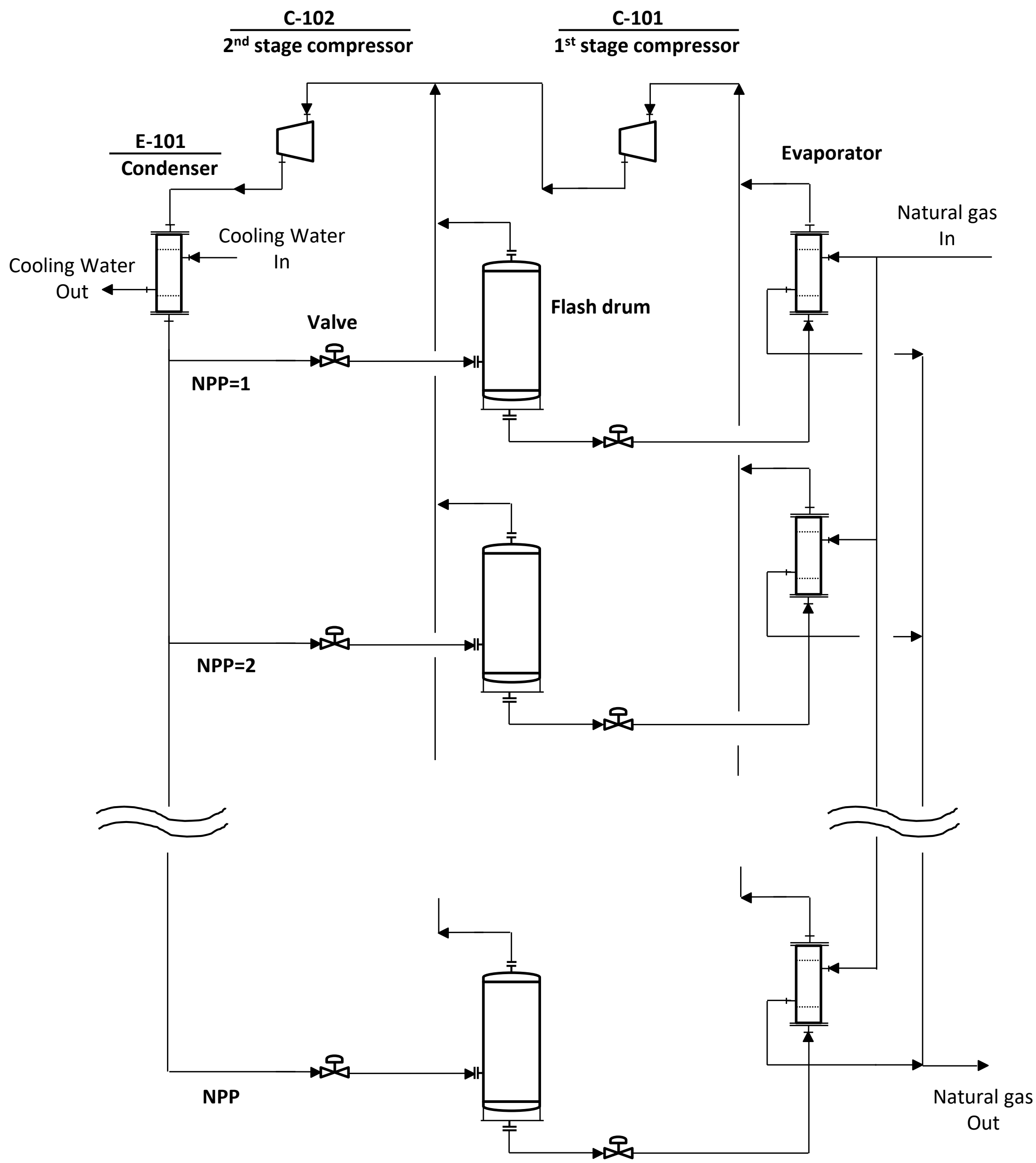

Figure 5 - Intended superstructure of refrigeration cycle

Making the plant inherently safer and economically more profitable are the two objectives of the present research. Here, the plant risk level is chosen as the first objective function for the plant inherent safety. In subsection 3.1 the methodology applied for calculating the risk level is discussed in more detail. Furthermore, subsection 3.2 presents the details of the economic objective function. Afterward, the optimization procedure is presented in subsection 3.3.

3.1. Risk analysis

The failures of vessels and columns account for 21% of accidents in refineries, (CCPS 2003). Since in the present case study (Figure 5) the largest material inventory is located in the flash drums, this paper focuses on the drum(s) as hazard source(s).

In the present research, it is assumed that the phenomena of boiling liquid expanding vapor explosion (BLEVE) occurs during the accident, in which a sudden loss of containment of a pressure vessel (containing a superheated liquid or liquefied gas) occurs due to the explosion. The release of hazardous material is assumed to be followed by a fireball that consumes all of the released material. Since the propane refrigerant is a flammable material, the consequence of the combustion of the entire contents of hazardous materials in the release point is worse than any dispersion scenario. Therefore, a design based on BLEVE is more conservative than any other scenario and is in fact, the worst-case scenario. Consequences of this type of accidents can be very severe, especially in areas close to the release point (CCPS, 2000). It should be noted that for the case of toxic materials (e.g., ammonia, or chlorine), the dispersion may represent more hazard and need to be fully modeled.

In this study, different potential damage receptors were supposed:

- 80 operators in the surrounding area (in 130m radius).
- 8 buildings (B4-Type according to API (1995) definition) at a distance of 300 m downwind; each building has four occupants.

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The meteorological data of the region in the present study comprising temperature, humidity, atmospheric stability class, and wind velocity, are very important to consequence modeling and for QRA procedure (Table 1).

Table 1 - Metrological data of the region

Ambient temperature	30 ºC
Ambient pressure	1 bar
Ambient relative humidity	40%
Class stability	F
Wind speed	1.5 m/s

3.1.1. Frequency estimation:

Table 2 displays some generic frequency data for pressure vessels (LNE, 2009). According to this table, the release frequency for the selected scenario (catastrophic rupture of the drums) is equal to 5E-5.

Table 2 - Frequency data (LNE, 2009)

Loss of equipment event	Frequency(year-1)
Catastrophic rupture	5×10^{-5}
Large breach	2.2×10^{-3}
Medium breach	2.2×10^{-3}

According to the BEVI guide (2009), for the medium size instantaneous spill, the probability of BLEVE/fireball is 50% among all outcomes. This probability is calculated by the product of the probability of immediate ignition rather than non-immediate ignition and probability of BLEVE/fireball rather that explosion. Therefore, the frequency of a BLEVE/fireball outcome can be calculated using Equation (10):

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$$f_{BLEVE/FIREBALL} = f_{leak/rupture} \times (P_{immediate\ ignition} \times P_{BLEVE/fireball}) \quad (10)$$

$$= (5 \times 10^{-5}) \times (0.50) = 2.45 \times 10^{-5}\ year^{-1}$$

3.1.2. Consequence analysis:

There are several damages such as loss of human life, structural damages and environmental damages related to accidents. In this study loss of human life, human injuries and structural damages are considered as the accidents consequences.

To model the consequences of the selected scenarios, it should be noted that a BLEVE has various effects; fireball is the important effect for flammable release materials. The combined action of BLEVE and fireball can be summarized as the following effects:

- Blast wave
- Thermal radiation

For these outcomes, detailed procedure to model the consequences has been presented by Eini et al. (2015). The applied consequence modeling has two features. The explosion severity is calculated based on the TNT equivalence indicator (Casal, 2008), which is used in order to quantify the severity of overpressure conditions produced under boiling liquid expanding vapor explosion (BLEVE) conditions. The potential for fire damage is quantified in terms of fireball duration and thermal radiation, using the source point method (Casal, 2008). Then, the Probit analysis is applied in order to relate the overpressure and fire effects , to the probability of damages for any of the above mentioned vulnerable elements in specified distances. Therefore, the outdoor fatality and injuries due to overpressure and thermal radiation, as well as the damages to buildings (either collapse or major structural damage) due to overpressure, are

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calculated using appropriate Probit models. Finally, by using the following items, the total accident costs can be estimated:

- The percentage of collapsed buildings
- The percentage of buildings which receive major structural damage
- The number of fatalities
- The number of injuries

The building cost has been considered to be 100% of the cost of the building in the case of collapse and 70% for major structural damage (Medina et al., 2009).

Finally, the total cost of the accident (C_{total}) can be calculated summing the cost imposed to each vulnerable element. In other words, the accident cost is expressed as Equation (11):

$$\begin{aligned} C_{total} = \; & (number\ of\ fatalities * cost\ of\ a\ fatality) \\ & + (number\ of\ injuries * cost\ of\ an\ injury) \\ & + (number\ of\ collapsed\ building * cost\ of\ a\ building) \\ & + (number\ of\ damaged\ building * 70\,\%\ of\ the\ cost\ of\ a\ building) \end{aligned} \quad (11)$$

Table 3 shows the cost data that have been used in the consequence modeling.

Table 3 - Cost data (Eini et al., 2015)

Cost parameters	Cost ($)
Cost of a fatality	350,000
Cost of an injury	160, 000
Cost of one building	100,000

3.1.3. Risk level calculation:

As it is shown in Figure 5 the superstructure consists of several drums in parallel. Consequently, it is possible that a number of drums prone to the similar accident at the same time. Therefore, the general equation that determines the risk should be expanded to consider all of the scenario combinations to obtain the realistic results.

The risk associated with the simultaneous explosion of "n_f" drums in terms of its probability and financial consequence can be calculated as:

$$R_{nf} = n_f \times C_{total} \times P_{nf} \times f_{BLEVE/FIREBALL} \tag{12}$$

In the above equation, C_{total} is the total cost of the accident and P_{nf} is the probability of occurrence of this accident as an independent event (Equation (13)).

$$P_{nf} = \left(\frac{1}{n}\right)^{n_f} \tag{13}$$

The number of accident combinations that can occur when n_f units suffer an occurrence out of "n" (the total number of drums in the cycle) is calculated as the Equation (14):

$$c_n^{n_f} = \frac{n!}{n_f!\,(n-n_f)!} \tag{14}$$

Finally, overall risk ($R_{overall}$, as the second objective function to be optimized) can be expressed as Equation (15):

$$R_{overall} = \sum_{n_f=1}^{n} c_n^{n_f} \times (n_f \times C_{total}) \times P_{nf} \times f_{BLEVE/FIREBALL} \tag{15}$$

3.2. Economic Objective function

As mentioned earlier, the refrigeration cycle shown in Figure 5 includes four major elements: (i) compressor, (ii) condenser, (iii) evaporator, and (iv) flash drum. Consequently, the costs associated with these elements are as follows:

- Purchasing cost and energy cost of the compressors.
- Purchasing cost and energy cost of the condenser.

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- Purchasing cost of the evaporators(s).
- Purchasing cost of the flash drum(s).

The methods applied for designing and sizing process equipment were adopted from Towler and Sinnott (2008). Also, the cost estimation methods were taken from Seider et al. (2009). Other costs included the instrumentation and piping as well as land-use costs. Instrumentation cost was estimated to be 10 percent of the total plant investment cost (Perry, 1950). The piping cost was considered to be 86.3 $/m (Han et al., 2013). The land-use cost depends on the plant location and may vary case by case. In this paper, the value of 100 $\$/m^2$ was considered.

The total annualized cost (TAC) was considered as the economic objective function. The TAC includes the capital costs of procurement and the installation of process equipment and costs associated with the operation of the refrigeration cycle.

$$TAC = \text{ } Annualized\ cost\ of\ the\ investment + annual\ operating\ costs \qquad (16)$$

For this purpose, the investment cost (such as the purchasing cost of the equipment and land cost) should be annualized using capital recovery factor (CRF) (Peters et al., 2003). In this paper, the annual interest rate and the plant life time are considered as 18% and 15 years respectively.

In the present study, the number of parallel paths (NPP) was being optimized which affects the required land area. For a plant consisting of m×n flash drum (NPP = m×n), the layout is shown in Figure 6. Here, “a” and “b” are the length and the width of the plant, respectively. The parameter “d” as shown in this figure is the safe distance between two flash drums. This parameter is determined using consequence modeling and is based on the maximum heat flux that reaches the nearby vessels through radiation upon the evaporation of the total material inventory and fire accident. According to General Specification for safety GS 253 (TOTAL, 2012), the radiation level of 9.5 kW/m^2 can be considered conservatively. Therefore, for the case

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study in this paper, a fire (flash fire) consequence modeling was performed in order to determine the safe distances of the flash drums (Casal, 2008).

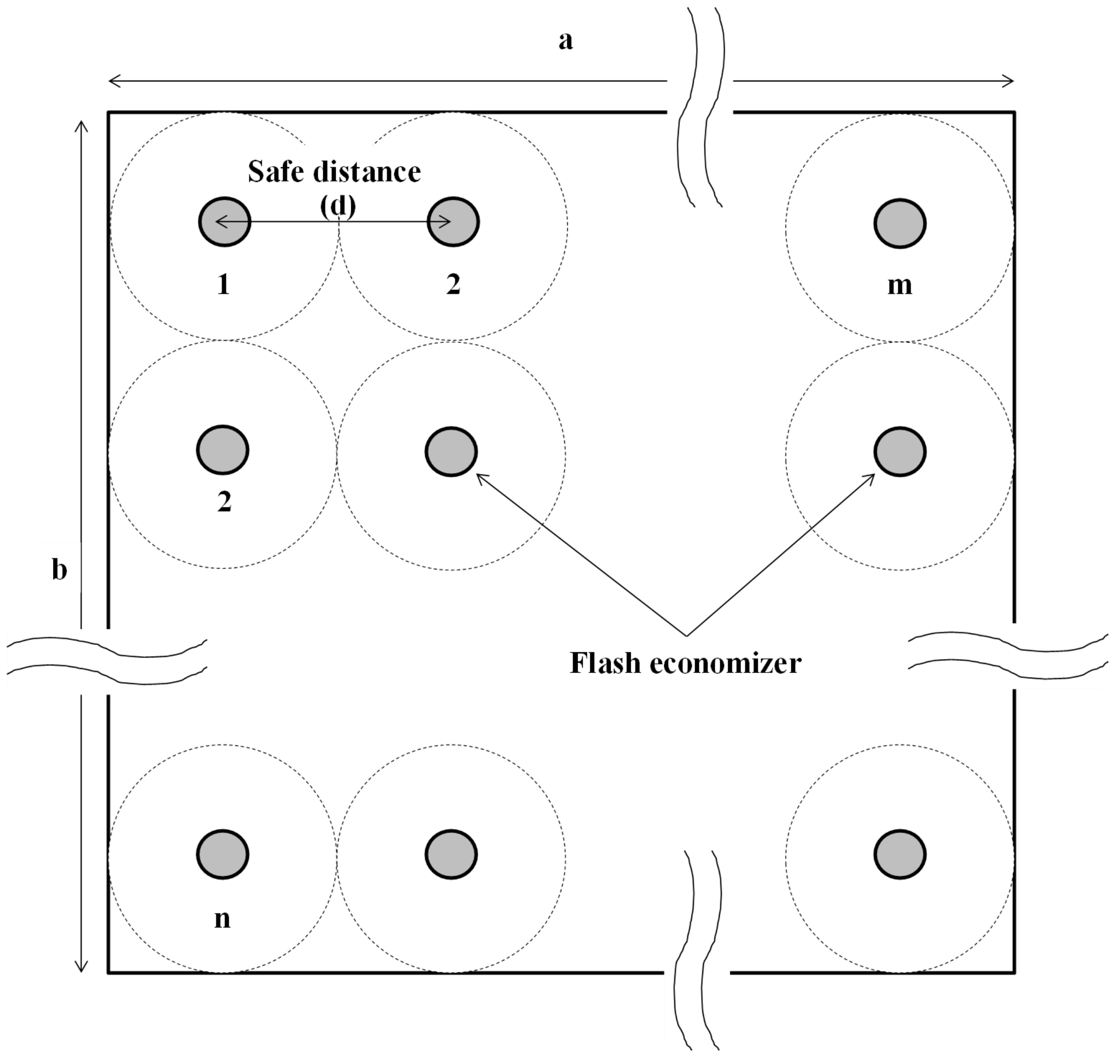

Figure 6 - Flash drum layout

The layout optimization involves two additional decision- variables, “a and “b”. The area of the layout is calculated by multiplying a and b, (Equation (17)). This area needs to be larger than the summation of flash drum safe areas (Equation (18)). The required cost of piping was assumed to be proportional to the total perimeter.

$$Area = a \times b \tag{17}$$

$$a \times b \geq \pi \left(\frac{d}{2}\right)^2 \times NPP \tag{18}$$

$$Perimeter = 2 \times (a + b) \tag{19}$$

In conclusion, the economic objective function (the annualized cost of the plant) can be presented as follows:

$$\begin{aligned} &Annualized\ cost \\ &= \left[Purchasing\ costs\ of\ the \begin{cases} compressors \\ condenser \\ evaporators \\ flash\ economizers \end{cases} \right. \\ &\left. + Instrumentation\ cost + Piping\ cost + Land\ cost \right] \times CRF \\ &+ [Compressors\ and\ condenser\ energy\ costs] \end{aligned} \tag{20}$$

3.3. Implementation of the optimization–simulation program

In this paper, the superstructure is developed in the HYSYS process simulator. The formulations of both risk level and plant annualized cost are codified in MATLAB as well as the MOO algorithm. The optimization algorithm proposes the values of the decision variable and sends them to the simulator. By fixing the specifications of the superstructure (i.e., degrees of freedom), it is possible to execute the simulation program. The value of the objective functions in terms of the performance of each candidate solution is evaluated using the extracted data (such as flow, density, etc.) from the simulator. The iterative calculation of objectives functions provides the opportunity to the optimizer to generate all non-dominated solutions (Pareto front) based on the elitist non-dominated sorting genetic algorithm (NSGA-II). In the last step, final optimum points are then chosen using LINMAP and TOPSIS decision-making methods. Also in this part, in order to explore the reasonable status of various solutions, the deviation index of each solution from the ideal and non-ideal solution is evaluated.

4. Results and discussion

The proposed multi-objective optimization problem including economic and safety measures was optimized using the NSGA-II procedure. In this regard, flash drum operating pressure ("P"), the number of parallel paths ("NPPs"), the length of the plant layout ("a"), and the width of the plant ("b") with corresponding constraints expressed in Equations (21) were considered as the decision variables. In order to define the optimum design variables, the multi-objective optimization problem can be formulated as follows:

$$\begin{aligned}
&\mathit{Minimize\ Risk\ Level} \quad f_1(\vec{x}) \\
&\mathit{Minimize\ Plant\ annualized\ costs} \ \ f_2(\vec{x}) \\
&x = \{P, NPP, a, b\} \\
&\text{Subject to} \\
&300 \le P \le 1200 \\
&1 \le NPPs \le 20 \\
&10 \le a \le 2000 \\
&10 \le b \le 2000
\end{aligned} \tag{21}$$

In the present case study, the plant annualized cost (TAC) and risk level must be minimized simultaneously (Figure 2- case a). The tuning parameters selected for the NSGA-II algorithm procedure are presented in Table 4. In addition, it is possible to visualize Pareto front in a two-dimensional space. Visualization of the Pareto front enables decision-makers to compare different solutions according to their fitness with respect to the competing objectives.

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Table 4 - Specified NSGA-II options for multi-objective optimization

Specified Options	value
Population Size	30
Maximum Generations	300
Tournament Size	2
Crossover Function	Intermediate
Crossover Probability	0.9
Mutation Function	Constraint Dependent
Mutation Probability	0.1
Pareto Fraction	0.6

Figures (8a) show the Pareto front for multi-objective optimization of designing an inherently safer refrigeration cycle, in which the competitions and conflicts between the considered objectives are clearly demonstrated. Since, the range of varying of the objective functions in a multi-objective optimization problem might be different, in order to facilitate the optimization procedure, the dimension and scales of the objective functions were normalized. To do so, the method of Euclidian was applied (Farsi and Shahhosseini, 2015). In this method, the matrix of objectives at various points of the Pareto front is denoted by F_{ij} where i is the index for each point on the Pareto front and j is the index for each objective in the objectives space. Therefore a non-dimensionalized objective F_{ij}^{n} is defined as:

$$F_{ij}^{n} = \frac{F_{ij}}{\sqrt{\sum_{i=1}^{n} F_{ij}^{2}}} \tag{22}$$

Therefore, all non-dominated optimal solutions are plotted in non-dimensional form in Figure 8.

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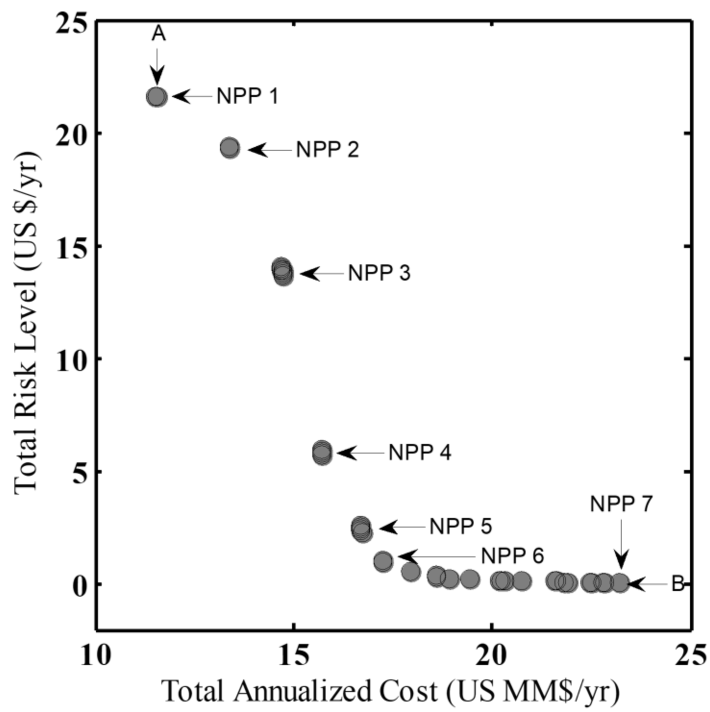

Figure 7 - Pareto optimal Front in the objectives space

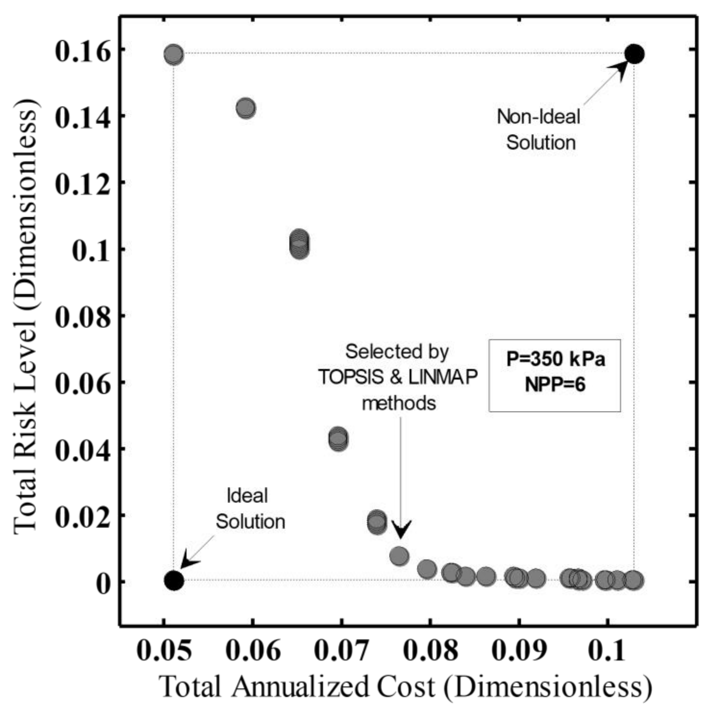

Figure 8 - The set of non-dimensional Pareto optimum solutions using LINMAP and TOPSIS methods to specify the final optimal design point

The Pareto front in Figure 7 shows that the lowest risk level is at design point B (0.0727 US \$/yr), while the TAC has its highest value at this point (23.2×10^6 US \$/yr). On the other extreme, the lowest TAC is at design point A (11.5×10^6 US \$/yr) while the risk level has its highest value at this point (21.621 US \$/yr).

The values of decision variables are shown in Figure 7 for some of the points on the Pareto front in order to clarify the trend of the Pareto front with respect to the decision variables.

If only the TAC was considered as the objective function (single-objective optimization), the design point A (Figure 7), would be chosen as the optimal solution point of the system, while the design point B (Figure 7), indicates the optimum system performance considering the risk level as the objective function. In Figure 8, the ideal point is the point at which each single objective has its optimum value regardless of satisfaction of other objectives (Points A and B, as discussed earlier). In contrast, the non-ideal point is the point at which each objective has its worst value. In Figure 8, the final optimal solution selected by LINMAP and TOPSIS decision-makings is indicated. The results are an ideal solution and also a non-ideal solution.

Table 5 lists the final optimal results of multi-objective optimization and single-objective optimization in detail. In order to quantify the fitness of various solutions, the deviation index of each solution from the ideal solution is also calculated and reported. The fifth column of Table 5 represents the deviation indexes for the results in each optimization approach. As is clear, the deviation indexes (0.0055 and 0.0055) for the multi-objective optimization are less than those for minimum Cost and maximum Risk which are 0.9820 and 0.018, respectively. Therefore, the final optimal solution selected by both of TOPSIS and LINMAP decision-making methods which show the minimum deviation index from ideal solution in multi-objective optimization is most preferred. The last row of Table 5 represents the numerical values of optimum design parameters and objective functions which were corresponded to the coordinate that was determined by decision-making methods.

Table 5 - Comparison between optimal solutions for multi-objective and single-objective optimizations

<table>
<tr><th rowspan="2">Optimization algorithms</th><th rowspan="2">Decision-makings</th><th colspan="2">Objectives</th><th>Deviation index</th><th rowspan="2">P (kpa)</th><th rowspan="2">NPP</th></tr>
<tr><th>Non-dimensional TAC</th><th>Non-dimensional Risk</th><th>d</th></tr>
<tr><td rowspan="2">NSGA-II</td><td>LINMAP</td><td>0.0766</td><td>0.0075</td><td>0.0055</td><td>350</td><td>1</td></tr>
<tr><td>TOPSIS</td><td>0.0766</td><td>0.0075</td><td>0.0055</td><td>350</td><td>1</td></tr>
<tr><td>Minimum TAC</td><td></td><td>0.0511</td><td>0.1585</td><td>0.9820</td><td>383</td><td>1</td></tr>
<tr><td>Minimum Risk Level</td><td></td><td>0.1029</td><td>0.0053</td><td>0.018</td><td>351</td><td>20</td></tr>
<tr><td colspan="7">Optimum design variables and objective functions based on TOPSIS and LINMAP decision-making</td></tr>
<tr><td colspan="2">P (kpa)</td><td>NPP</td><td colspan="2">TAC (US $/yr)</td><td colspan="2">Risk (US $/yr)</td></tr>
<tr><td colspan="2">350</td><td>6</td><td colspan="2">17.3×10^{6}</td><td colspan="2">1.0262</td></tr>
</table>

The value of optimization variables for the base case design (Figure 4), P=676 kPa, NPP=1), the solution reported by Eini et al. (2015) (P= 600kPa, NPP= 11), and the optimum solution found in this study (P= 350 kPa, NPP= 6) are shown in Table 6. Table 6 suggests that, in comparison to the base-case, for 19 percent increase in the TAC, it is possible to increase the level of process safety by 1 order of magnitude. With respect to the previous results by Eini et al. (2015), the new solution is much more realistic as the number of parallel paths is almost halved (i.e., less complexity) but the associated risk is only increased by 17%, In addition, the new solution considers the costs of land-use, piping, and instrumentation that were ignored in the previous study.

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Table 6 - Comparison of optimum point characterizations of base-case, single-objective optimization case (Eini et al., 2015), and multi-objective optimization case (present work)

Optimum point characterizations	Base-case	Eini et al. (2015)	Present study
Drum operating pressure (kPa)	676	600	350
Number of parallel paths (NPP)	1	11	6
Plant annualized costs (US $/yr)	14.5×10^6	22.1×10^6	17.3×10^6
Risk (US $/yr)	21.8256	0.4462	1.0262

5. Conclusion

In this paper, a general framework to design inherently safer processes is developed. In the proposed framework, the two competing and conflicting objectives of process economy and inherent safety are considered simultaneously. The new algorithm is developed in order to consider the level of process inherent safety based on the frequency and the consequence of potential accidents. The solution of the multi-objective optimization (MOO) forms a Pareto front which quantifies the trade-off between competing objectives and enables the decision-makers to choose the optimal design based on the satisfaction of the objectives.

The proposed optimization framework was implemented for the case of a simple refrigeration cycle. The objective functions used in the case study were the plant risk level as well as the plant total annualized costs. Furthermore, a layout optimization was implemented in order to consider, the costs of instrumentation, piping, and land-use. NSGA II was utilized as the MOO algorithm in order to produce the Pareto front. Two well-known and common types of decision-making techniques (LINMAP and TOPSIS) were applied in order to specify the final optimal solution. The results of multi-objective optimization problem suggested that for about 19 percent increase in the total annualized costs, it is possible to decrease the risk level by one order of magnitude in

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comparison with the base-case. While the demonstrating example of the refrigeration cycle provides the proof of concept, the results are deemed to be general and extendable to other industrial processes.

The dynamic behavior of a process strongly depends on its design. Therefore, the decision-making domains of process and control engineers overlap (Sharifzadeh and Thornhill, 2012, 2013; Sharifzadeh, 2013a, 2013b). Moreover, it should be noted that accidents have a dynamic nature. Therefore, the inherent safety level of a process should be assessed not only in the steady state condition but also in dynamic mode and the future researches should address the dynamic aspects of ISD strategies. Furthermore, there is a strong interaction between involved materials and process inherent safety (Ten et al., 2015). Therefore, there are great opportunities for integrating ISD concepts during product design stage using computer-aided molecular design (CAMD) techniques. Based on CAMD techniques, it is possible to select or design new materials that meet specific thermophysical properties. Consequently, CAMD can be used as a good tool in order to design new molecules that feature desirable safety indicators such as moderated flammability, toxicity, and etc. This leads to implementation of the substitution strategy of inherent safety.

6. Nomenclature /Abbreviations

$F^{non-ideal}$	non-ideal solution vector on Pareto front
C_{total}	total cost of the accident [accident cost, for example, $]
F^{ideal}	ideal solution vector on Pareto front
P_{ch}	chiller (evaporator)pressure [kPa]
P_{cond}	condenser pressure [kPa]

P_{nf}	probability of occurrence of an accident as an independent event
$C_{(x.y)_i}$	consequence of scenario i in the risk receptor location (x, y) [accident cost]
F_{ij}	solution i of jth objective on the Pareto front
P_{econ}	optimum drum operating pressure [kPa]
$R_{(x,y)_i}$	risk level associated with an accident scenario i in the risk receptor location (x, y) [accident cost* time^{-1}]
$R_{(x,y)}$	risk level associated with all scenarios in the (x, y) location [accident cost* time^{-1}]
R_{nf}	risk associated with the simultaneous explosion of "n_f" drums [accident cost* time^{-1}]
$R_{overall}$	overall risk [accident cost* time^{-1}]
Y_i	assessment parameter in decision-making
$c_n^{n_f}$	number of accident combinations that can occur when n_f units suffer an occurrence out of "n"
d_{i-}	distance of each solution (i) from the non-ideal solution
d_{i+}	distance of every solution (i) on the Pareto front from the ideal solution
$f_{BLEVE/FIREBALL}$	frequency of a BLEVE/fireball outcome [time^{-1}]
f_i	frequency of scenario i [time^{-1}]
$f_k(\vec{x})$	objective function number k (x is a vector of decision variables)
n_f	number of drums that suffer an occurrence
ALARP	As Low As Reasonably Practicable
BLEVE	Boiling Liquid Expanding Vapor Explosion
CAMD	Computer-Aided Molecular Design
CRF	Capital Recovery Factor
ETA	Event Tree Analysis
FTA	Fault Tree Analysis
ISD	Inherently Safer Design
ISEOD	Inherently Safer and Economically Optimal Design
LINMAP	Linear Programming Technique for Multidimensional Analysis of Preference
MOO	Multi-Objective Optimization
n	the total number of drums in the cycle

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NPP	Number Of Parallel Paths
NSGA	Non-Dominated Sorting Genetic Algorithm
QRA	Quantitative Risk Assessment
TAC	Total Annualized Cost
TOPSIS	Technique for Order Preference by Similarity to an Ideal Solution
VCE	Vapor Cloud Explosion
VCF	Vapor Cloud Fire

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