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## Research Article

# Influence of the Inherent Safety Principles on Quantitative Risk in Process Industry: Application of Genetic Algorithm Process Optimization (GAPO)

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Inherent safety (IS) refers to a set of measures that enhance the safety level of processes and equipment, rendering additional equipment and/or add-ons. The early design phase of processes is suited best for implementation of IS strategies as some of such strategies either are impossible to be implemented at the operation phase or substantially increase costs. The purpose of this study is to present a new approach called genetic algorithm process optimization (GAPO), by which processes can be made inherently safer even at the operation phase. This study simulates the IS principle, assessing its impact on quantitative risk and the possible consequences of process incidents identified by Hazard and Operation Study (HAZOP). The principle of intensification was simulated through GAPO, and feasibility of implementation was approved by HYSYS. Moreover, the integrated inherent safety index (I2SI) was used to evaluate and quantify the level of IS following implementation of GAPO compared to the initial design. Our result shows that GAPO substantially reduced the risk of consequences and quantitative risks and concomitantly improved the I2SI. The proposed GAPO can be applied to process operation as an approach to enhance IS at no cost and without decrease in production.

## 1. Introduction

Engineers and safety activists have always tried to optimize and increase the level of safety in industry through utilizing knowledge and advanced technologies to reduce the probability and severity of human and financial consequences [1–3]. Meanwhile, given the inherent nature of processes, reactions, raw materials, and products, process industries contribute a special role in the occurrence of incidents [4–6]. In process industries including petrochemical facilities, raw materials are converted into intermediate or final products

using a physical and/or chemical chain of circumstances. In such industries, production, storage, transportation, use, and disposal of chemicals are inherently dangerous, and the potential for catastrophic accidents is a significant concern. Since simple negligence in these industries may lead to loss of life, damage to equipment, economic losses, and environmental pollution, great efforts have been made to minimize the chance for occurrence of such incidents.

In a general classification, approaches towards achieving higher levels of safety can be divided into two groups: conventional and inherent [7–10]. Conventional approaches

include control of hazards by safety add-ons such as active or passive engineering strategies, procedural corrective actions, and preventive laws and regulations [3]. In passive safety systems, hazards are controlled through process or equipment design features without additional active functioning of any device. Active safety systems include process controls, safety instrumented systems (SIS), and mitigation systems. Such preventative measures mitigate hazards through controls and systems designed to monitor and maintain specific conditions, which may be triggered by an event. Procedural safety systems use personnel education and management, including standard operating procedures (SOPs), safety rules and procedures, training, emergency response plans, and management systems to control the hazards [10].

Many safety activists applied the inherent safety principles to reduce or eliminate risks and make processes or plants safer without knowing or categorizing the techniques as inherent safety [3, 11, 12]. In 1970, Klets came up with the idea that “What you do not have, cannot leak, or burn” [11]. Ten years after the explosion of Flixborough, and just a few weeks before the Bhopal tragedy, Klets introduced the four basic principles for inherent safety including intensification, substitution, attenuation, and limitation of the effects of failures. During the following years, these principles were reviewed and modified by various researchers [11]. For example, the I2SI described the inherent safety principles (ISPs) in five elements as limitation of effects, minimization, substitution, attenuation, and simplification [3].

Inherent safety refers to a set of measures that enhance the processes and equipment safety level without the need for further equipment and/or add-ons and prevents or reduces the severity of possible incidents [13]. Inherent safety seeks to eliminate the risk with different approaches rather than ignoring or controlling them [14, 15]. Inherent safety design strategies eliminate or reduce hazards to avoid or mitigate the consequences of incidents through principles such as substitution, moderation, and simplification of conventional safety approach. Although implementation of ISPs seems logical, simple, and obvious at first glance, it is challenging because of the required modification in process design, tools, and layouts. Moreover, enforcement of ISPs in a simple process is more difficult due to limited options for achieving inherent safety. For instance, chemicals may not be toxic, and processes are not complicated. These challenges are greater when the process is at the operation stage of the lifecycle, because any modification in the process must be logically feasible, justifiable, and cost-effective [16]. Many studies have emphasized that implementation of ISPs in the early stages of the system lifecycle is more economical and practical due to the lack of need to change the equipment and process layout [17–19].

In the 1970s, quantitative risk assessment (QRA) was initially introduced to the nuclear industry and then integrated into the process industry as legal criteria. During the last four decades, substantial emphasis has been placed on QRA [20]. QRA can be used to numerically quantify the existing risks, determine the unacceptable risks according to a numerical criterion, and prioritize the risk control

measures [21]. QRA is based on identifying the incident scenarios and evaluating the risk by defining the probability of failure, the prospect of various consequences, and the potential impact of those consequences. The QRA risk is defined as a function of probability, frequency, and consequence of a particular incident scenario. The QRA is commonly presented as individual and societal risk. The individual risk expresses the likelihood of experiencing fatal effects at a given location and is not affected by the distribution of population in the area. In other words, the term “individual risk” is used to calculate the risk of fatality for someone at a specific location, assuming an employee is always present at the location [22, 23]. The societal risk is a measure of the risk that the incidents pose to the population and takes into account population distribution in the area. The societal risk is expressed in terms of the likelihood of incident outcomes that affects a given number of people in a single incident. Societal risk is expressed using an F-N curve, which indicates that the expected frequency (F) of incident scenarios resulted in the number of N or more fatalities. The  $x$ -axis of the F-N curve represents the number of fatalities (N), which is depicted on a logarithmic axis with a minimum value of 1. The  $y$ -axis of the F-N curve represents the cumulative frequency of events with the number of fatalities equal to N or more [6, 9, 20]. PHAST software package is a tool that helps in calculating QRA. In 2020, Wu et al. used PHAST to study quantitative analysis of ground flare [24]. Also, Wang and Ma (2021) applied PHAST to calculate quantitative risk for hydrogen refueling station [25]. In 2019, Shuang et al. used QRA to conduct fire and explosion risk assessment in urban natural gas pipeline [26]. In 2016, Tong et al. studied long-distance oil and gas pipelines [23]. However, PHAST software can be used to develop consequence modeling and draw out valid data on QRA.

Genetic Algorithm is an approach, in which the machine can simulate the natural selection mechanism. This is done by searching the problem space to find the better answer, not necessarily the optimal one [27–30]. GA is widely used in studies, in which the stochastic search algorithms are applied to find the optimal or the most immediate answer. In such algorithms, optimization strategies are defined by mixed continuous discrete variables and discontinuous and/or nonconvex system spaces [30]. As with early random generations, initial responses produced randomized generations of children by modifying and combining initial parent answers [31, 32]. This cycle will continue until the full recognition of specified process conditions. Approaching the optimal solution is a necessary condition for the process completion [30]. In optimization problems with various processes, variables, and conditions, GA can be used to find the best/optimum operating conditions for equipment and process to enhance inherent safety without reducing the production of final product (s) at industries.

Numerous studies have been conducted into the assessment of ISPs in reducing both the frequency (more influenced by the vessels construction material) and severity (mostly affected by nature and volume of chemical and process condition) [2–5, 7–10]. Most of these studies reach the conclusion that the best chance to make process

inherently safer is at the design phase of process life cycle. Implementation of these approaches in operation phase would be costly or, in the best situation, need to change the design layout that is not practically applicable in all processes. For instance, Chen (2011) cited the purpose of the Explosion-Proof Technology in Oil Storage and Transportation Devices [5]; Palaniappan et al. (2004) suggested that layout design is playing a key role on making process inherently safer [15]; Rathnayaka et al. (2014), Tugnoli et al. (2008), and Kossoy et al. (2012) suggested the same point of view as Palaniappan [7, 8, 18]. Also, Syaza et al. (2016) purposed a graphical approach to make process inherently safer through research and development phase of process design. Although the earlier phase of process design is the greater opportunity to make the process inherently safer, there is a chance to implement the inherent safety in other phases of process life cycle. The present study aims to simulate the genetic algorithm process optimization (GAPO) and evaluate its effects on quantitative risk and inherent safety status at the operation phase of a methane recovery unit.

## 2. Methodology

The present study was carried out at the methane recovery unit of a petrochemical plant in the south of Iran to simulate the GAPO and evaluate its effects on quantitative risk. In GAPO, the level of produced methane was kept constant compared to the existing state, providing a higher level of safety without reducing methane separation or any add-on. The study was carried out in the following steps (Figure 1).

Figure 2 represents the process flow diagram of the studied methane recovery unit. The process consists of two drums for the refrigeration cycle, a feeding drum, a demethanizer tower, and two heat exchangers. First, the solid particles and the natural gas moisture are removed by filters and dryers. The feed gas (with the composition listed in Table 1) is then cooled to  $-94^{\circ}\text{C}$  by the propane refrigeration (blue in Figure 2) and pumped into different parts of the demethanizer unit. The demethanizer tower is heated with a reboiler, which is embedded at the bottom (first tray) of the tower. Eventually, methane is separated from natural gas based on its bubble point and is exhausted from the top of the tower. The liquid gas, which is known as C2+, is exhausted from the bottom of the tower.

In this study, GAPO was used to optimize propane refrigerant consumption. For this purpose, the initial process was optimized using the GA Module in MATLAB. The implementation feasibility was investigated in terms of compatibility of the stability and energy equilibrium equations with fluids and thermodynamics rules using Aspen HYSYS (Figure 3) process simulator. The statistical population in GA was 10, and calculations are completed for 10 generations.

The role of 8 variables in reducing propane refrigerant consumption was investigated in this study. The initial value and the range of their changes are presented in Table 2.

The intended range of variables for optimization of propane consumption was determined according to the sensitivity analysis performed in the PHAST-Risk software for

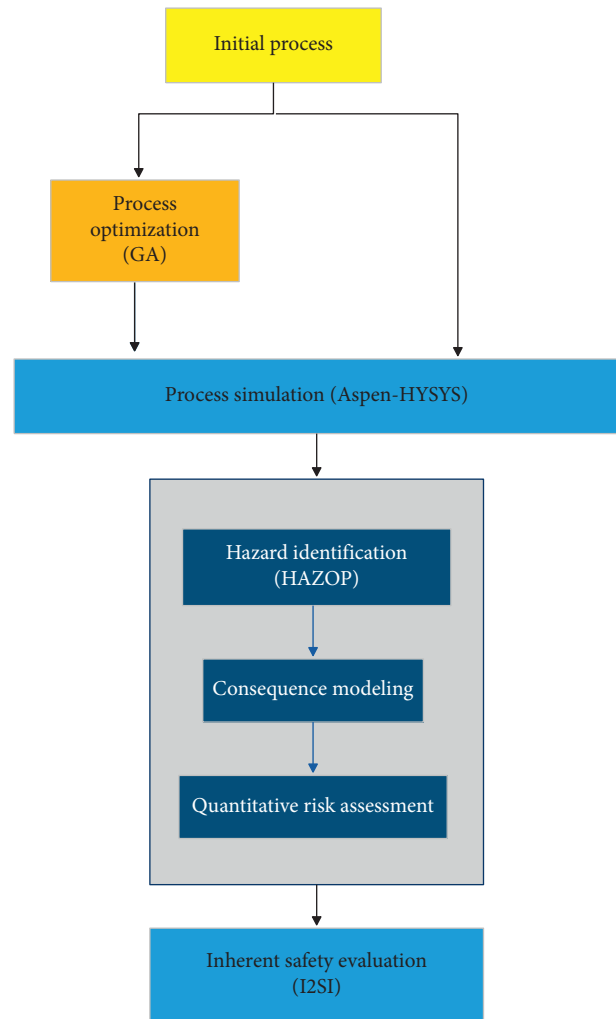


FIGURE 1: Overview of the procedure used in this study.

quantitative risk reduction, as well as variables changes versus the objective function. The objective function of the study was to reduce the propane refrigerant consumption and modify operational conditions to reduce the quantitative risk. Therefore, the optimal answer with minimum quantitative risk has been achieved. In addition, during the initial demethanizer process, the temperature of lines 22–26 (Figure 1), which plays the role of a reboiler in the system, was changed so that the LP steam consumption is approaching zero. The constraints of the problem are shown in Table 3; the objective function has been defined as the ratio of final to initial propane mass flow (kg/hr).

Next, the feasibility of GAPO was confirmed by Aspen HYSYS simulation to check whether the initial process was simulated for Aspen-HYSYS validation. The equation of the state of mixture fluid was PRSV.

The HAZOP method was used to identify the process hazards in the studied process unit. To this end, the process and equipment were divided into separate sections and nodes according to the nature of operation, including process lines, process vessels, process equipment, offsite systems, emergency shutdown systems, isolation at battery limits, and interface with other facilities. Members of the

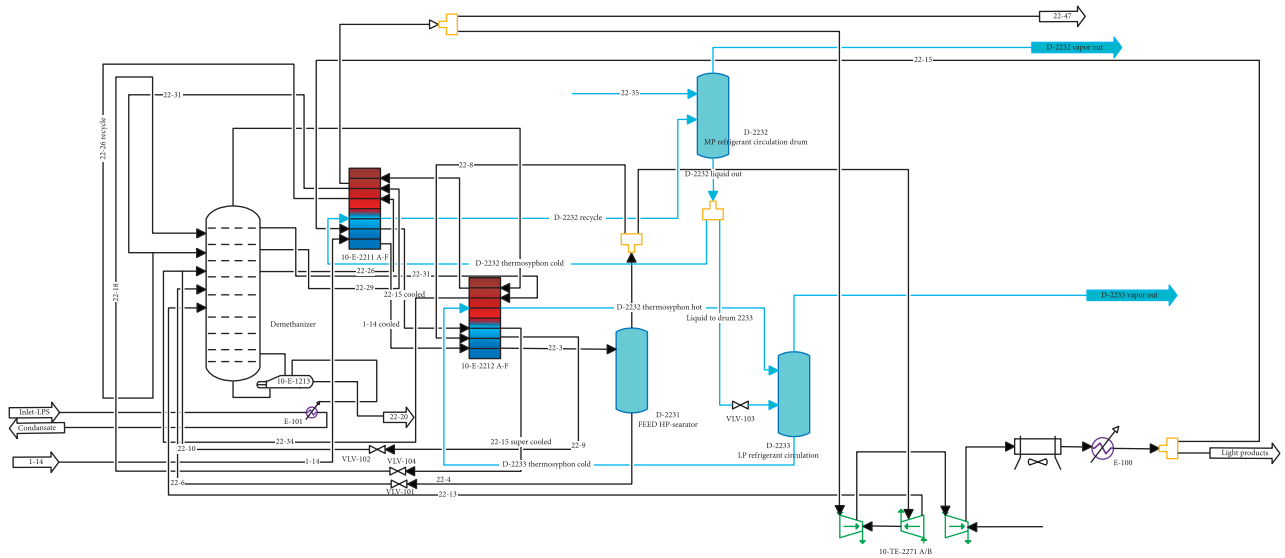


FIGURE 2: Process flow diagram for initial process of studied methane recovery.

TABLE 1: Feed composition in a studied methane recovery unit.

Composition	Mole fraction
Nitrogen	0.0356
CO <sub>2</sub>	0.0102
Methane	0.8677
Ethane	0.0553
Propane	0.0209
i-Butane	0.0038
n-Butane	0.0055
i-Pentane	0.0004
n-Pentane	0.0003
n-Hexane	0.0001
n-Heptane	0.0001
n-Octane	0.0001

TABLE 2: Designed parameters applied for process optimization with genetic algorithm.

Input variable	Value
X1: temperature of stream 22-3 (°C)	-59.94
X2: molar flow of stream 22-8 (Kgmol/h)*	293306
X3: molar flow of stream 22-15 (Kgmol/h)**	129306
X4: temperature of stream 22-31 (°C)	-17.22
X5: temperature of stream 22-34 (°C)	-49.75
X6: boil up ratio	0.8012
X7: outlet pressure of expander	32.01
X8: pressure of top stage of column	31.51

\*Expander is assumed to work in the range of 95%~105% of its normal capacity. \*\*Reflux Ratio is considered to be in the range of 65%~110% of its normal flow rate.

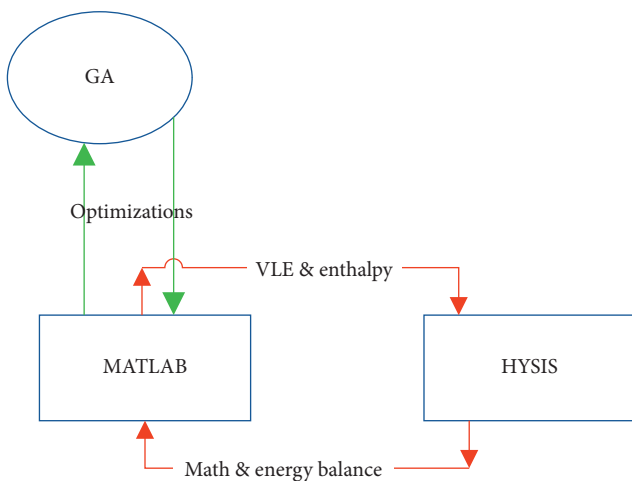


FIGURE 3: Implemented architecture links between Genetic algorithm, MATLAB, and HYSYS (GA: Algorithm Genetic-VLE: Vapor-liquid equilibrium).

TABLE 3: Constraints of genetic algorithm.

Constrains	Base case
C1 recovery % (from demethanizer (T-2211)) > 80	82
Minimum approach temperature of 10-E-2211 A-F > 4.1°C	4.3
Minimum approach temperature of 10-E-2212 A-F > 0.54°C	0.54

HAZOP team, consisting of 17 process, safety, and mechanical engineers, identified the hazards and possible incident scenarios for each node (Table 4).

The consequences of possible scenarios in the studied process unit were modeled using the PHAST software package. The information needed for consequence modeling was derived from the HAZOP study and the operational conditions contained in the P and IDs and PFDs (Table 5). Leakage size and their frequencies were selected based on the

TABLE 4: Identified scenarios for consequence modeling extracted from HAZOP study in the studied methane recovery unit.

Scenario	Composition	Description	Leak size (mm)	Frequency (occurrence/year)	Phase to release	Outcome consequence
Sc01-T01-S	Composition from Table 1	Small leak of demethanizer tower	25	$1.38E - 0.03$	Gas	Jet fire flash fire vapor cloud
Sc02-T01-M	Composition from Table 1	Medium leak of demethanizer tower	100	$5.4E - 5$	Gas	Jet fire flash fire vapor cloud
Sc03-T01-CR	Composition from Table 1	Large leak of demethanizer tower	609	$4.8E - 5$	Gas	Jet fire flash fire vapor cloud
Sc04-D32-S	C <sub>3</sub> H <sub>8</sub> (propane)	Small leak of MP REFR circulation drum	25	$1.38E - 0.03$	Liquid	Jet fire flash fire vapor cloud
Sc05-D32-M	C <sub>3</sub> H <sub>8</sub> (propane)	Medium leak of MP REFR circulation drum	100	$5.4E - 5$	Liquid	Jet fire flash fire pool fire vapor cloud
Sc06-D32-CR	C <sub>3</sub> H <sub>8</sub> (propane)	Large leak of MP REFR circulation drum	609	$4.8E - 5$	Liquid	Fireball flash fire vapor cloud jet fire pool fire
Sc07-D31-S	Composition from Table 1	Small leak of feed HP separator	25	$1.38E - 0.03$	2 phase	Jet fire flash fire vapor cloud
Sc08-D31-M	Composition from Table 1	Medium leak of feed HP separator	100	$5.4E - 5$	2 phase	Jet fire flash fire vapor cloud
Sc09-D31-CR	Composition from Table 1	Large leak of feed HP separator	609	$4.8E - 5$	2 phase	Jet fire fireball flash fire vapor cloud
Sc010-D33-S	C <sub>3</sub> H <sub>8</sub> (propane)	Small leak of LP REFR. Circulation drum	25	$1.38E - 0.03$	Liquid	Jet fire flash fire pool fire vapor cloud
Sc011-D33-M	C <sub>3</sub> H <sub>8</sub> (propane)	Medium leak of LP REFR. Circulation drum	100	$5.4E - 5$	Liquid	Jet fire flash fire pool fire vapor cloud
Sc012-D33-CR	C <sub>3</sub> H <sub>8</sub> (propane)	Large leak of LP REFR. Circulation drum	609	$4.8E - 5$	Liquid	Jet fire flash fire pool fire vapor cloud

TABLE 5: Process information for the initial process design of the studied methane recovery unit.

Equipment	Capacity (m <sup>3</sup> )	Tem. (°C)	Pressure (bar)	Inventory (kg)
Demethanizer	1137	-94.6	33.5	84250
MP REFR circulation drum	49.1	-13.5	3.8	26840
LP REFR circulation drum	54.4	-43.8	1.2	31800
Feed HP separator	82.6	-60	55.6	8119

guidelines of OGP (Risk Assessment Data Directory, Release Failure Frequency, 2010) and DNV. The required climatic information was obtained from the hourly records during the last five consecutive years by the Meteorological Organization (Table 6). Due to weather difference, consequence

modeling was carried out in two climatic conditions of spring/summer (Weather 1) and fall/winter (Weather 2).

In this stage, quantitative risks (societal and individual) were calculated using PHAST-Risk software for the initial process design (IPD) and proposed GAPO. The quantitative

TABLE 6: Meteorological data used for quantitative risk assessment.

Period	Average temperature (°C)	Relative humidity (%)	Wind velocity (m/s)	Prevailing wind direction	Stability class
Weather 1	31.75	46.83	2.71	WNW	A
Weather 2	21.13	52.25	2.69	WNW	B

risk was assessed based on process information derived from simulated processes (Aspen-HYSYS), consequence modeling, and population dispersion. The aim was to assess the effectiveness of GAPO in reducing the risks.

This study implemented I2SI, presented by Faisal Khan et al. (2004), to assess the process inherent safety status in GAPO compared to IPD. I2SI is calculated by dividing the inherent safety potential index (ISPI) to the hazard index (HI) for each subset or equipment (equation 1), and finally, for the entire system (equation 2). An increase in the score of I2SI reflects the improvement of the inherent safety status [33].

$$I2SI = \frac{ISPI}{HI}, \quad (1)$$

$$I2SI_{\text{system}} = \left( \prod_{i=1}^B I2SI_i \right)^{0.5}. \quad (2)$$

In this study, after determining the scenario and identifying the high-risk equipment in the process, I2SI was calculated for optimized process with GA compared to the IPD. Inherent safety status of process and equipment was calculated through I2SI approach according to the field expert's opinion and information from consequences modeling (for each equipment and for the whole system).

### 3. Results and Discussion

**3.1. GAPO and Aspen-HYSYS.** Figure 4 shows mean GA fitness generation for 10 populations in each module compared to the best fitness. Best fitness refers to the fitness of the best individual in the population compare to the goal and condition of study. Each generation provides a new average population fitness that is called mean fitness. In this study, as can be seen, after 10 generations, the mean fitness approached the best fitness. Meanwhile, not only the difference between the mean fitness and best fitness is as low as acceptable (about 0.017934), but also the mean fitness after seven generations has been stabilized, showing that the obtained final objective function is optimum.

The optimized values of the parameters selected as genetic algorithm generations are shown in Table 7. As indicated, by increasing the temperature of stream 22–31 (variable X4) from  $-17.22^{\circ}\text{C}$  to  $-5.25^{\circ}\text{C}$ , the required propane refrigerant mass flow rate increased due to refrigeration reduction in 10-E-2211 cold box. Finally, the refrigerant mass flow rate was decreased by increasing propane temperature in stream 22–26. As the temperature of stream 22–3 (inlet stream to 10-D-2231) (variable X1) increased from  $-59.94^{\circ}\text{C}$  to  $-56^{\circ}\text{C}$ , propane refrigeration decreased due to

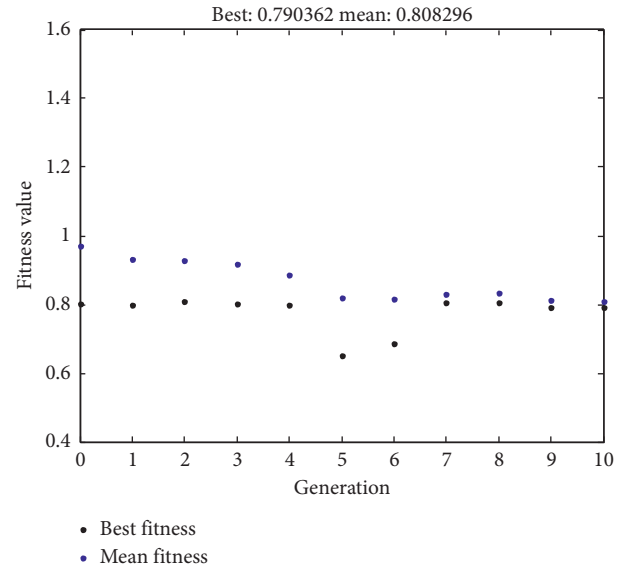











FIGURE 4: Fitness of generation versus best fitness.

increasing conversion of liquid to gas. The increase in gas was caused partly by the stream entering into the 10-TE-2271 expander. Since the pressure drop in the expander caused a cool down, the streams also reduced propane refrigeration flow rate. The pressure drops at the tower from 31.51 barg to 29 barg caused a reduction in the propane refrigeration flow rate. By reducing both the tower pressure (variable X8) and boil-up ratio (variable X6), the temperature of the outlet methane stream decreased, and consequently, the required cooling reduction was achieved. As the boil-up ratio dropped from 0.8012 to 0.7900, the gas flow in the tower also declined, which resulted in a flow rate reduction at tower side streams. The decrease in the rate at side streams eventually reduced the amount of propane refrigeration.

Table 8 shows the process information of methane recovery unit after simulation with genetic algorithm. As can be seen, after implementing the GAPO model, vessels have been changed to the lowest volume and safest status. The drop-in values of all parameters shown in Table 7 indicate a reduction in energy consumption. In other words, while the percentage of methane separation (production of methane and C2+) remained constant, the amount of propane consumption was reduced by 20%, which reduces the volume of vessel, thereby reducing quantitative risk and increasing inherent safety of the process. Therefore, a feasible approach to improve inherent safety at no cost and without decrease in production would be the application of the proposed genetic algorithm process optimization.

TABLE 7: Main properties and results of genetic algorithm optimization applied in this study.

Properties	Amount
Population size	10
Selection method	Stochastic uniform
Probability of crossover	0.8
Number of generations	10
<i>Input variable</i>	Optimized values
X1: temperature of stream 22-3 (°C)	-56 
X2: molar flow of stream 22-8 (Kgmol/h) *	260000 
X3: molar flow of stream 22-15 (Kgmol/h) **	85000 
X4: temperature of stream 22-31 (°C)	-15.25 
X5: temperature of stream 22-34 (°C)	-48 
X6: boil-up ratio	0.79 
X7: outlet pressure of expender	29.3 
X8: pressure of top stage of column	29.00 
Objective function	0.8 



\*Increase  decrease  (changing from main amount).

TABLE 8: Process information of methane recovery unit after simulation with genetic algorithm.

Involved equipment	Capacity (m <sup>3</sup> )	Tem. (°C)	Pressure (bar)	Inventory (kg)
Demethanizer 1	1043	-96.37	29	29220
MP REFR circulation drum	42.1	-13.5	3.8	23020
LP REFR. Circulation drum	27.85	-43.8	1.2	16280
Feed HP separator	70.81	-56	55.6	6352

3.2. Hazard Identification and Consequence Modeling.

Table 4 presents the identified scenarios for consequence modeling extracted from HAZOP study. This table reveals a total of 12 scenarios and details about the 4 most hazardous equipment devices including demethanizer, MP REFR circulation drum, Feed HP separator, and LP REFR. The circulation drum was extracted from HAZAOP study.

Table 9 represents the various consequences of scenarios in the process optimized with GA and the IPD. As can be seen, the vapor cloud radius decreased in all scenarios related to the demethanizer tower (scenarios 1 to 3). The highest reduction was observed in scenario 1, where the vapor cloud radius dropped to 44% at 23780 ppm in GAPO. This reduction is related to the 23% and 20% related to scenarios 2 and 3, respectively. But in scenarios 4 and 5, due

TABLE 9: Results of consequence modeling for GAPO compared to IPD for average annual weather conditions.

Scenario	Consequence	IPD	GAPO
Sc01-T01-S	Vapor cloud-23780 ppm (m <sup>2</sup> )	55	31
	Jet fire-lethality of 100% (m)	23	21
	Flash fire radius (m)	12-32	10-26
Sc02-T01-M	Vapor cloud-23780 ppm (m <sup>2</sup> )	4093	3141
	Jet fire-lethality of 100% (m)	82	75
	Flash fire radius (m)	125-186	110-168
Sc03-T01-CR	Vapor cloud-23780 ppm (m <sup>2</sup> )	160756	129135
	Jet fire-lethality of 100% (m)	410	373
	Flash fire radius (m)	668-850	625-784
Sc04-D32-S	Vapor cloud-10000 ppm (m <sup>2</sup> )	179	174
	Jet fire-lethality of 100% (m)	31	31
	Flash fire radius (m)	21-37	20-36
Sc05-D32-M	Vapor cloud-10000 ppm (m <sup>2</sup> )	5028	5049
	Jet fire-lethality of 100% (m)	106	106
	Flash fire radius (m)	99-138	99-138
	Pool fire zone-lethality of 100% (m <sup>2</sup> )	5028	5028
Sc06-D32-CR	Vapor cloud-10000 ppm (m <sup>2</sup> )	80759	62686
	Jet fire-lethality of 100% (m)	478	426
	Flash fire radius (m)	353-480	313-426
	Pool fire zone-lethality of 100% (m <sup>2</sup> )	20601	15386
Sc07-D31-S	Vapor cloud-22370 ppm (m <sup>2</sup> )	118	106
	Jet fire-lethality of 100%(m)	28	27
	Flash fire radius (m)	17-44	16-42
Sc08-D31-M	Vapor cloud-22370 ppm (m <sup>2</sup> )	6161	5863
	Jet fire-lethality of 100% (m)	96	94
	Flash fire radius (m)	152-220	148-218
Sc09-D31-CR	Vapor cloud-22370 ppm (m <sup>2</sup> )	43481	37566
	Jet fire-lethality of 100% (m)	480	468
	Flash fire radius (m)	406-496	390-467
	Fireball zone-lethality of 100% (m <sup>2</sup> )	40049	34618
Sc010-D33-S	Vapor cloud-10000 ppm (m <sup>2</sup> )	75	52
	Jet fire-lethality of 100% (m)	20	16
	Flash fire radius (m)	11-20	9-17
	Pool fire zone-lethality of 100% (m <sup>2</sup> )	452	254
Sc011-D33-M	Vapor cloud-10000 ppm (m <sup>2</sup> )	1195	939
	Jet fire-lethality of 100% (m)	40	33
	Flash fire radius (m)	28-46	25-42
	Pool fire zone-lethality of 100% (m <sup>2</sup> )	3215	1962
Sc012-D33-CR	Vapor cloud-10000 ppm (m <sup>2</sup> )	6800	4961
	Jet fire-lethality of 100% (m)	141	133
	Flash fire radius (m)	76-117	68-104
	Pool fire zone-lethality of 100% (m <sup>2</sup> )	5805	3419

to constant temperature and pressure in the drum, there is no decrease in the vapor cloud. However, in the worst-case scenario for this drum (Scenario 6), there is a 22% reduction in the vapor cloud radius. The radius of the vapor cloud in the feed drum is not significantly different due to a similar reason. In LP drum, due to reduction in the temperature and





FIGURE 5: Individual risks contours (1pmpy) for GAPO compared to IPD (IPD: Initial Process Design; GAPO: Genetic Algorithm Process Optimization).

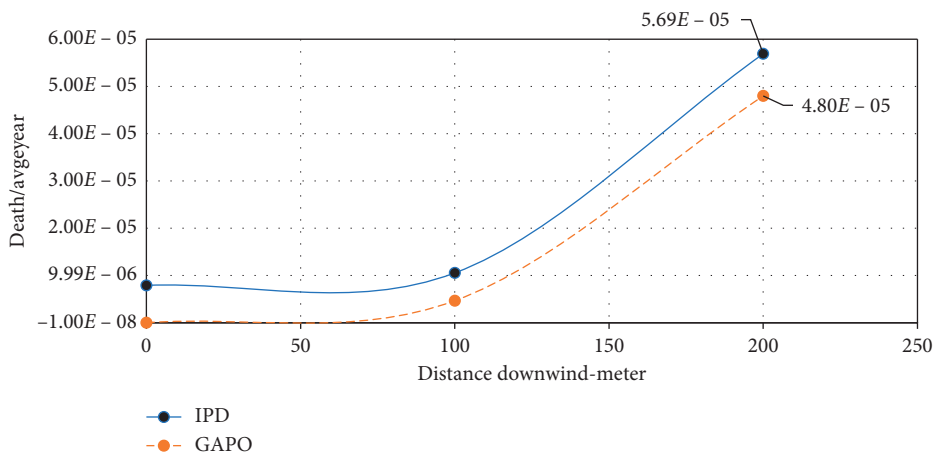


FIGURE 6: Calculated individual risk for GAPO compared to IPD (IPD: Initial Process Design; GAPO: Genetic Algorithm Process Optimization).

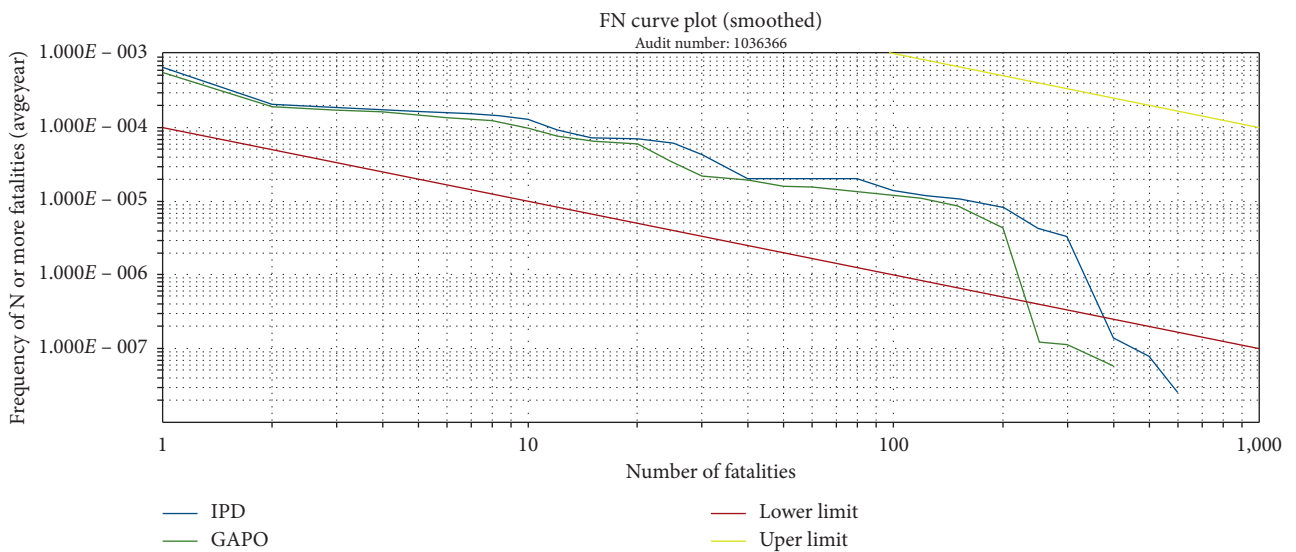


FIGURE 7: Calculated social risk (F-N Curve) for GAPO compared to IPD (IPD: Initial Process Design; GAPO: Genetic Algorithm Process Optimization).

TABLE 10: Result of I2SI for initial Process Design (IPD) compared to Genetic Algorithm Process Optimization (GAPO).

Equipment	Hazard index (HI)		Inherent safety potential index (ISPI)		Integrated inherent safety index (I2SI)		Total I2SI of process	
	IPD	GAPO	IPD	GAPO	IPD	GAPO	IPD	GAPO
Demethanizer tower	3.13	2.00	1.20	2.26	0.38	1.13		
MP REFR circulation drum	1.47	1.75	0.53	1.18	0.32	0.68	0.23	0.79
Feed HP separator	2.00	2.40	0.49	1.45	0.25	0.60		
LP REFR. circulation drum	1.32	1.85	2.39	2.50	1.81	1.35		

inventory, the vapor cloud radius decreased from 21% to 31% (Scenarios 10 to 12) in GAPO approach compared to the initial process.

After optimization of the studied methane process, the operating process of equipment was not significantly changed, and therefore, intensity of jet fire was not highly different. For example, in all three scenarios related to the demethanizer tower in GAPO, the jet fire was reduced by 9%. In scenarios for MR drum and feed drum, the amount of jet fire was almost identical. But in the LP drum scenarios, the jet fire dropped from 6% to 20% due to the reduction of temperature and inventory in GAPO. For the other fire scenarios, the intensity of incidents has decreased; for instance, intensity of pool fire decreased by 44% for LP drum (Scenario 11). Finally, implementing GAPO, it can reduce both the hazardous materials in the process and the capacity of the vessels while keeping production constant.

**3.3. Cumulative Quantitative Risk Assessment.** The individual risk contour of 1 pmpy, for GAPO compared to the IPD, is shown in Figure 5. As illustrated, implementation of GAPO was associated with reduction in 1 pmpy individual risk from 726473.54 m<sup>2</sup> in IPD to 596901.44 m<sup>2</sup> in GAPO. This decrease was more tangible in the downwind, due to the vapor cloud tending to spread in the wind direction; therefore, the individual risk was higher in the downwind incidents.

Figure 6 shows the individual risk transect for GAPO compared to the IPD in 200 m from the incident location, where the workers are resting. As can be seen, the individual risk at the employee's resting place reduced from 69.5E-05/Avgeyear in IPD to 03.5E-05/Avgeyear in GAPO.

In Figure 7, the results of societal risks are presented in GAPO and supported by Aspen HYSYS, compared to the IPD, which exists in the operation phase. As shown, the frequency of deaths is not significantly different in GAPO from the existing process. This uniformity is because the present study focused on the severity of incident consequences. As indicated, in the IPD, the number of deaths is 200 in almost frequency of 105/Avgeyear, which is reduced to 107/Avgeyear in GAPO. The number of deaths in integrated consequences of 12 scenarios in the IPD reduced from 600 to 400 in GAPO, which shows a 33% decrease.

**3.4. Inherent Safety Assessment.** Results of assessing process for inherent safety by I2SI for IPD and GAPO are present in Table 10. As the tables show, reducing hazard index for

demethanizer tower has great impact on total inherent safety of initial process. Since the demethanizer tower is the most hazardous equipment on the process, implementing inherent safety into the process will improve the safety of the whole operation. This table also shows that the total I2SI of process increased significantly in the optimized process without a need to add safety equipment or use conventional safety methods and procedures.

#### 4. Conclusion

The aim of this study was to investigate the effect of genetic algorithm process optimization on inherent safety enhancement and reduction of quantitative risks in operation phase of process. The results showed that, after optimizing the process with the genetic algorithm, the number of deaths decreased by one-third without reducing the amount of methane production. In addition, process optimization led to reduced energy consumption and improved efficiency. In conclusion, genetic algorithms can be implemented at no extra cost in all phases of the process life cycle to optimize processes and equipment, especially during the operation phase.

#### Abbreviations

GAPO:	Genetic algorithm process optimization
HYSYS:	Hyprotech system
PFD:	Process flow diagram
NG:	Natural gas
PHAST:	Process hazard analysis software tools
I2SI:	Integrated inherent safety index
IS:	Inherent safety
HI:	Hazard index
ISPI:	Inherent safety potential index
IPD:	Initial process design
ISP:	Inherent safety principle
P and ID:	Piping and instrumentation diagram
GA:	Genetic algorithm
RCY:	Recycle operator
TEE:	Flow splitter
FB:	Fire ball
MC:	Maximum concentration
QRA:	Quantitative risk assessment
HAZOP:	Hazard and operability study
ESDV:	Emergency shut down valve
NRV:	None return valve
VLE:	Vapor-liquid equilibrium

ISDS: Inherently safer design strategy  
 D-2232: MP refrigerant circulation drum  
 D-2231: FEED HP-separator  
 D-2233: LP refrigerant circulation  
 Pmpy: Part million per year  
 VLE: Vapor-liquid equilibrium  
 PRSV: Peng–Robinson–Stryjek–Vera equations of state  
 SIS: Safety instrument system  
 SOP: Standard operation procedure  
 DNV: Det Norske veritas  
 OGP: Oil and gas producers  
 P and ID: Piping and instrumentation diagram.

## Data Availability

The data used to support the findings of this study are included within the article.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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