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Reference:

Eini Saeed, Abdolhamidzadeh Bahman, Reniers Genserik, Rashtchian Davood.- *Optimization procedure to select an inherently safer design scheme*

Process safety and environmental protection / Institution of Chemical Engineers [London] - ISSN 0957-5820 - 93(2015), p. 89-98

DOI: http://dx.doi.org/doi:10.1016/j.psep.2014.05.002

Optimization procedure to select an inherently safer design scheme

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Abstract

There are different well-established strategies for making a process plant inherently safer. The benefits of applying these strategies on reducing the overall risk inside a plant are obvious. However, some of these changes are rejected many times because they appear to be too costly. But if the effects of applying inherently safer design strategies are investigated not only on the processing costs of a plant but also on the potential accident costs, the decision would in fact be different. In this paper an optimization procedure is proposed which integrates both processing and accident costs for different design schemes. In this procedure, some of the design variables are chosen with regard to inherently safer design strategies. The objective function is the sum of accident costs and plant lifecycle processing costs. For assessing accident costs, consequence modeling techniques and probit functions are applied. Consequence modeling formulas and an objective function are codified in an optimizer package (MATLAB) and to accomplish the optimization process a process simulator (called HYSYS) is coupled with this package. The application of the proposed procedure is demonstrated by selecting an optimum process scheme for a Refrigeration plant as a case study.

Keywords: *Process Safety, Optimization, Inherently Safer Optimum Design, Consequence Modeling, safety economics.*

1. Introduction

A chemical manufacturing process is inherently safer if hazards associated with materials and operations have been reduced or eliminated. This reduction or elimination should be permanent and inseparable. This strategic approach is best implemented at an early stage in the process or plant design (Bollinger et al., 1996). Khan and Amyotte indicate that inherent safety can be incorporated at any stage of design and operation, and that its application at the earliest possible stages of any process yields the best results (Khan and Amyotte, 2002, 2003).

There are four basic principles of inherently safer design (Kletz, 1991):

- Minimize: Use smaller quantities of hazardous substances (also called intensification).
- Substitute: Replace a material with a less hazardous substance.
- 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 and limitation).
- Simplify: Design facilities which eliminate unnecessary complexity and make operating errors less likely.

Application of inherent safety strategies can lead to improving safety in a plant and also lowering capital and operating costs (CCPS, 2000; Edwards and Lawrence, 1993; Hendershot, 2000). Khan and Amyotte (2002) replicated similar findings in their studies, which stated that considering the lifetime costs of a process and its operation, an inherently safer approach is a cost-optimal design option. However, implementation of inherent safety strategies requires a comprehensive economic analysis and risk assessment of all parts of a process since applying inherent safety to reduce a particular hazard may result in the increase of other hazards or may lead to unacceptably higher processing costs.

Generally, the evaluation and comparison of the inherent safety level with respect to different design options can be categorized in two groups:

- Evaluation by scoring the process features and the development of indices.
- Quantitative assessment using consequence modeling and the calculation of accidents' consequences.

The majority of the attempts have been made in order to obtain indices to evaluate the inherent safety level. One the earliest indices was proposed by Edwards and Lawrence (Edwards and

Lawrence, 1993; Lawrence, 1996). An overall inherent safety index prototype was developed to illustrate the inherent safety potential of different process routes for manufacturing the same end products (Edwards et al., 1996). Another inherent safety index was developed using fuzzy logic by Gentile et al. (2003), using if-then rules to calculate the index. Palaniappan et al. (2002) developed a systematic methodology and an automated tool (known as i-Safe) to compare process routes for their inherent safety level and select the inherently safer ones developing flowsheets among different design options. A detailed review of available tools and techniques for evaluating inherent safety using indices is given by Khan and Amyotte (2003, 2005). Also, a conceptual framework was proposed by Khan and Amyotte (2005) to integrate an inherent safety index throughout the life cycle of process design.

The application of indices is a simple approach to evaluate inherent safety levels and to compare risk levels of different design schemes. However, it only provides a relative evaluation of the level of risk between different design options and does not consider vulnerable elements in the surrounding environment as possible hazard receptors. More important however, these indices do not demonstrate the possible, and often important, economic benefits of implementing inherent safety.

In the second approach of evaluating inherent safety, it is possible to consider hazard receptors and to have a more clear understanding of the risk, using consequence modeling. Mohd Shariff et al. (2006) have developed a demonstrative tool called “integrated Risk Estimation Tool” (iRET) that uses process simulation software (HYSYS) and spreadsheets (MS Excel) as platforms. iRET was developed for estimating risk levels and consequence analysis from vapor cloud explosions by using the TNT equivalence method and the TNO correlation method. Leong and Shariff (2008) reviewed available techniques for quantification of inherent safety levels and addressed the shortcomings of current techniques by proposing the direct integration of a process design simulator with an integrated inherent safety index called “inherent safety index module” (ISIM). An optimization methodology was proposed by Medina et al. (2009), in which both cost and risk were taken into account to obtain an optimum solution with respect to both economic aspects and safety features. The objective function defined by Medina et al. (2009) includes both investment costs and the cost of potential accidents. They applied the proposed procedure for two case studies, a toxic release and a BLEVE/fireball, to determine the optimum number of storage tanks in a chemical plant. Another tool called “Toxic release consequence analysis tool” (TORCAT) was developed by Shariff and Zaini (2010) to analyze the consequence of a toxic release in order to evaluate the inherent safety level of different process options by determining the concentration of the released gas at a specific distance. Patel *et al.* (2010) applied a "Computer Aided Molecular Design" (CAMD) technique to select inherently safer solvents for a solvent operation. In their work, consequence modeling and regulatory guidance from EPA RMP had been integrated into the process simulation to incorporate principles of inherently safer design into the early stages of conceptual process design. Recently, Bernechea and Arnaldos Viger (2013) presented a method for optimizing the design of storage plants and for minimizing the risk by calculating the ideal number of tanks. Unlike Medina et al. (2009), they used a probabilistic approach to assess risk.

To the best of the authors' knowledge, there is no comprehensive study that provides an optimization procedure to obtain the optimal inherently safer design schemes by considering the evaluation of economic benefits of implementing inherent safety strategies. Although Medina et al. (2009) and Bernechea and Arnaldos Viger (2013) used both financial and accident costs to obtain an optimum design scheme, they did not provide any conceptual procedure to consider inherent safety strategies in their optimization procedure.

In this paper, a procedure is developed to integrate inherent safety assessments in the synthesis of flowsheets and for the optimization of processes. In this procedure, the inherent safety strategies are considered in the synthesis and optimization procedure by considering decision parameters associated with each strategy. To study the effects of implementing inherent safety concepts the costs of accidents are considered besides other processing costs.

2. Methodology

In addition to the difference in processing costs (summation of fixed and operating costs), different designs and options have a different potential of accident occurrence and severity. It is possible that a design, which has lower processing costs, has more associated hazards and consequently more accident costs. An accident is linked to all kinds of direct and indirect costs (Reniers and Audenaert, 2009). To perform a realistic optimization, all costs associated with a process, including accident costs, which are influenced by decision parameters of a design procedure, should be taken into account, since in considering inherently safer design alternatives there are often conflicting benefits and deficiencies associated with each different option (Bollinger et al., 1996). It is thus essential to evaluate the effects of inherent safety implementation on all potential hazards and all economic aspects of the plant.

The Developed procedure to incorporate accident costs into the optimization procedure is shown in Figure 1 and will be explained further.

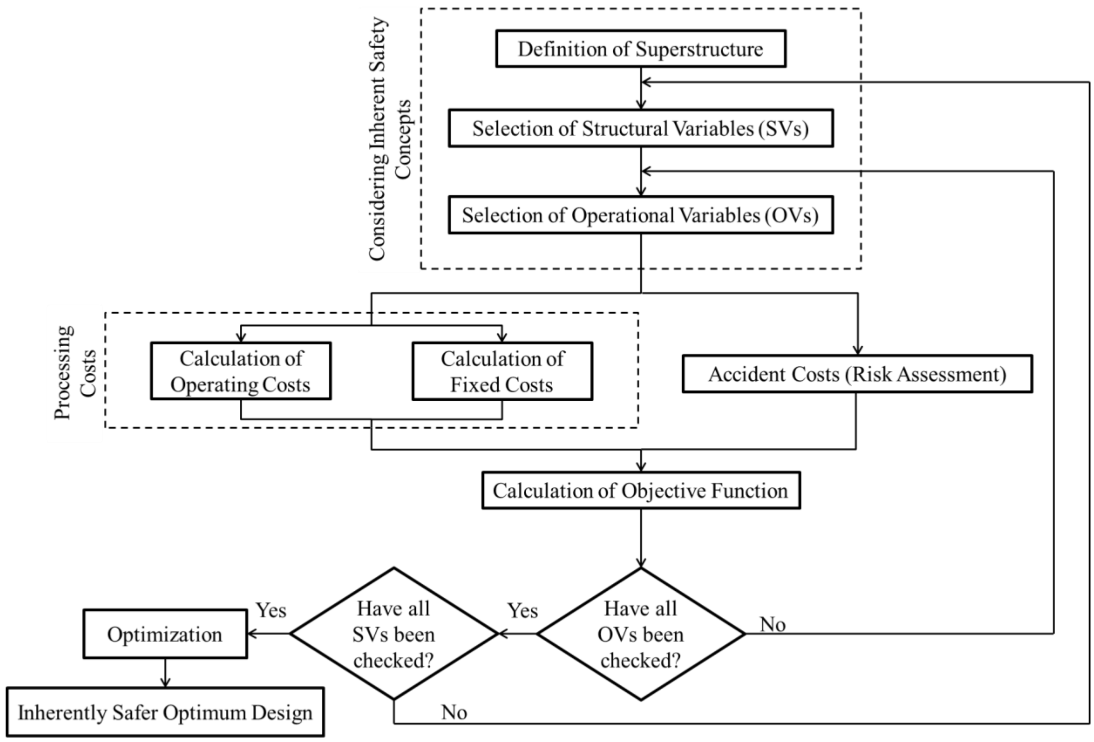

Figure 1: Synthesis and Optimization Procedure including risk assessment

2.1 Definition and Determination of Superstructure

In the first stage to obtain the optimum design, a reducible structure, known as “superstructure”, should be created in which all feasible process options and all feasible interconnections that are candidates for an optimal design structure, are embedded. In this superstructure, some decision variables regarding the inherent safety strategies should also be considered.

2.2. Determination of Variables

Structural variables (such as column sequencing, type of reactor, etc.) specify the path, sequence and framework of an operation and operational variables (such as pressure ratio for compressors, heat exchanger outlet temperatures, etc.) adjust operating conditions in any process path. Whether structural or operational, the variables can be classified in two categories. The first category concerns variables required during the design of a process. Although these variables affect the inherent safety level, the effect is indirect. The second type of variables concern those that are chosen and changed according to the strategies of inherent safety. For example:

- Alternate reaction chemistry;
- Different heat carriers, different solvents and the alike;
- Type of equipment (e.g. different reactor technologies, etc.);
- Equipment arrangement (series or parallel);
- Alternate processing or storage conditions such as temperature, pressure, concentration;
- Distances between equipment (Plant layout).

Selecting any of these variables is based on the nature of the system being considered for optimization. Application of any of these different alternatives will lead to different levels of inherent safety and different processing costs. An optimization procedure of selecting the optimum design variable takes into account the probable processing costs as well as the accident costs.

2.3 Cost Estimation

2.3.1 Processing costs

After selecting a specific process scheme, fixed and operating costs can be calculated. For calculating these costs, the numbers of equipment, their sizes, capacities, and other specifications influencing the cost such as energy consumption, should be determined.

2.3.2Accident costs

When an accident occurs, it imposes some direct and indirect costs. Direct costs include for example medical payments for injured people, costs of fatalities, and costs of damages to structures. Indirect costs encompass losses arising from business interruptions and penalties from the authorities. This paper focuses on direct costs only. An approach that can be used to help calculating direct costs, is consequence modeling. After the selection of a hazardous material release scenario, source modeling is performed. The results include the total quantity released, the release rate and the material phase. Subsequently, dispersion modeling provides the downwind concentration and area affected. The next step of consequence modeling contains fire and explosion modeling from which the results may include blast overpressure and the radiant heat flux. 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 considering the costs of any affected element, the total costs of any accident scenario can be obtained. The application of consequence modeling to calculate accident costs will be shown in more detail while discussing the case study in section 3.3.2 of this paper.

2.4. Objective Function

The optimization objective function establishes the relationship between the overall cost and the decision variable as:

$$Overall\ Cost = f(\text{Decision Variable}) \tag{i}$$

In this study the overall cost is the sum of all costs for each design scheme which can be expressed as:

$$Overall\ Cost = \sum_{Equipments} Processing\ Costs + \sum_{Hazard\ Sources} Accident\ Costs \tag{ii}$$

and the processing costs as:

$$Processing\ Costs = \sum_{Equipments} (Fixed\ Costs + Operating\ Costs) \tag{iii}$$

The accident costs express the costs regarding with all elements affected by accident such as injuries costs, fatalities costs, damages to structures and properties, and etc.

Fixed costs and accident costs are usually expressed in capitalized format (e.g., $), while operating costs are usually expressed with annualized dimensions (e.g., $/year). Therefore, to insert them simultaneously into an objective function, all relevant costs should be annualized or capitalized for the plant life cycle. The optimal design would be the scheme having the lowest objective function value. This research displays all processing costs in capitalized form to be consistent with accident costs obtained from damage assessment based on consequence modeling.

3. Case Study

3.1Refrigeration Cycle

Refrigeration cycles are used in the process industries for many reasons, including separation and chemical storage at low temperatures. Usually, this unit imposes great costs to a plant. This is due to the significant energy that is usually consumed by the compressor in the cycle. In chemical processes, especially gas and petroleum processing plants, with respect to high required refrigeration load and availability of hydrocarbons, the use of a hydrocarbon refrigeration cycle is very common. However, hydrocarbons have a great flammability hazard potential. So, the optimal design of this particular unit, in terms of both processing costs and safety, is very important with respect to plant safety and economics. Different design options are available. Due to the crucial importance of this cycle and the availability of different design options, the refrigeration cycle is selected to be studied in this paper. It is evident that the proposed procedure is generic and thus potentially applicable to any other chemical processing plant.

The selected case is based on a real industrial plant in which the target is refrigerating dry natural gas to -13.2 ^{o}C. The specification of dry natural gas is given in Table 1.

Table 1: Specification of gas stream which is intended to be chilled

Component, Mole %	
Methane	0.843
Ethane	0.054
Propane	0.021
Other Hydrocarbons	0.020
Nitrogen	0.034
Carbon Dioxide	0.021
Sulphur Compounds	0.007
Molecular Weight	19.5
Pressure, barg	70.4
Temperature, ^{o}C	7.9
Flow, kg/h	612,140

A typical single-stage refrigeration cycle is shown in Figure 2 and is characterized with four major elements: Compressor, Condenser, Evaporator and JT-Valve. Another common cycle can be designed as depicted in Figure 3: the refrigerant enters a drum after passing through the JT-Valve and only the liquid phase is used in the evaporator.

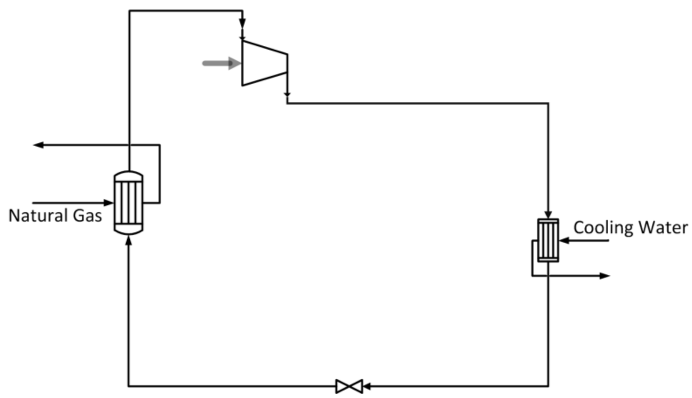

Figure 2: Typical Single-Stage Refrigeration Cycle

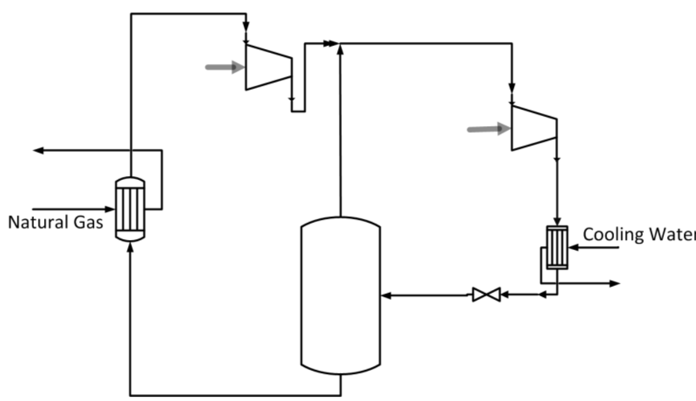

Figure 3: Single-Stage Refrigeration Cycle with a Flash Drum

It is shown that cycle efficiency can be increased by adding a Flash Economizer using two stages of pressure drop as shown in Figure 4 (Manning and Thompson, 1991).

Therefore, these typical design schemes can be used as base cases to construct the superstructure and to determine decision variables in the optimization process.

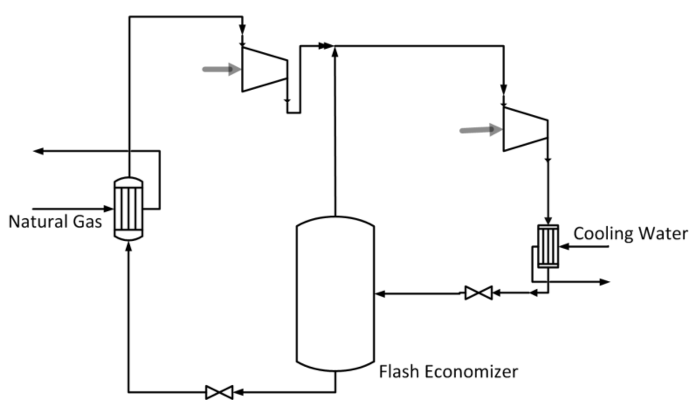

Figure 4: Two-Stage Refrigeration Cycle with a Flash Drum (Flash Economizer)

3.2Decision Variables for Refrigeration Cycle

For the cycle under study, water is used as coolant in the condenser and a typical temperature difference of 5^{o}C is used for both the condenser and the evaporator (Smith, 2005). Consequently, the final compression pressure is calculated based on the refrigerant saturation pressure and condenser refrigerant pressure drop. The number of pressure drop stages is equal to two, except for the single-stage cycles (Figure 2 and Figure 3) in which case it is equal to one. Therefore, the chosen decision variables, which complete the design of the cycle, are the following:

- Refrigerant type
- Flash Economizer operating pressure

However, these variables affect the inherent safety level and consequently the severity of damages and may have some conflicts with one or more strategies of inherent safety.

According to the Minimization strategy of inherent safety, the number of parallel paths (NPPs) of pressure drop, shown in Figure 5, can also 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. Here, only the structure (NPP) of the process has been considered variable and the type of the material of structure and equipment has been supposed to be fixed.

Refrigeration type as a decision variable is considered as an operational variable which can be determined by changing the refrigerant composition. Likewise the operating pressure is considered as an operational variable. The NPP as a structural variable is determined in the superstructure. The superstructure is shown schematically in Figure 5.

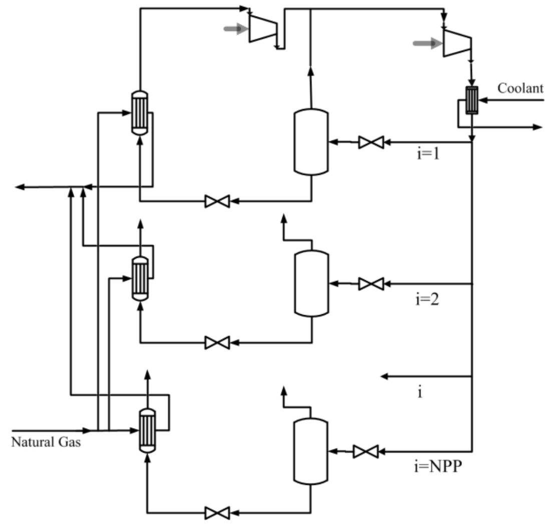

Figure 5: Intended superstructure of refrigeration cycle

The superstructure is simulated in a process simulator (HYSYS). Other calculations (equipment sizing, consequence modeling and cost estimation) are codified in MATLAB as well as an optimization algorithm to find the optimal value of the objective function (sum of processing and accident costs).

3.3 Estimation of Costs

3.3.1 Processing costs

Processing costs are the sum of fixed and operating costs. Fixed and operating costs can be calculated using the number, type, size and required energy for any equipment. For the refrigeration cycle, as shown in Figure 5, the only processing costs that are considered in this study are as follows:

- Purchasing cost and required energy cost of the compressors
- Purchasing cost and required energy cost of the condenser
- Purchasing cost of the flash drum(s)
- Purchasing cost of the evaporators(s)

The material of all equipment in this paper is supposed to be carbon steel as a base material in cost estimation. The piping cost is considered to be 13% of the total fixed costs (Peters et al., 1968). Required input data which are necessary in equipment sizing and thus cost estimation are extracted from the process simulator HYSYS. This required input information as well as the output information which is necessary for optimization, is listed in Table 2. This table also lists the outputs of this step, required to establish the objective function and to perform consequence modeling. Details of equipment sizing and designing can be found in Towler and Sinnott (2008).

Table 2: Processing costs estimation stage required input and output data

Equipment	Required Input Data	Required Output Data
Drum (s)	Inlet Flow and Density (Two phases)	Diameter, Height, Liquid and Vapor inventories, Fixed costs
Compressor (s)	Power Consumption	Fixed and Operating costs
Condenser	Area, Cooling Water Consumption	Fixed and Operating costs
Evaporator (s)	Area	Fixed costs

3.3.2 Accident costs

As mentioned earlier, in this study the consequence modeling approach is used to estimate accident costs. When release scenarios are selected based on a hazard identification study, the modeling of the consequences gives the analyst a realistic understanding of the damage potential regardless of scenarios' frequencies.

For the refrigeration cycle in this paper, hydrocarbons are used as refrigerant and an instantaneous release of the entire contents of hazardous materials in the flash drum(s) due to an explosion (BLEVE), followed by a fireball, is considered as worst-case scenario. The concept of worst-case scenario is thus used as the basis for further calculation of maximum total costs. Consequences of this type of accidents can be very severe, especially in areas close to the release point (CCPS, 2000). In the refrigeration cycle, the Flash Economizer has the largest inventory of hydrocarbons and consequently may be the origin of the most severe accident scenarios in comparison with other equipment. This assumption is supported by a CCPS (2003) report which compared the number of losses by type of equipment. This report assigns the largest losses to vessels and columns by 21 percent of total losses in refineries and petrochemical plants. Therefore, this paper only focuses on the drum(s) as hazard source(s).

Since an instantaneous release is assumed and also due to BLEVE/fireball accidents occurring at the release point, source modeling and dispersion modeling is not required.

The outcome of a BLEVE is a blast wave which produces overpressure. The TNT equivalence method is used to model this accident. In addition, the source point method is selected to model fire and to calculate the fireball duration and thermal radiation resulting from this accident. More details of these methods can be found in Casal (2008). Table 3 shows the required inputs to model these accidents and indicates output information that is required for other steps of consequence modeling.

Table 3: BLEVE/fireball consequence modeling input and output data

Accident	Required Input Data	Output Data
BLEVE	✓ Vessel Volume ✓ Refrigerant Density ✓ Liquid Inventory ✓ Vessel Pressure ✓ Refrigerant Temperature ✓ Refrigerant Normal Boiling Point ✓ Refrigerant Latent Heat	✓ Blast Overpressure profile
Fireball	✓ Refrigerant Inventory ✓ Vulnerable Element Distance to Accident Center ✓ Atmospheric Relative Humidity ✓ Ambient Temperature ✓ Vessel Pressure ✓ Heat of Combustion of the Refrigerant	✓ Radiation Intensity profile ✓ Fireball duration

For the consequence modeling of the selected scenario, atmospheric conditions need to be specified. Prevailing atmospheric conditions in the region where the process is going to be constructed are shown in Table 4.

Table 4: Atmospheric conditions of the region

Ambient Temperature	30 ^oC
Ambient Pressure	1 bar
Ambient Relative Humidity	40 %
Stability Class	F
Wind Velocity	1.5 m/s

In this case study, different potential damage receptors were identified:

- 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.

In the case under study, it is assumed that there was not any major equipment in the vicinity of the refrigeration cycles. So damages to equipment are not studied.

Probit analysis is used to relate the overpressure profile and also the fireball duration and the thermal radiation profile, resulting from BLEVE modeling and fireball modeling, to the probability of damages for any of the above mentioned vulnerable elements in specified distances. So the outdoor fatality due to overpressure and thermal radiation, as well as the damages to buildings due to overpressure, are calculated using appropriate probit models. For buildings, two levels of damages are considered: collapse and major structural damage. Hence, four probit models are used to calculate damages: a probit model to calculate the probability of outdoor fatalities due to overpressure, a probit model to calculate the probabilities of outdoor fatalities due to thermal radiation, a probit model to calculate the probabilities of the collapse of buildings, and a probit model to calculate the probabilities of major structural damages. Details of these probit equations can be found in Casal (2008). The probability of indoor fatalities is calculated using the approach presented in API (1995) and Badri et al. (2013). In addition, the number of injuries due to each accident (BLEVE and fireball) is a function of the number of fatalities resulting from that accident (Casal, 2008; Medina et al., 2009). In this paper it is assumed that thermal radiation does not affect buildings and their occupants.

Finally, by using (i) the percentage of collapsed buildings, (ii) the percentage of buildings which receive major structural damage, (iii) the number of fatalities, and (iv) the number of injuries, the total accident costs can be estimated. This estimation evidently requires costs of each element. Assigning a value to a life or to an injured person is very challenging and a function of many factors (such as social factors, age, damage severity, etc.) that vary from country to country. The cost of a fatality in Iran in this paper is considered approximately 350,000 $ based on a study done by Mohammad Fam et al. (2007) and the cost of an injury has been considered as 160,000$ according to the same reference. The cost of one building has been taken as 100,000$ per unit. Also the 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).

3.4Optimization Framework

Figure 6 shows the flow of data between different optimization elements. The Optimizer determines and sends the decision variable to the Simulator to complete a design. The evaluation variables (such as flow, density, etc.) are extracted from the Simulator to perform consequence modeling and cost estimation. Finally, the optimum design in which the overall costs are as low as possible, are determined.

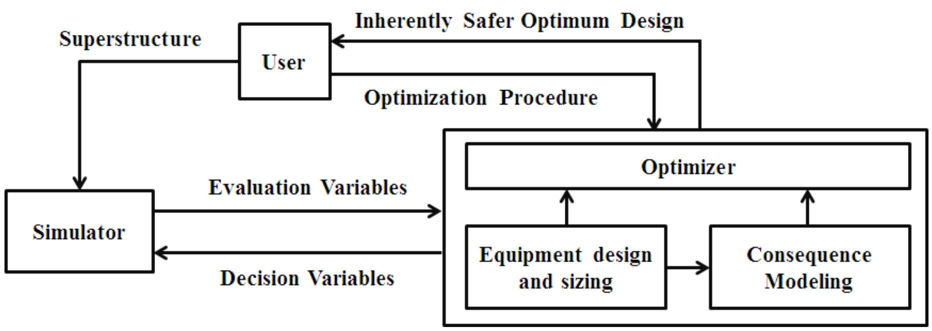

Figure 6: Optimization Elements Interaction

4. Results

For a complete study of inherent safety strategies and the accompanying decision variables, the effects of the different safety strategies on all aspects of a process, should be investigated. In this section 4, the effects of decision variables such as refrigerant type, drum operating pressure, and multiple parallel paths, on processing costs (summation of fixed and operating costs), accident costs, and hence on overall costs (summation of processing and accident costs) are presented.

4.1 Study the Effect of refrigerant type

The operating temperature of the Evaporator is one of the basic criteria to select the refrigerant type, which has also significant effects on processing costs. On the other hand, the Substitution strategy of inherent safety states that the right choice of refrigerant type leads to a lower risk level.

Table 5 presents the different refrigerants which were considered for this case study. The effect of these refrigerants on the overall cost (sum of processing and accident costs) is shown in Figure 7. The effect of this variable is studied for the single-stage cycles (Figure 2 and Figure 3).

Table 5: Different refrigerants considered in this study

Refrigerant Name	Composition	Normal Boiling Point (^{o}C)
R290	100% Propane	-42
HCB1	30% Propane + 70% i-Butane	-22
HCB2	70% Propane+ 30% Ethane	-54

The processing costs are reduced by adding a drum for a specific refrigerant. This reduction is due to the fact that by adding a drum, only the liquid phase passes through the Evaporator. Because the heat capacity of the liquid stream is higher than that of the two phase stream, the required flow for the cycle with a drum is less than the typical cycle.

For the single-stage cycle with drum, the compression ratios for propane, HCB1 and HCB2, are 5.7, 8.5 and 5.5 respectively. As HCB2 is lighter than two other refrigerants and consequently has lower latent heat, more flow is needed for the cycle and as the compression ratio for this cycle and for the propane cycle is approximately equal, the HCB2 compressors require more energy. For HCB1, a lower flow is needed, but the compression ratio is much higher than that of the two other options and consequently the outcome of these two factors results in more compressor required energy in comparison with the propane cycle.

The typical cycle doesn’t have any flash drum, and consequently there is no considerable hazard according to the assumption that the cycle main hazard source is the drum. A refrigeration cycle with a heavier refrigerant has lower accident costs, because the required flow rate for heavier refrigerant is less than that of a lighter one. Consequently the drum size becomes smaller and the available mass for any accident is reduced. So the overall cost is lower for the typical single-stage cycle (Figure 7).

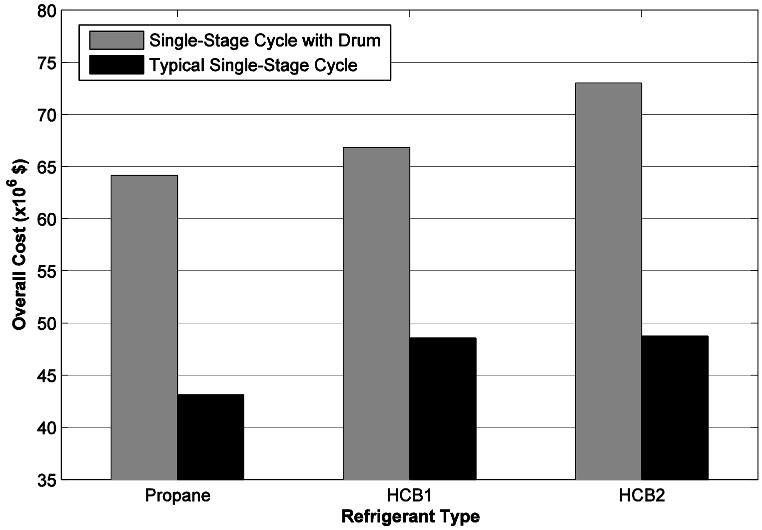

Figure 7: The effect of refrigerant type on overall cost for single-stage cycles

4.2 Study the effect of drum operating pressure

Figure 8, Figure 9, and Figure 10 show the variation in processing costs, accident costs and overall cost, respectively, by changing the operating pressure of the drum.

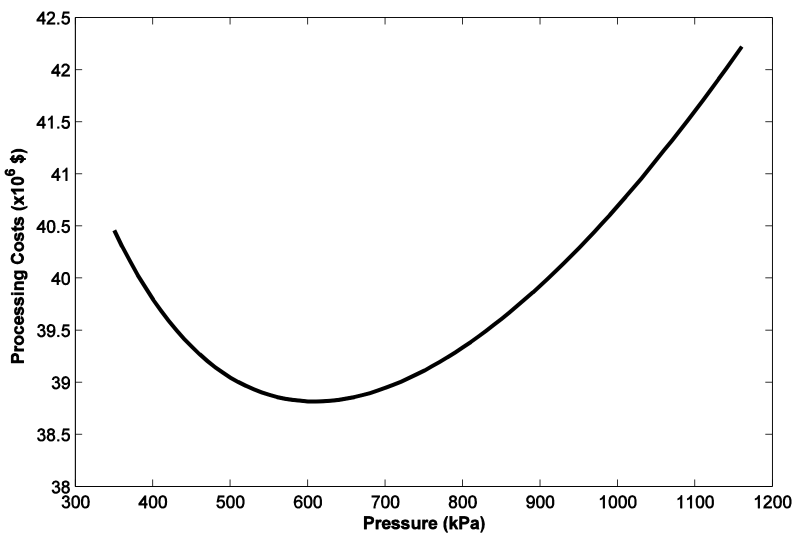

Figure 8: The effect of drum pressure on processing costs for a two-stage cycle

As can be seen in Figure 8, the processing cost has an optimum in 610 kPa but the accident costs are increased (Figure 9) with increasing pressure, due to two reasons. Firstly, as the pressure increases the severity of any probable BLEVE will be higher. Secondly, due to increasing the liquid fraction entering the drum, the liquid hold up in the drum increases and consequently more hydrocarbon inventory will be available in any subsequent fireball.

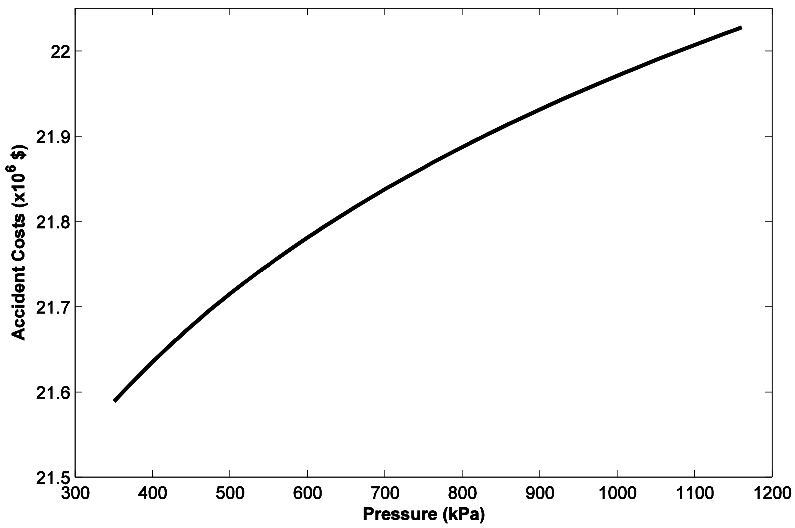

Figure 9: The effect of drum pressure on accident costs for a two-stage cycle

Similar to the processing costs, the overall cost has an optimum too, as shown in Figure 10. But this optimum pressure (590 kPa) does not differ considerably from the optimum value for processing costs (610 kPa) because the pressure does not have a significant effect on accident costs in comparison with processing costs for this case.

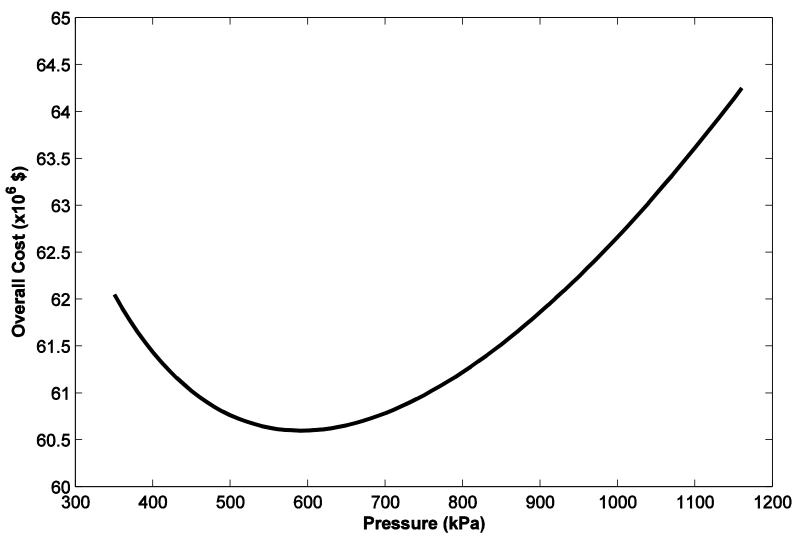

Figure 10: The effect of drum pressure on overall cost for a two-stage cycle

4.3 Study the effect of multiple parallel paths

For a two-stage cycle, the effect of increasing the number of parallel paths (NPPs) on the costs is shown in Figure 11, Figure 12, and Figure 13.

By increasing this variable, operating costs remain constant but fixed costs increase approximately linearly because of the change in the number of drums and evaporators. Drum pressure is fixed at 400 kPa.

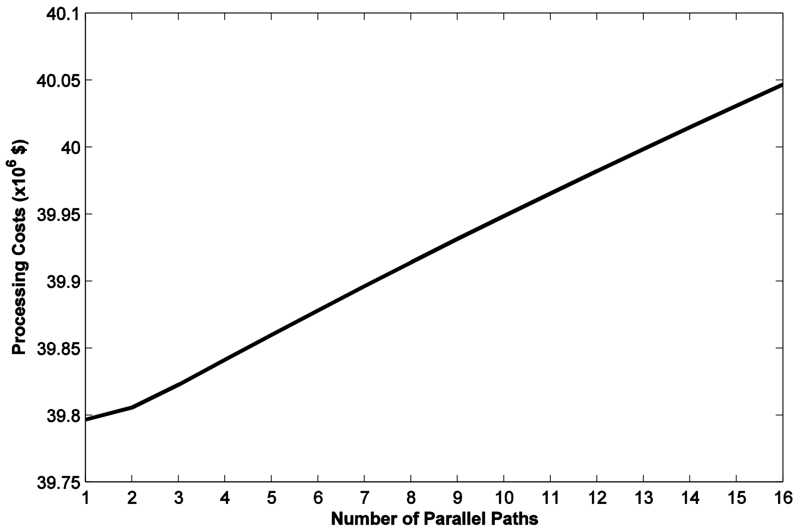

Figure 11: The effect of number of parallel paths on processing costs

As the NPP increases, the refrigerant flow in each path decreases and consequently the size of each drum and its inventory reduces. This leads to lower accident costs. There is a major change in adding the second path to the first due to the considerable reduction of consequences. By increasing the number of paths, the accident costs continue to decrease but the reduction rate decreases as the number of paths increases.

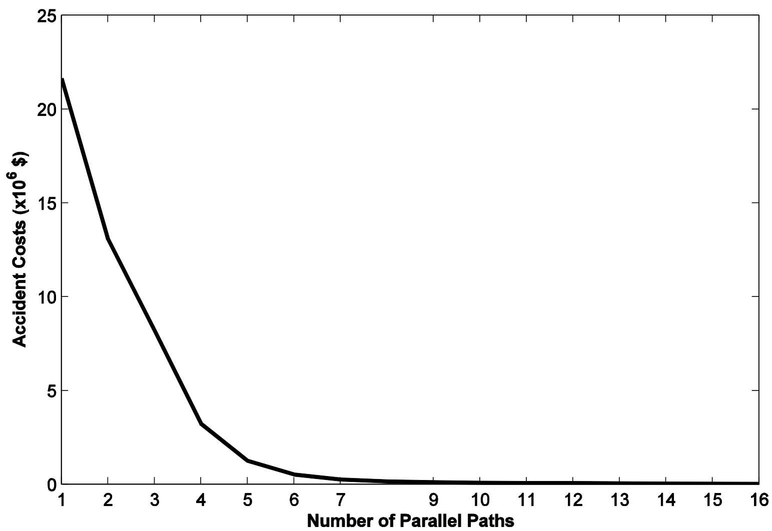

Figure 12: The effect of number of parallel paths on accident costs

A gradual increase of processing costs eventually counterbalances accident costs reduction and this leads to a theoretical optimum point for overall cost, once NPP equals to approximately 11. Of course, this value for NPP produces a high complex cycle.

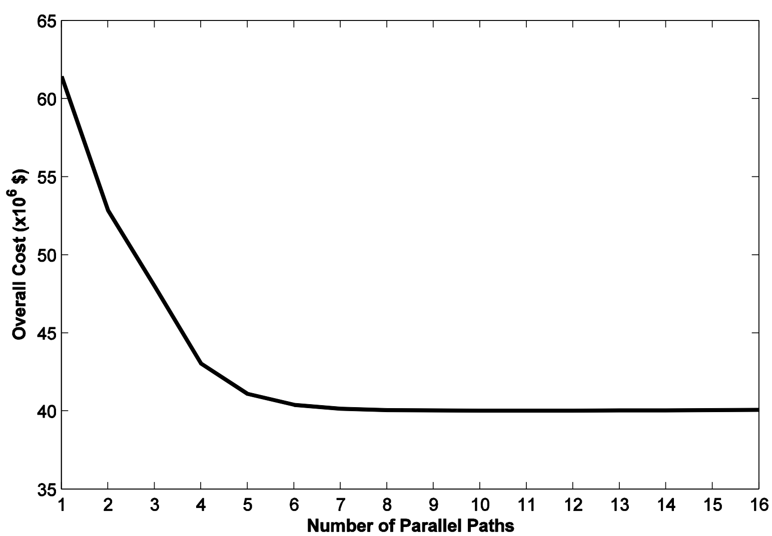

Figure 13: The effect of number of parallel paths on overall cost

4.4 The Inherently Safer Optimum Design

The application of the proposed procedure for the refrigeration cycle under study, considering all of the above mentioned variables, determines the optimum design scheme with the parameters shown in Table 6.

Table 6: Optimum Design Characteristics

Refrigerant	Propane
Number of Pressure Drop Stages	2 stages
Number of Parallel Paths	11 Paths
Drum Pressure	600 kPa
Processing Costs	$39.0\text{x}10^6$ $
Accident Costs	$0.10\ \text{x}10^6$ $
Overall Cost	$39.1\ \text{x}10^6$ $

The optimum NPP according to the optimization output is fixed at 11. So this design scheme will lead to the lowest overall cost. But another factor shall be considered. The complexity of operation and incident frequency (such as leak frequency) may be increased by increasing NPP. Sensitivity analysis such as the one described further may help deciding about the optimum number of parallel paths.

Table 7: Optimum Designs for different number of parallel paths

Number of Parallel Path	Drum Pressure (kPa)	Processing Costs ($\text{x}10^6$ $)	Accident Costs ($\text{x}10^6$ $)	Overall Cost ($\text{x}10^6$ $)
1	590	38.80	21.78	60.60
2	540	38.92	13.47	52.39
3	410	39.72	8.28	47.99
4	470	39.26	3.63	42.89
5	530	39.01	1.63	40.64
6	560	38.96	0.75	39.71
7	590	38.94	0.39	39.34
8	590	38.96	0.23	39.19
9	600	38.98	0.16	39.14
10	600	39.00	0.12	39.12
11	600	39.00	0.10	39.10

Table 7 shows the optimum found characteristics for different refrigeration cycles with different given NPP. This table demonstrates that for more than 6 NPP the overall cost does not change considerably and further increasing NPP does not affect the costs significantly.

In comparison with a typical cycle, the inherently safer optimum design (with 6 NPP) has 9 percent lower overall cost. Also this optimum design shows $21 x 10^6$ \$ reduction in accident costs in comparison with a two-stage cycle (NPP=1, a common cycle in industries), while the processing costs are increased insignificantly.

As mentioned before, the complexity of the cycle is increased by increasing the NPP. It seems that "simplification" is an underrated strategy in Inherently Safer Design.

5. Conclusions

This paper considers processing- and accident costs to optimize design decisions with respect to costs and safety. The approach is applicable for all stages of a plant life cycle where modification or optimization is required. A case study was used to show the applicability and the benefits of the proposed procedure. Case study results show that the consideration of inherent safety strategies in process synthesis can reduce significantly potential accident costs; while often other processing costs change slightly. This procedure provides an absolute, objective and financial measure for managers with regard to benefits of implementing inherent safety concepts. Although consequence modeling is the best way to estimate accident damages and finally to specify effectiveness of inherent safety strategies, the accidents have a probabilistic nature. Therefore, the accident frequency and the effects of ISD strategies on it should be taken into account in future research. Also it is essential that future works focus on developing a method to consider the 'Simplification' strategy of inherent safety in the design process.

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