Quality and Reliability Engineering International

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RESEARCH ARTICLE OPEN ACCESS

Multi-Criteria Decision-Making Methodologies Applied to Hazard and Operability Studies in High-Hazard Industries

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Received: 28 October 2024 | **Revised:** 7 February 2025 | **Accepted:** 10 October 2025

Keywords: AHP | Hazard and Operability (HAZOP) | Multi-Criteria Decision Making (MCDM) | PROMETHEE | process safety | TOPSIS

ABSTRACT

Major accidents causing fatalities and significant environmental and asset damage continue to occur in high-hazard industries, despite regulatory requirements and organisational mitigation measures. The Hazard and Operability (HAZOP) study is a widely used risk assessment method to identify hazards and implement mitigation measures, but it has limitations, including the effort required and challenges in prioritising recommendations. This study reviews the integration of Multi-Criteria Decision Making (MCDM) methodologies with HAZOP in high-hazard industries. A case study using Analytical Hierarchy Process (AHP), Preference Ranking Organisation Method for Enrichment Evaluation (PROMETHEE) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) demonstrated varying results based on effort, time and outcome verification. The results informed a guide that selects the most suitable MCDM method based on the number of recommendations, residual risk ranking and degree of separation. This paper demonstrates that MCDM methodologies can enhance HAZOP studies by improving recommendation prioritisation in high-hazard industries.

1 | Introduction

Major accidents resulting in fatalities and significant environmental and asset damage continue to occur in process, chemical and petrochemical (high hazard) industries. They occur despite the regulatory requirements and organisational mitigation measures that have been implemented. These accidents are caused by hazards associated with creating products that are ubiquitous in our daily lives. These products include home cleaning and washing liquids, petrol or diesel for our cars and food. Some of the raw materials used are flammable and toxic materials that can lead to fires, explosions, environmental damage, asset destruction and loss of life when released [1–3].

The Hazard and Operability (HAZOP) study is one of several risk assessment tools used extensively in high-hazard industries. It is a vital part of ensuring that processes that lead to hazardous scenarios and result in loss of life, significant environmental and asset damage have been systematically reviewed, and adequate mitigations have been implemented to reduce the level of risk to acceptable levels. (HAZOP) Studies are conducted by a team of persons experienced in aspects of a process topic [4–6]. HAZOP studies have aided a reduction in accidents in high-hazard industries. However, known gaps include how to prioritise identified recommendations with limited budget and resources and how to confirm the output of the HAZOP study when there is limited technical information and experience within the HAZOP team [7–9].

The use of HAZOP studies in process industries started in 1963. Kletz detailed how the Heavy Organics Chemicals Division of ICI introduced the concept. The intention was to formally detail the deficiencies of projects that were perceived as being overly focused on minimising capital costs at the expense of robust design. Currently, HAZOP is widely used by various industries, including petrochemical and energy [10, 11]. A high-level summary of the literature review of the advantages of HAZOP indicates that the process is ubiquitous, systematic and thorough. Conversely, the disadvantages indicate it is labour intensive, a manual process, repetitive and susceptible to misapplication due to its methodology [12]. Major HAZOP improvements include increasing automation of the process and reducing the subjectivity of the results.

Multi-Criteria Decision Making (MCDM) methodologies have been used in several industries to solve complex problems due to their adaptability and applicability. Sectors such as energy, transportation, sustainability, manufacturing and production have used MCDM, with extensive literature documenting their success [13, 14].

A review of all MCDM papers on Web of Science (WoS) and Scopus databases from January 1997 to April 2022 was conducted. This review demonstrates the widespread use of MCDM, with authors from 131 countries publishing 23,494 papers. China, India and Iran have shown considerable interest in MCDM, contributing 18.5%, 10.62% and 7.75% of the published papers, respectively [15]. Another review accounted for 37 different methods [16]. The most commonly used MCDM methods include the Analytical Hierarchy Process (AHP), Analytical Network Process (ANP), Vlisekriterijumska Optimizacija Kompromisno (VIKOR) and the Preference Ranking Organisation Method for Enrichment Evaluation (PROMETHEE). AHP and ANP are pairwise comparison methodologies, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and VIKOR are distance-based methodologies, and ELECTRE and PROMETHEE are outranking methodologies [17–20].

There is limited literature on the use of MCDM methodologies for high-hazard industries, specifically for HAZOP studies. The MCDM in HAZOP studies within the petrochemical industries reviewed in this literature review includes six case studies. A high-level summary of these case studies confirms that the application of MCDMs in HAZOP is rare, that existing cases are mostly hybrid involving other methodologies, that their application is not restricted to specific processes, and that MCDMs have mostly been used for ranking hazards.

A case study where three different types of MCDM methodologies are applied to the HAZOP of a process plant would help develop a framework for selecting the appropriate MCDM methodology for HAZOP studies. The results of this study and the developed framework can be used as a reference for future research and be applied to HAZOP studies to prioritise recommendations.

A critical review of the following MCDM HAZOP case studies: An expanded HAZOP study with Fuzzy-AHP— Application in a sour crude-oil processing plant [21]; A fuzzy multi-attribute HAZOP technique—Application to gas wellhead facilities [22]; Prioritising HAZOP analysis using AHP process [23], indicated minimal difference between certain MCDM methodologies, more distinguishable ranking between MCDM ranking and the typical HAZOP risk matrix, and the complexity of using multi-level MCDM criteria.

In summary, MCDM can address the limitations of the HAZOP process. The challenge is to determine the most suitable MCDM methodology type (pairwise comparison, distance-based and outranking) based on effort, accuracy, verification and if a framework can be developed to guide the selection of the appropriate MCDM methodology for any HAZOP study.

The objective of this paper is to provide guidance on implementing MCDM methodologies to HAZOP studies. This will be achieved by creating an MCDM in HAZOP framework and demonstrating its use by applying it to a case study.

Based on the objective above, the remainder of the paper includes: Section 2 provides an overview of the methodology adopted to apply MCDM to an HAZOP study and describes the case study, Section 3 discusses the results of the case study and Section 4 concludes the report and lists areas for future work.

2 | Methodology

2.1 | Process Overview

MCDM is a decision-making methodology used to rank alternative options based on a set criteria [17]. As established in the literature review, there is sufficient evidence that MCDM methodologies have been successfully used in several industries.

The aim of this project is to efficiently and successfully apply the MCDM methodology types (pairwise comparison, distance-based and outranking) to HAZOP studies in high-hazard industries, consequently contributing to the limited literature available on this topic and addressing the prioritisation of recommendations. This will be demonstrated through a case study.

The innovation of this project is in applying and comparing three different MCDM methodologies to address the subjectivity and prioritisation limitations of an HAZOP study. Additionally, a framework has been developed to integrate these MCDM methodologies into the HAZOP process.

2.2 | MCDM Methodologies Selected

The MCDM methodologies selected are: AHP, TOPSIS and PROMETHEE.

2.2.1 | AHP

The AHP process is illustrated in Figure 1 [24]. The key formulas and parameters include eigenvector ($\lambda_{\max}$), consistency index (CI) and consistency ratio (CR). The Saaty's table is used to create the pairwise comparison matrix, and the random index (RI) is used to determine the CR. The mathematical representation of the formulas for these parameters are shown as follows:

$$\mathrm{CI} = \frac{(\lambda_{\max} - n)}{n - 1} \tag{1}$$

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{2}$$

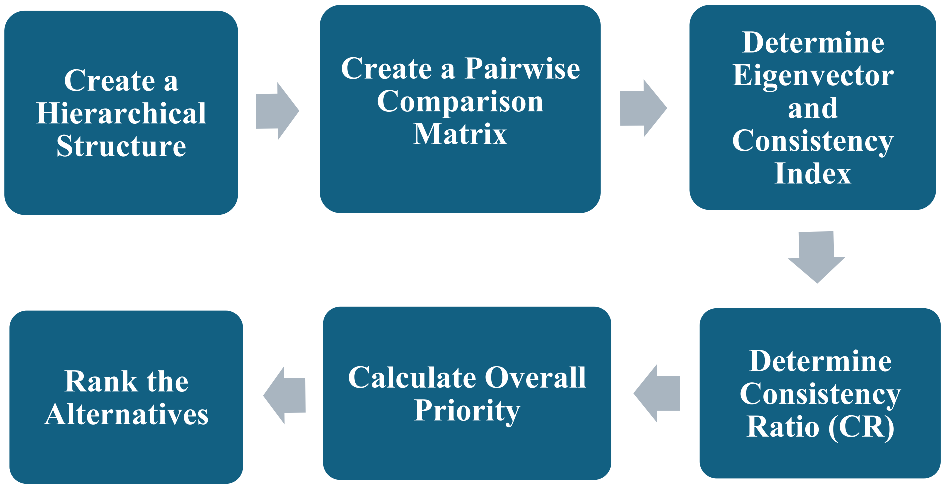

FIGURE 1 | Basic flow diagram of the Analytical Hierarchy Process (AHP) process.

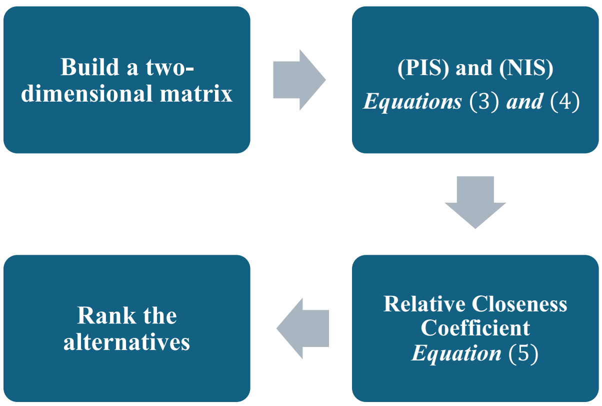

FIGURE 2 | Basic flow diagram of the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) process.

2.2.2 | TOPSIS

The TOPSIS process is shown in Figure 2 [25]. Key formulas and parameters include the positive ideal solutions (PISs), S_i^+, negative ideal solutions (NISs), S_i^-, and the relative closeness coefficient (CC_i). The pairwise comparison matrix is used to create the required two-dimensional matrix. The mathematical representation of the formulas for these parameters are shown as follows:

$$S_i^- = \sqrt{\Sigma_{j=1}^n \left(v_{ij} - v_{ij}^-\right)^2} \tag{3}$$

$$S_i^+ = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_{ij}^+\right)^2} \tag{4}$$

$$CC_i = \frac{Si^-}{Si^- + Si^+} \tag{5}$$

2.2.3 | PROMETHEE

The PROMETHEE process is shown in Figure 3 [27]. The key formulas and parameters include the preference functions (a_j, a_k), the leaving outranking flow (φ^-), the entering outranking flow (φ^+) and the net outranking flow (φ). The pairwise comparison matrix is used to create the required two-dimensional matrix. The mathematical representation of these formulas for these parameters is shown as follows:

$$\left(a_j, a_k\right) = \Sigma_{i=1}^n W_i \times P_i Pi\left(a_j, a_k\right) \tag{6}$$

$$\varphi\left(a_j\right) = \frac{1}{m-1} \Sigma_A^n \pi\left(a_j, a\right) \tag{7}$$

$$\varphi\left(a_j\right) = \frac{1}{m-1} \Sigma_A^n \pi\left(a, a_j\right) \tag{8}$$

$$\varphi\left(a_j\right) = \varphi^+\left(a_j\right) - \varphi^-\left(a_j\right) \tag{9}$$

2.3 | MCDM Applied to an HAZOP Study

An HAZOP study is typically executed in four phases: definition, preparation, examination and documentation/follow-up phases [28]. These phases involve defining the scope, objectives, roles and responsibilities, issuing a Terms of Reference (ToR), establishing guidewords and deviations, collecting data and documentation, completing the examination, determining the output of the study, issuing a report and tracking the recommendations to closure.

It is important to record HAZOP study in detail so that team members participating in the MCDM section can access valuable information in the HAZOP worksheets.

This project's objective will be achieved by applying the MCDM methodologies to an HAZOP study, using the framework developed in Figure 4, which integrates three MCDM methodology types into a typical HAZOP flowchart.

Figure 4 serves as the foundation for the case study conducted for this paper. It can be applied to different case studies where assumptions are identified and problem statements are determined, thereby contributing to the literature on MCDM application in HAZOP studies.

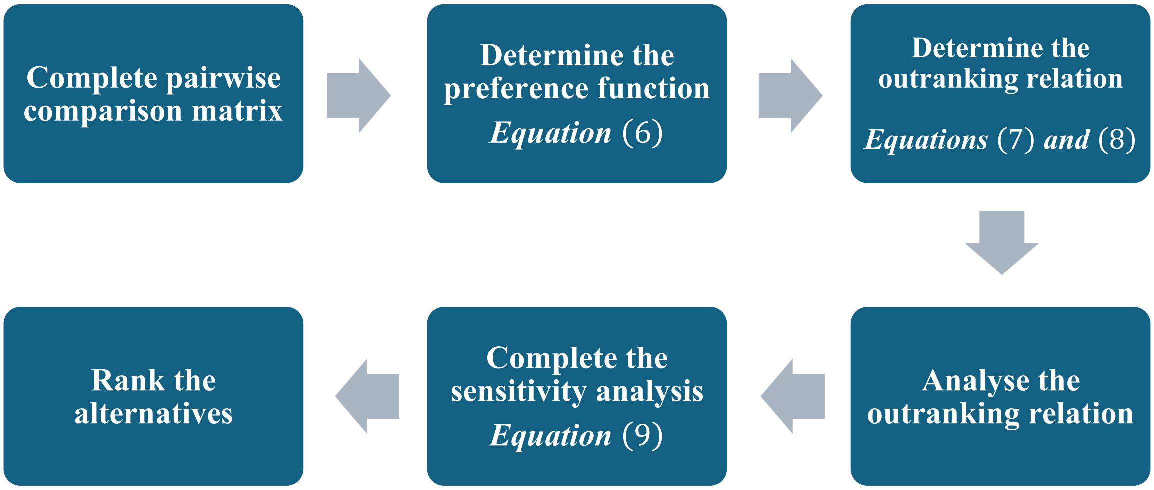

FIGURE 3 | Basic flow diagram of the Preference Ranking Organisation Method for Enrichment Evaluation (PROMETHEE) process.

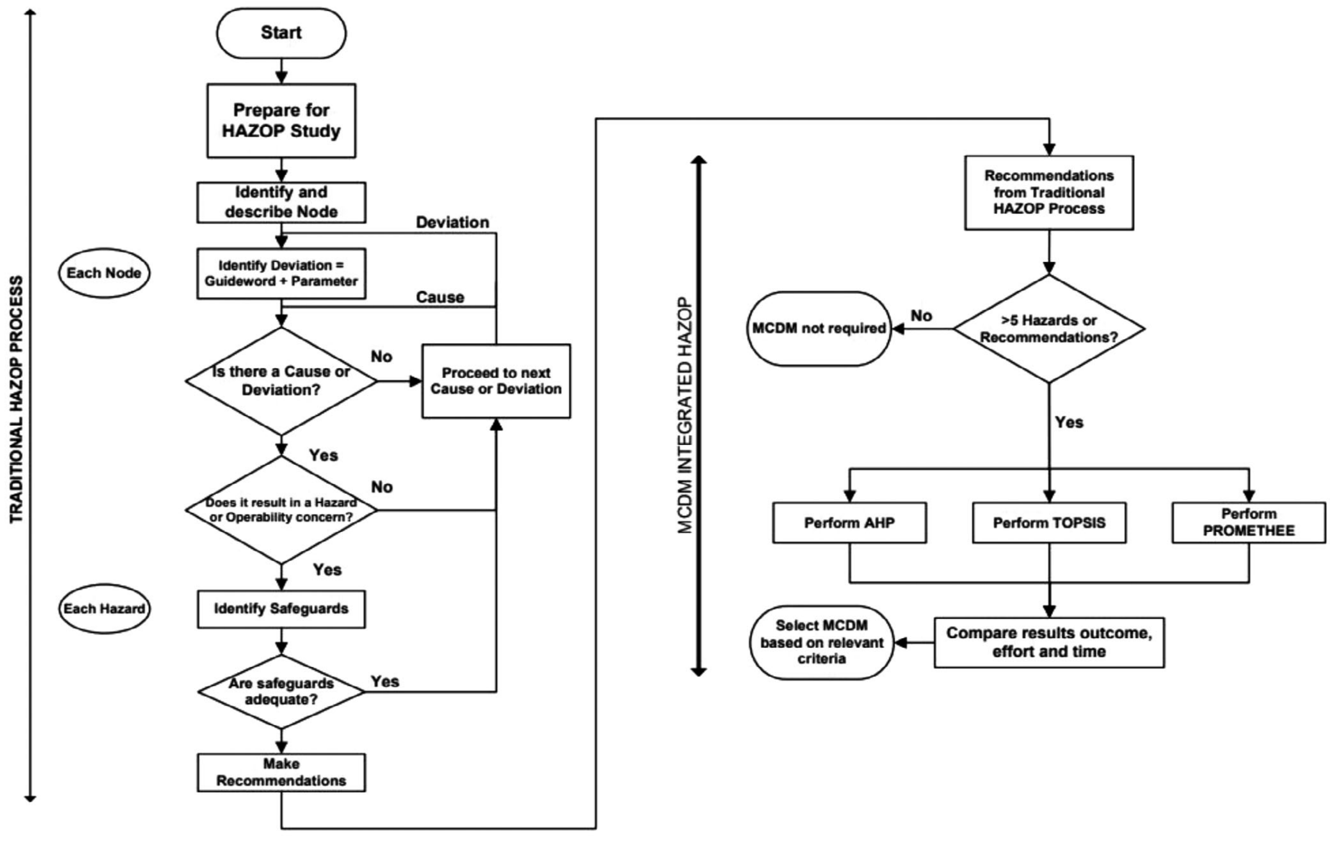

FIGURE 4 | Framework for applying the Multi-Criteria Decision Making (MCDM) methodology to this Hazard and Operability (HAZOP) case study.

The traditional HAZOP section of the framework covers the definition, preparation and examination phases of the HAZOP process. The MCDM-integrated HAZOP section is applied before the final documentation and follow-up phase. After recommendations are made, the MCDM methodology process begins with the application of AHP, TOPSIS and PROMETHEE methodologies as detailed in Section 3.2.

The results are analysed to determine the most suitable MCDM for HAZOP studies using the criteria developed from the results. A criterion is introduced to assess whether integrating MCDM into the traditional HAZOP process adds value. Currently, a minimum threshold of five recommendations is set, as ranking fewer alternatives is considered to offer limited value.

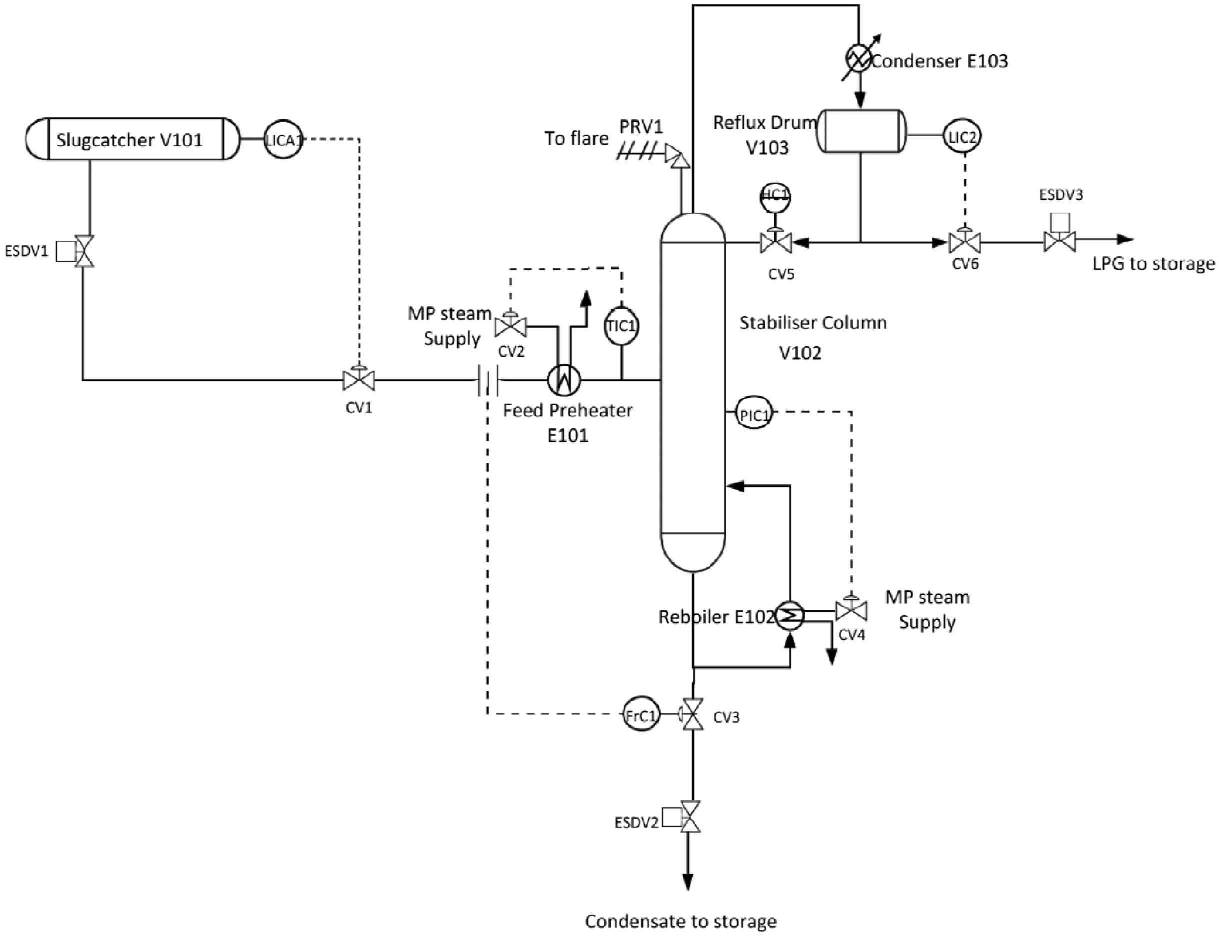

FIGURE 5 | PFD for the Hazard and Operability (HAZOP) case study [29].

2.4 | MCDM in HAZOP—A Case Study

This case study demonstrates the application of the MCDM in HAZOP framework developed in section 3. The case study is an HAZOP study for a hypothetical onshore gas reception terminal in Australia [29]. The gas reception terminal includes a slugcatcher, feed preheater, stabilisation column, reflux drum, condenser and a reboiler as the main equipment. The safety systems in scope include a pressure relief valve (PRV1) on the stabiliser column (V102), set at 15 barg and discharges to the flare system, a V102 low level alarm which requires an operated initiated shutdown of an inlet ESDV1, and condensate and LPG outlets ESDV2 and ESDV3. It also includes basic process control systems (BPCS) as illustrated in Figure 5.

3 | MCDM in HAZOP Case Study—Results and Discussions

This section presents the results of applying the developed framework to the HAZOP case study. It identifies the nodes within the traditional HAZOP framework, deviations considered, safeguards and recommendations, and a list recommendations. For the MCDM section, it discusses the result of applying AHP, PROMETHEE and TOPSIS MCDM methodologies to these recommendations and ranks the methodologies based on set criteria.

3.1 | HAZOP Results and Discussions

3.1.1 | Node Identification and Marking

Five nodes and boundaries were identified from the PFD review as shown in Figure 6. Although Piping and Instrumentation Diagrams (P&ID) are preferred for HAZOP studies due to the level of detail required, this PFD was used to simplify the process. This choice ensures the paper's focus is on integrating MCDM in HAZOP framework.

3.1.2 | HAZOP Worksheets

The HAZOP worksheet covers the components identified in the framework, including deviation and safeguard identification, and recommendation determination for each node according to the structured HAZOP process. A worksheet was created for each node and represented as a table. Table 1 illustrates the results of Node 1.

The worksheets include the node description, design intention and assumptions. They also include cause, consequence, initial risk ranking and subsequent risk ranking. A typical 5 × 5 matrix was used for ranking and the People, Environment, Asset and Reputation (PEAR) categorisation was adopted. Note that HAZOP studies typically focus of people and environmental consequences.

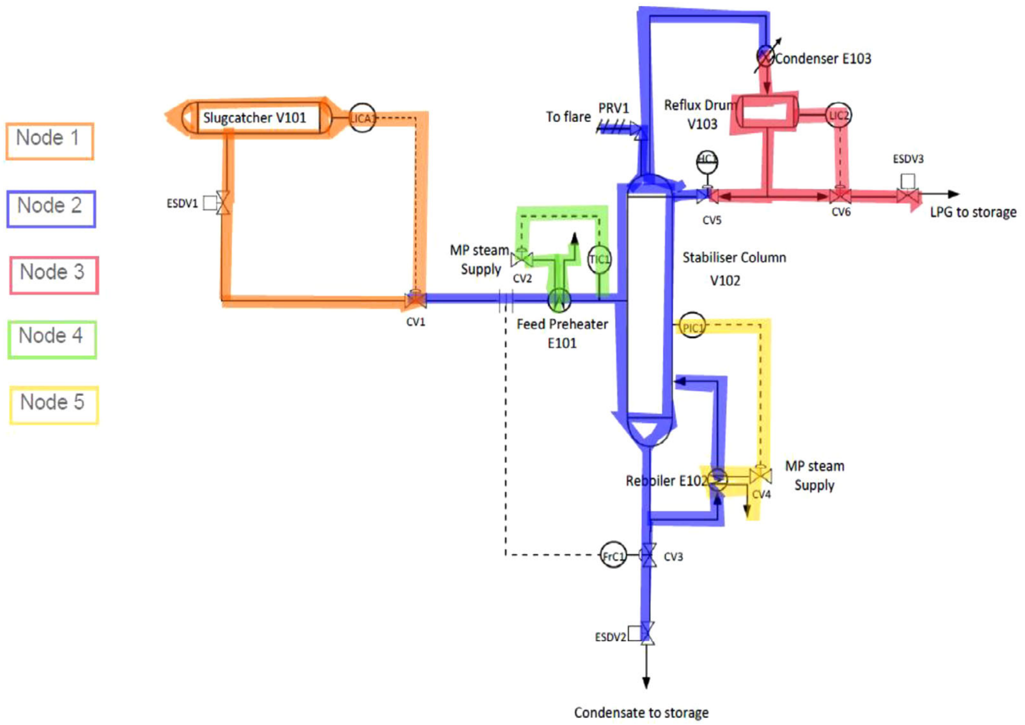

FIGURE 6 | Marked PFD highlighted the nodes for the (HAZOP) case study.

3.1.3 | HAZOP Recommendations List

Table 2 lists the 20 recommendations identified through the HAZOP process, including deviations, causes, consequences and residual risks after safeguards. The table shows several deviations with the same residual risk of 6, 8 and 12, and will be used to apply MCDM methodologies identified. Typically, residual risks are used to prioritise recommendations. However, when these residual risks are the same, a different approach is needed to prioritise recommendations, particularly when resources are limited. Applying the resulting MCDM methodology will help rank these recommendations.

A high-level review of the recommendation list reveals that the flow parameter is the primary concern, occurring in half of the recommendations. Note that level and pressure are usually interrelated in high-hazard industries. In addition, the 'low' or 'no' guideword was the most frequently used, and Node 1 which has the largest equipment had the most recommendations. In contrast, Node 2, which involves the most associated equipment such as valves and BPCS initiators and final element, had the fewest recommendations. This is likely due to existing safeguards like the PRV1.

The recommendations are split into hardware safeguards [independent Safety Integrity Functions (SIFs), BPCS transmitters, alarms] and dissimilar check valves. Other recommendations include conducting a study to select an appropriate mitigation measure and performing an intrusive piping inspection to determine if a section needs replacement.

HAZOP studies should be based on up-to-date P&ID and other associated engineering drawings. However, a PFD was used for this paper to simplify the process.

3.2 | MCDM Results and Discussions

3.2.1 | AHP

The AHP basic flow diagram in Figure 1 was applied to the 20 recommendations list in Table 2.

3.2.1.1 | AHP Results. The AHP steps start with the creation of a pairwise comparison matrix using the 20 alternative/options (HAZOP recommendations). To complete the pairwise comparison, the Saaty's scale in Table 3 is required. This enables ranking of options against each other based on the level of importance. The results of the ranking are shown in Table 4.

In the pairwise comparison shown in Table 5, the orange-highlighted cells represent the input values derived from applying Saaty's scale, where each recommendation is compared to the other 19 recommendations across the matrix. The diagonal values of the matrix are set to one, as any recommendation compared with itself equals one.

The white-highlighted cells of the matrix add the inverse of the input provided for the reverse comparison, that is, where Recommendation 1 versus Recommendation 6 (Rec 1 vs. 6) is assessed as 5, the reverse Recommendation 6 versus Recommendation 1 becomes 0.2. This is consistent with all results on the matrix.

The criteria weight for each recommendation is determined using the sum of the results of the pairwise comparison. This involves dividing all recommendations on each column by the total weight at the bottom of the column and summing the results at the end of each row to determine the criteria weight.

TABLE 1 | HAZOP Node 1 worksheet including stabiliser column (V102) and other equipment.

Node	Node 1
Node description	This node consists of the Slugcatcher (V101), the ESDV-1, the level controller (LIC) and CV-1 (isolation valve) as the boundary
Mode of operations	Continuous
Drawing number	Drawing 1
Design intention	Operating parameters: as provided Design parameters: size/volume—relatively large Slugcatcher Design intention: receive feed flow (gas and liquid) and separate the liquids from the gas during normal operation
Supporting notes	As agreed.
Assumptions	As agreed

		Consequence		Risk ranking before				Risk ranking after			Recommendation		
Deviation	**Cause**	**Consequence**	**Cat**	***S***	***L***	***R***	**Safeguard**	***S***	***L***	***R***	**ID**	**Recommendation**	**Assignee**
Flow—low/no	Malfunction/ closure of ESDV-1	Increase in level in Slugcatcher V101. Blocked outlet due to failed ESDV1. If continued for a long period of time this will result in a V101 overfill scenario leading to loss of containment and resulting in a fire and explosion.	P	5	3	15	None provided. No risk reduction to take.	5	3	15	1	SIF—Consider installing the level trip function (SIF that shuts the valve upstream of V101	Contractor
Flow—low/no	Inadvertent closure of ESDV-1	Increase in level in Slugcatcher V101. Blocked outlet due to failed ESDV1. If continued for a long period of time this will result in a V101 overfill scenario leading to loss of containment and resulting in a fire and explosion.	P	5	3	15	None provided. No risk reduction to take.	5	3	15		See recommendation 1	Contractor

		Consequence		Risk ranking before				Risk ranking after			Recommendation		
Deviation	**Cause**	**Consequence**	**Cat**	***S***	***L***	***R***	**Safeguard**	***S***	***L***	***R***	**ID**	**Recommendation**	**Assignee**
Flow—low/no	Spurious closure of CV-1	Increase in level in Slugcatcher V101. Blocked outlet due to failed ESDV1. If continued for a long period of time this will result in a V101 overfill scenario leading to loss of containment and resulting in a fire and explosion.	P	4	3	12	None provided. No risk reduction to take.	4	3	12		See recommendation 1	Contractor

(Continues)

TABLE 1 | (Continued)

		Consequence		Risk ranking before				Risk ranking after			Recommendation		
Deviation	**Cause**	**Consequence**	**Cat**	***S***	***L***	***R***	**Safeguard**	***S***	***L***	***R***	**ID**	**Recommendation**	**Assignee**
Flow—more/high	Inadvertent full opening of CV-1	Reduction in level in Slugcatcher V101. Significant increase in flow leading to an overfill scenario in Stabiliser column (V102) resulting in loss of containment, fire and explosion.	P	4	3	12	PRV1—Relieve increase in feed to flare. BPCS—V102 flow controller (FrC1) to control flow and in this situation full opening to mitigate the impact.	4	1	4	2	SIF—Consider installing pressure trip function that shuts down an inlet valve to V102.	Contractor
Flow—reverse	Other source of high pressure from V102 to V101	Increase in level in V101. If continued for a long period of time this will result in a V101 overfill scenario leading to loss of containment and resulting in a fire and explosion.	P	4	3	12	None provided. No risk reduction to take.	4	3	12	3	Consider the installation of dissimilar check valves between V101 and V102.	Contractor
Operability	Integrity of the existing ESDV-1 valve to V102 piping due to aging and mode of operation	Oil spill leading surrounding environment. Significant oil spill leading to significant damage and effort to contain.	En	4	3	12	Regular non-intrusive inspection. No risk reduction credit taken.	4	2	8	4	Consider completion of intrusive inspection and replacement of section with least wall thickness.	Dutyholder
Containment	Sludge and sand production	Corrosion potential at pipe bends and high-pressure equipment leading to loss of containment resulting in fire and explosion.	P	4	2	8	Clamp on sand monitors. No risk reduction credit taken.	4	2	8	5	Consider a sludge and sand production study to determine suitable operating conditions and installation of permanent sand monitors.	Dutyholder

An example is using the Recommendation 6 column in Table 5, where the sum of all the results is 28. Each result in Column 6 is divided by 28 to achieve the results in the Recommendation 6 column in Table 4. In the Rec 1 versus 6 example above, 5 divided by 28 is 0.18 and the sum of all weighted results in row one is 0.12, which is the criteria weight for Recommendation 1 as shown in Table 4. This approach is used for all other recommendations, and their resulting criteria weights are used to rank the 20 recommendations.

This AHP ranking is validated by the CR, which should be less than 10%. Equations (1) and (2) were used to calculate the eigenvalue ($\lambda_{\max}$) and the CR, respectively.

The weighted sum criteria (WSC) are deduced from the sum of the horizontal weighted average of the pairwise comparison outcomes. The WSC is subsequently divided by the criteria weights to deduce the eigenvalue ($\lambda_{\max}$) for the recommendations.

The CI is determined from Equation (2), which shows a relationship between the sum of the eigenvalues and the number of recommendations. The outcomes of these calculations are shown in Tables 6 and 7. The RI deduced from Table 8 and the CI were used to calculate the CR shown in Table 7 using Equation (2). The resulting CR of 9% is below the threshold of 10% that verifies the consistency of the ranking.

Note that the initial CR result was 70% which is significantly higher than the threshold of 10% so the pairwise comparison matrix had to be revisited. Quite a lot of 7s that are 'very strong importance' were used. This is valid as the recommendations were comparing an SIF safeguard with an alarm.

The range of the resulting criteria was significantly wider compared to the comparison matrix with CR considerations. The highest criteria weights are also quite different, as the comparison matrix without CR consideration is 0.29 while that with CR

TABLE 2 | HAZOP recommendation list with associated deviation, cause and consequence for Node 1.

Node	Rec no.	Deviation	Cause	Consequence	Recommendation	Risk after
1	1	Flow—low/no	Malfunction/closure of ESDV-1.	Increase in level in slug catcher V101.	SIF—install a level trip function (SIF that shuts the valve upstream of V101.	15
1	2	Flow—more/high	Inadvertent full opening of CV-1.	Reduction in level in slug catcher V101.	SIF—install a pressure trip function that shuts down an inlet valve to V102.	4
1	3	Flow—reverse	Other source of high pressure from V102 to V101.	Increase in level in V101.	Install dissimilar check valve between V101 and V102.	12
1	4	Operability	Integrity of ESDV-1 to V102 piping due to aging and mode of operation.	Oil spill leading surrounding environment.	Complete an intrusive inspection and replacement of the section with least wall thickness.	8
1	5	Containment	Sludge and sand production.	Corrosion.	Complete a sludge and sand production study to determine use of permanent sand monitors.	8
2	6	Flow—low/no	Malfunction/closure of ESDV-2.	Increase in level in stabiliser column V102.	Alarm—install a low-pressure alarm of V102.	8
2	7	Flow—more/high	Inadvertent full opening of V102 overhead route.	Reduction in level in stabiliser column V102.	SIF—install a level trip function that shuts down an inlet valve to V102.	12
2	8	Flow—more/high	Inadvertent full opening of V102 overhead route.	Reduction in level in stabiliser column V102.	BPCS—install a level controller on V102.	12
2	9	Flow—reverse	Other source of high pressure.	Increase in level in V102.	Install dissimilar check valves between LPG storage and V102.	8
3	10	Flow—low/no	Malfunction/closure of CV6.	Increase in level in reflux drum (V103).	SIF—install a high-high level trip function that shuts down an inlet valve to V103.	12
3	11	Flow—low/no	Malfunction/closure of CV6.	Increase in level in reflux drum (V103).	Alarm—install a high-level alarm on V103.	12
3	12	Flow—more/high	Inadvertent full opening of CV6.	Reduction in level in reflux drum (V103).	SIF—install a low-low level Trip function that closes ESDV3.	8
3	13	Flow—more/high	Inadvertent full opening of CV6.	Reduction in level in reflux drum (V103).	Alarm—install a low-level alarm on V103.	8

(Continues)

TABLE 2 | (Continued)

Node	Rec no.	Deviation	Cause	Consequence	Recommendation	Risk after
3	14	Temperature—low/no	Condenser E103 overcools the V102 overheads.	Low temperature embrittlement of piping.	Alarm—add low temperature alarm to V103.	6
4	15	Temperature—low/no	MP steam supply valve (CV2) fails closed.	Loss of steam to the feed preheater resulting in inability to complete stabilisation.	Alarm—add low temperature alarm to TIC1.	6
4	16	Temperature—more/high	Temperature controller (TIC1) fails at a high set point.	Temperature above feed preheater (E101) design.	Alarm—add high temperature alarm to TIC1.	8
4	17	Temperature—more/high	Temperature controller (TIC1) fails at a high set point.	Temperature above feed preheater (E101) design.	SIF—add high temperature trip to V102.	8
5	18	Temperature—low/no	MP steam supply valve (CV4) fails closed.	Loss of steam to the Reboiler E102 resulting in inability to recover more NGL.	Alarm—add low pressure alarm to TIC1.	6
5	19	Temperature—more/high	Pressure controller (TIC1) fails at a high set point.	Temperature above Reboiler (E102) design.	Alarm—add high temperature alarm to V102	12
5	20	Temperature—more/high	Pressure controller (TIC1) fails at a high set point.	Temperature above Reboiler (E102) design.	BPCS—add temperature transmitter to V102.	12

TABLE 3 | Saaty's scale [30].

Value (k)	Definition	Explanation
1	Equal importance	i and j are equally important
3	Weak importance	i is slightly more important than j
5	Strong importance	i is strongly more important than j
7	Very strong importance	i is very strongly more important than j
9	Extreme importance	i is absolutely more important than j
2, 4, 6, 8	Intermediate values	Used when a compromise is needed

consideration is 0.12. This narrows the degree of separation of the resulting recommendation ranking. However, it ensures the result verification criteria of CR < 10% is achieved.

3.2.1.2 | AHP Results Discussions.

The following key points have been discussed.

3.2.1.2.1 | Verification Using the CR Threshold.

The initial application of the AHP methodology for this project resulted in a CR of 70% which is significantly above the 10% threshold. However, the level of importance selected during the pairwise comparison process was appropriate. A comparison of the results with or without CR considerations shows how the level of importance of the recommendations was reduced to achieve the required CR. Note that a degree of separation between the various recommendations particularly differentiating between SIFs and alarms was still maintained.

These adjustments and considerations emphasise the rigour required during pairwise comparisons to ensure the CR threshold is maintained.

TABLE 4 | AHP criteria weight and ranking (CR consideration).

Rec.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Criteria weight	Rank
1	0.08	0.07	0.06	0.07	0.06	0.18	0.06	0.11	0.05	0.06	0.40	0.06	0.16	0.16	0.15	0.16	0.05	0.16	0.16	0.09	**0.12**	**1**
2	0.08	0.07	0.06	0.07	0.06	0.07	0.06	0.11	0.05	0.06	0.16	0.06	0.06	0.06	0.06	0.06	0.05	0.06	0.06	0.09	**0.07**	**3**
3	0.08	0.07	0.06	0.07	0.06	0.07	0.06	0.05	0.05	0.06	0.16	0.06	0.06	0.06	0.06	0.06	0.05	0.06	0.06	0.05	**0.07**	**4**
4	0.08	0.07	0.06	0.07	0.06	0.07	0.11	0.05	0.05	0.06	0.16	0.06	0.06	0.06	0.06	0.06	0.09	0.06	0.06	0.05	**0.07**	**2**
5	0.08	0.07	0.06	0.07	0.06	0.07	0.06	0.05	0.05	0.06	0.16	0.06	0.06	0.06	0.06	0.03	0.05	0.03	0.03	0.05	**0.06**	**7**
6	0.02	0.03	0.03	0.03	0.03	0.04	0.06	0.05	0.05	0.06	0.08	0.06	0.03	0.03	0.03	0.03	0.05	0.03	0.03	0.05	**0.04**	**13**
7	0.08	0.07	0.06	0.03	0.06	0.04	0.06	0.05	0.05	0.06	0.08	0.11	0.06	0.06	0.06	0.06	0.09	0.06	0.03	0.05	**0.06**	**6**
8	0.04	0.03	0.06	0.07	0.06	0.04	0.06	0.05	0.05	0.06	0.16	0.06	0.03	0.06	0.06	0.06	0.05	0.06	0.06	0.05	**0.06**	**8**
9	0.08	0.07	0.06	0.07	0.06	0.04	0.06	0.05	0.05	0.06	0.08	0.06	0.06	0.03	0.03	0.03	0.05	0.06	0.06	0.05	**0.06**	**10**
10	0.08	0.07	0.06	0.07	0.06	0.04	0.06	0.05	0.05	0.06	0.16	0.06	0.06	0.06	0.06	0.06	0.05	0.06	0.06	0.05	**0.06**	**5**
11	0.02	0.03	0.03	0.03	0.03	0.04	0.06	0.03	0.05	0.03	0.08	0.06	0.03	0.03	0.03	0.03	0.05	0.03	0.03	0.05	**0.04**	**15**
12	0.08	0.07	0.06	0.07	0.06	0.04	0.03	0.05	0.05	0.06	0.08	0.06	0.06	0.06	0.06	0.06	0.05	0.06	0.06	0.05	**0.06**	**9**
13	0.02	0.03	0.03	0.03	0.03	0.04	0.03	0.05	0.03	0.03	0.08	0.03	0.03	0.03	0.03	0.03	0.05	0.03	0.03	0.05	**0.04**	**19**
14	0.02	0.03	0.03	0.03	0.03	0.04	0.03	0.03	0.05	0.03	0.08	0.03	0.03	0.03	0.06	0.06	0.05	0.03	0.03	0.05	**0.04**	**14**
15	0.02	0.03	0.03	0.03	0.03	0.04	0.03	0.03	0.05	0.03	0.08	0.03	0.03	0.02	0.03	0.03	0.05	0.03	0.03	0.05	**0.03**	**20**
16	0.02	0.03	0.03	0.03	0.06	0.04	0.03	0.03	0.05	0.03	0.08	0.03	0.03	0.02	0.03	0.03	0.05	0.03	0.03	0.05	**0.04**	**17**
17	0.08	0.07	0.06	0.03	0.06	0.04	0.03	0.05	0.05	0.06	0.08	0.06	0.03	0.03	0.03	0.03	0.05	0.03	0.03	0.05	**0.05**	**11**
18	0.02	0.03	0.03	0.03	0.06	0.04	0.03	0.03	0.03	0.03	0.08	0.03	0.03	0.03	0.03	0.03	0.05	0.03	0.03	0.05	**0.04**	**18**
19	0.02	0.03	0.03	0.03	0.06	0.04	0.06	0.03	0.03	0.03	0.08	0.03	0.03	0.03	0.03	0.03	0.05	0.03	0.03	0.05	**0.04**	**16**
20	0.04	0.03	0.06	0.07	0.06	0.04	0.06	0.05	0.05	0.06	0.08	0.06	0.03	0.03	0.03	0.03	0.05	0.03	0.03	0.05	**0.05**	**12**

3.2.1.2.2 | Comparing Alternative With Alternatives or Criteria. The AHP methodology requires the subjective comparison of alternatives with alternatives or criteria with criteria resulting in a clear degree of separation in the criteria weight and resulting ranking. However, for HAZOP studies where people or environmental risk reduction are the only criteria, there is a higher probability of obtaining the same criteria weight and ranking for alternatives resulting in a limited degree of separation.

3.2.1.2.3 | Criteria Weight Degree of Separation. A look at the criteria weights in Table 4 indicates several weights were quite similar at two decimal points, and the ranking was based on the use of three decimal points. This indicates the degree of separation could be better. This degree of separation criteria will be looked at in other methodologies.

3.2.1.2.4 | Impact of Number of Alternatives. Another criteria worth considering is the performance of this methodology relative to the number of alternatives. It appears there is a linear impact on the effort and time required if the recommendations were half the current number, 10, or double the current number, 20. The comparison matrix will be bigger and the degree of separation of the alternative ranking might not be as pronounced; however, the biggest concern would the impact on attaining the CR threshold.

3.2.1.2.5 | Random Index (RI) Number for Higher Number of Alternatives. The RI table available is normally limited to 20. The RI table used for this project required a bit more effort to find and verify. RI for alternatives more than 50 might not be easily available.

3.2.2 | PROMETHEE

The PROMETHEE basic flow diagram in Figure 3 was applied to the 20 recommendations list in Table 4.

3.2.2.1 | PROMETHEE Results Using the AHP Criteria Weight. The PROMETHEE process starts with normalising the evaluation matrix between the alternatives and the residual risk reduction rankings, then evaluating the difference between each alternative and all other alternatives.

Unlike the AHP methodology that compares criteria with criteria or alternatives with alternative to create a comparison matrix, the PROMETHEE methodology compares an alternative with a criterion to create an evaluation matrix. For this case study, the AHP criteria weight will be used. Note that use of the AHP criteria results in no independence between AHP and PROMETHEE.

The PROMETHEE process would normally create a greater separation between alternatives; however, it is a very time-consuming process as it creates a submatrix within a matrix. Equation (6)

TABLE 5 | AHP pairwise comparison matrix (CR consideration).

Pairwise comparison	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	1	1.0	1.0	1.0	1.0	5.0	1.0	2.0	1.0	1.0	5.0	1.0	5.0	5.0	5.0	5.0	1.0	5.0	5.0	2.0
2	1.0	1	1.0	1.0	1.0	2.0	1.0	2.0	1.0	1.0	2.0	1.0	2.0	2.0	2.0	2.0	1.0	2.0	2.0	2.0
3	1.0	1.0	1	1.0	1.0	2.0	1.0	1.0	1.0	1.0	2.0	1.0	2.0	2.0	2.0	2.0	1.0	2.0	2.0	1.0
4	1.0	1.0	1.0	1	1.0	2.0	2.0	1.0	1.0	1.0	2.0	1.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.0
5	1.0	1.0	1.0	1.0	1	2.0	1.0	1.0	1.0	1.0	2.0	1.0	2.0	2.0	2.0	1.0	1.0	1.0	1.0	1.0
6	0.2	0.5	0.5	0.5	0.5	1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
7	1.0	1.0	1.0	0.5	1.0	1.0	1	1.0	1.0	1.0	1.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.0	1.0
8	0.5	0.5	1.0	1.0	1.0	1.0	1.0	1	1.0	1.0	2.0	1.0	1.0	2.0	2.0	2.0	1.0	2.0	2.0	1.0
9	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1	1.0	1.0	1.0	2.0	1.0	1.0	1.0	1.0	2.0	2.0	1.0
10	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1	2.0	1.0	2.0	2.0	2.0	2.0	1.0	2.0	2.0	1.0
11	0.2	0.5	0.5	0.5	0.5	1.0	1.0	0.5	1.0	0.5	1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
12	1.0	1.0	1.0	1.0	1.0	1.0	0.5	1.0	1.0	1.0	1.0	1	2.0	2.0	2.0	2.0	1.0	2.0	2.0	1.0
13	0.2	0.5	0.5	0.5	0.5	1.0	0.5	1.0	0.5	0.5	1.0	0.5	1	1.0	1.0	1.0	1.0	1.0	1.0	1.0
14	0.2	0.5	0.5	0.5	0.5	1.0	0.5	0.5	1.0	0.5	1.0	0.5	1.0	1	2.0	2.0	1.0	1.0	1.0	1.0
15	0.2	0.5	0.5	0.5	0.5	1.0	0.5	0.5	1.0	0.5	1.0	0.5	1.0	0.5	1	1.0	1.0	1.0	1.0	1.0
16	0.2	0.5	0.5	0.5	1.0	1.0	0.5	0.5	1.0	0.5	1.0	0.5	1.0	0.5	1.0	1	1.0	1.0	1.0	1.0
17	1.0	1.0	1.0	0.5	1.0	1.0	0.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1	1.0	1.0	1.0
18	0.2	0.5	0.5	0.5	1.0	1.0	0.5	0.5	0.5	0.5	1.0	0.5	1.0	1.0	1.0	1.0	1.0	1	1.0	1.0
19	0.2	0.5	0.5	0.5	1.0	1.0	1.0	0.5	0.5	0.5	1.0	0.5	1.0	1.0	1.0	1.0	1.0	1.0	1	1.0
20	0.5	0.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1
Total	13	15	16	15	18	28	18	19	19	17	30	18	32	31	33	32	22	32	31	22

and the AHP criteria weight for the recommendations are used to calculate the preference function. A comparison matrix will be created once the difference with other alternatives has been evaluated, the preference function zeroed to remove negative numbers, and the aggregated preference has been multiplied by the alternative and summed.

Table 9 illustrates the resulting comparison matrix subsequently used to calculate the leaving and the entering and leaving outranking flows using the formula.

The entering and leaving outranking flows are determined using Equations (7) and (8). There are several negative values in this exercise, which resulted in several zeros in the matrix.

Equation (9) was used to calculate the net outranking flow, which is subsequently used to rank the alternatives as shown in Table 10. The ranking is based on the highest positive number, so the highest negative number becomes the lowest-ranked recommendations.

An example is using the Recommendation 10 row and column in Table 9, where the sum leaving and sum entering are 139 and 71, respectively. In Table 10, the net outranking flow of 68 for Recommendation 10 is determined by subtracting 71 from 139. This approach is used for all other recommendations, and their resulting net outranking values are used to rank the 20 recommendations.

3.2.2.2 | PROMETHEE Results Discussions. The following key points have been discussed below.

3.2.2.2.1 | Use of AHP Criteria Weights. PROMETHEE is an outranking MCDM methodology. Similar to the distance-based methodology, it creates an evaluation matrix, that is, comparing different alternatives and criteria, to create a criteria weight. In contrast, the pairwise comparison methodology creates a pairwise comparison matrix, that is, comparing different alternatives with each other, to create a criteria weight. The AHP criteria weights (subjective) also provide a greater degree of separation compared to using objective criteria weights. However, a comparison of AHP and integrated, subjective and objective criteria weight gave similar results.

3.2.2.2.2 | Net Outranking Degree of Separation. A look at the net outranking in Table 10 shows a range between 495 and −906, which is very adequate to separate 20 alternatives. The negative numbers extend the range, resulting a better degree of separation and no requirement to use decimal places like the results from the pairwise comparison and distance-based methodologies.

TABLE 6 | AHP eigenvalue determination for consistency index (CI) calculation (CR consideration).

Rec.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	WSC	$\lambda_{\max}$
1	0.12	0.12	0.12	0.12	0.12	0.58	0.12	0.23	0.12	0.12	0.58	0.12	0.58	0.58	0.58	0.58	0.12	0.58	0.58	0.23	**6.26**	**54.00**
2	0.07	0.07	0.07	0.07	0.07	0.14	0.07	0.14	0.07	0.07	0.14	0.07	0.14	0.14	0.14	0.14	0.07	0.14	0.14	0.14	**2.11**	**30.00**
3	0.07	0.07	0.07	0.07	0.07	0.13	0.07	0.07	0.07	0.07	0.13	0.07	0.13	0.13	0.13	0.13	0.07	0.13	0.13	0.07	**1.83**	**28.00**
4	0.07	0.07	0.07	0.07	0.07	0.14	0.14	0.07	0.07	0.07	0.14	0.07	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.07	**2.12**	**30.00**
5	0.06	0.06	0.06	0.06	0.06	0.12	0.06	0.06	0.06	0.06	0.12	0.06	0.12	0.12	0.12	0.06	0.06	0.06	0.06	0.06	**1.52**	**25.00**
6	0.01	0.02	0.02	0.02	0.02	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	**0.70**	**17.20**
7	0.06	0.06	0.06	0.03	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.06	0.06	**1.63**	**26.50**
8	0.03	0.03	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.12	0.06	0.06	0.12	0.12	0.12	0.06	0.12	0.12	0.06	**1.46**	**25.00**
9	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.11	0.06	0.06	0.06	0.06	0.11	0.11	0.06	**1.27**	**23.00**
10	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.13	0.06	0.13	0.13	0.13	0.13	0.06	0.13	0.13	0.06	**1.72**	**27.00**
11	0.01	0.02	0.02	0.02	0.02	0.04	0.04	0.02	0.04	0.02	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	**0.62**	**16.20**
12	0.06	0.06	0.06	0.06	0.06	0.06	0.03	0.06	0.06	0.06	0.06	0.06	0.12	0.12	0.12	0.12	0.06	0.12	0.12	0.06	**1.49**	**25.50**
13	0.01	0.02	0.02	0.02	0.02	0.04	0.02	0.04	0.02	0.02	0.04	0.02	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	**0.53**	**15.20**
14	0.01	0.02	0.02	0.02	0.02	0.04	0.02	0.02	0.04	0.02	0.04	0.02	0.04	0.04	0.08	0.08	0.04	0.04	0.04	0.04	**0.66**	**17.20**
15	0.01	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.03	0.02	0.03	0.02	0.03	0.02	0.03	0.03	0.03	0.03	0.03	0.03	**0.51**	**14.70**
16	0.01	0.02	0.02	0.02	0.04	0.04	0.02	0.02	0.04	0.02	0.04	0.02	0.04	0.02	0.04	0.04	0.04	0.04	0.04	0.04	**0.54**	**15.20**
17	0.05	0.05	0.05	0.02	0.05	0.05	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	**0.90**	**19.00**
18	0.01	0.02	0.02	0.02	0.04	0.04	0.02	0.02	0.02	0.02	0.04	0.02	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	**0.54**	**15.20**
19	0.01	0.02	0.02	0.02	0.04	0.04	0.04	0.02	0.02	0.02	0.04	0.02	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	**0.58**	**15.70**
20	0.02	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	**0.89**	**19.00**
Avg																						**22.93**

TABLE 7 | AHP consistency ratio (CR) calculation from CI and RI calculation.

CI	0.15
RI	1.63
CR	0.09

TABLE 8 | Random index.

Random indices								
Matrix size	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0.52	0.89	1.13	1.25	1.35	1.43	1.47	1.5
Matrix size	11	12	13	14	15	16	17	18
RI	1.53	1.54	1.56	1.57	1.59	1.6	1.61	1.61
Matrix size	19	20	21	22	23	24	25	26
RI	1.62	1.63	1.63	1.64	1.65	1.65	1.66	1.66
Matrix size	27	28	29	30	31	32	33	34
RI	1.66	1.67	1.67	1.67	1.67	1.68	1.68	1.68
Matrix size	35	36	37	38	39	40	41	42
RI	1.68	1.69	1.69	1.69	1.69	1.69	1.7	1.7
Matrix size	43	44	45	46	47	48	49	50

3.2.2.2.3 | Impact of Number of Alternatives. This outcome indicates that the PROMETHEE methodology can accommodate more alternatives without significantly affecting the level of separation. The negative numbers are significant in achieving adequate separation for ranking purposes, as shown in the results.

3.2.2.2.4 | Effort Required to Create the Evaluation Matrix. The significant degree of separation the PROMETHEE methodology offers comes at a price, as it requires creating several evaluation matrices, which are subsequently transformed into a comparison matrix. The exercise requires a lot of effort and is quite error prone.

3.2.3 | TOPSIS

The PROMETHEE basic flow diagram in Figure 2 was applied to the 20 recommendations list in Table 4.

3.2.3.1 | TOPSIS Results Using the AHP Criteria Weight. Similar to the PROMETHEE methodology, the TOPSIS process starts with normalising the evaluation matrix between the alternatives and the residual risk reduction rankings, then determining the maximum and minimum number of the criteria weights.

TABLE 9 | PROMETHEE determine leaving and entering outranking flows.

Rec.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	16	18	19	20	Sum (leaving)
1	0	1.8	1.6	1.8	1.5	1.1	1.5	1.4	1.3	1.6	1.0	1.4	1.0	1.0	1.0	1.0	1.2	1.0	1.0	1.2	25
2	2.3	0.0	16.6	0.0	8.5	2.8	9.2	6.9	5.3	12.2	2.5	6.8	2.3	2.5	2.3	2.4	3.5	2.3	2.4	3.4	94
3	0.0	0.0	0	0.0	17.2	3.3	20.5	11.7	7.8	45.7	3.0	11.4	2.7	3.0	2.6	2.7	4.5	2.7	2.8	4.3	146
4	0.0	361.7	15.9	0	8.3	2.7	9.0	6.7	5.2	11.8	2.5	6.6	2.3	2.5	2.2	2.3	3.5	2.3	2.4	3.4	451
5	0.0	0.0	0.0	0.0	0	4.1	0.0	36.1	14.3	0.0	3.6	33.4	3.2	3.6	3.1	3.3	6.0	3.2	3.4	5.8	123
6	0.0	0.0	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	28.8	0.0	14.4	31.7	12.6	16.2	0.0	14.6	19.7	0.0	138
7	0.0	0.0	0.0	0.0	108.1	3.9	0	27.1	12.6	0.0	3.5	25.5	3.1	3.5	3.0	3.2	5.7	3.1	3.3	5.5	211
8	0.0	0.0	0.0	0.0	0.0	4.6	0.0	0	23.7	0.0	4.0	444.5	3.5	4.0	3.4	3.6	7.2	3.5	3.7	6.9	513
9	0.0	0.0	0.0	0.0	0.0	5.7	0.0	0.0	0	0.0	4.8	0.0	4.1	4.9	3.9	4.2	10.4	4.1	4.4	9.7	56
10	0.0	0.0	0.0	0.0	27.6	3.6	37.1	15.6	9.4	0.0	3.2	15.1	2.9	3.2	2.8	2.9	4.9	2.9	3.0	4.8	139
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	28.6	0.0	22.5	37.2	0.0	29.8	62.2	0.0	180
12	0.0	0.0	0.0	0.0	0.0	4.7	0.0	0.0	25.0	0.0	4.0	0.0	3.5	4.1	3.4	3.6	7.4	3.5	3.8	7.0	70
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	105.8	0.0	0.0	0.0	0.0	0.0	106
14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	313.6	0.0	26.2	0	21.0	33.2	0.0	27.2	51.9	0.0	473
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	124.1	0.0	57.1	0.0	0.0	149.7	0.0	0.0	331
17	0.0	0.0	0.0	0.0	0.0	12.7	0.0	0.0	0.0	0.0	8.8	0.0	6.7	9.1	6.3	7.1	0	6.8	7.7	146.9	212
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	723.4	0.0	92.3	0.0	0.0	0	0.0	0.0	816
19	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.9	0.0	35.3	92.3	0.0	57.1	0	0.0	238
20	0.0	0.0	0.0	0.0	0.0	14.0	0.0	0.0	0.0	0.0	9.4	0.0	7.1	9.7	6.6	7.5	0.0	7.1	8.2	0	70
Sum (entering)	**2**	**363**	**34**	**2**	**171**	**63**	**77**	**105**	**105**	**71**	**393**	**545**	**1012**	**83**	**387**	**223**	**54**	**321**	**180**	**199**	

The ideal positive and negative values of the AHP criteria weight are determined as illustrated in Table 11. These are the maximum and minimum numbers of the criteria weight, respectively.

Secondly, the PIS and NIS are determined using the AHP criteria weights as shown in Equations (3) and (4).

Thirdly, the CC_i is determined using Equation (5).

Finally, the 20 recommendations are ranked based on the highest CC_i to the lowest CC_i. The outcome of the ranking and all associated steps are illustrated in Table 11.

Once the criteria weight is attained from the AHP methodology, application of the TOPSIS methodology is quite straightforward and easy to implement. This is reflected in the single table that is required to achieve the recommendation ranking. An example is using the Recommendation 20 in Table 11, where the PIS and NIS results are 0.07 and 0.01, respectively. CC_i is determined by dividing the sum of PIS and NIS by PIS, which results in 0.15. This approach is used for all other recommendations, and their resulting relative closeness coefficients are used to rank the 20 recommendations.

3.2.3.2 | TOPSIS Results Discussions. The following key points have been discussed below.

3.2.3.2.1 | Use of AHP Criteria Weights. TOPSIS is a distance-based MCDM methodology. Similar to the outranking methodology, it creates an evaluation matrix, that is, comparing different alternatives and criteria, to create a criteria/alternative weight. In contrast, the pairwise comparison methodology creates a pairwise comparison matrix, that is, comparing different alternatives with each other, to create a criteria weight.

For the HAZOP process, a singular criterion of risk reduction (or safety improvement) is available, and the only meaningful attribute consistent with all the alternatives is the associated residual risk ranking from the HAZOP. The residual risk can be quantified using a 5×5 matrix to create an evaluation matrix and criteria weights.

It is important to note that determining the outranking and distance-based criteria weights based on the evaluation matrix is regarded as an objective method, while the pairwise comparison criteria weight based on the pairwise comparison matrix is regarded as a subjective method because it depends on the experts' ranking alternative.

3.2.3.2.2 | Relative Closeness Coefficient (CC_i) Degree of Separation. A look at the distance based CC_i results in Table 11 shows a range between 0 and 1 with an adequate degree of separations between the 20 alternatives. However, with two

TABLE 10 | PROMETHEE determine net outranking and recommendation ranking.

Recommendation	Sum L	Sum E	Net OR	Rank
1	25	2	22	12
2	94	363	−269	17
3	146	34	112	7
4	451	2	450	2
5	123	171	−48	13
6	138	63	75	9
7	211	77	134	6
8	513	105	407	3
9	56	105	−48	14
10	139	71	68	10
11	180	393	−212	16
12	70	545	−475	19
13	106	1012	−906	20
14	473	83	390	4
15	0	387	−387	18
16	331	223	108	8
17	212	54	158	5
18	816	321	495	1
19	238	180	58	11
20	70	199	−129	15

decimal points, Recommendations 13 and 18 have the same CC_i of 0.01. There is a degree of separation for both recommendations when the number of CC_i decimal points is changed from 2 to 3.

3.2.3.2.3 | Impact of Number of Alternatives. This outcome indicates that the TOPSIS methodology is not the most suitable of the three options when there is a significant increase in number of the alternatives that need to be ranked. This limitation is more pronounced when a decimal point approximation is used for the CC_i results. This shows 0.4, 0.3, 0.2 and 0 with 4, 5, 2 and 6 similar results, respectively. This confirms that more alternatives will significantly affect the level of separation.

3.2.3.2.4 | Effort Required to Create the Evaluation Matrix. The effort required to derive the CC_i and rank the alternatives is the lowest of the three MCDM options once a beneficial criteria (alternative) weight has been determined for the recommendations. The PIS and NIS values are determined from simple formulas. In addition, the ideal positive and negative numbers are determined from the range of the weighted column, which does not require any calculations.

3.3 | MCDM in HAZOP Case Study Key Outcomes

The results of the three different MCDM methodologies have been summarised and captured in the previous section. The goal of this section is to cover how these results affect the decision-making process in terms of the verification of the results, selection criteria (based on outcome, effort and time) for implementing MCDM to HAZOP studies, and an update to the framework. These insights will guide the project's conclusion and recommendations for future work.

3.3.1 | Comparison of Results

A comparison of the MCDM results of the AHP, PROMETHEE and TOPSIS methodologies applied to the HAZOP case study is represented in Table 12. The table also includes the initial and residual risk ranking associated with the recommendations based on coarse ranking.

It is clear from the table that ranking the recommendations based on the quantified resulting risk will result in eight recommendations with the same rank. This is a key justification for using the MCDM methodology.

A comparison of the three results shows that the AHP and TOPSIS rankings are more similar than the PROMETHEE ranking. It is noteworthy that TOPSIS and PROMETHEE use an evaluation matrix while AHP uses a comparison matrix. The former compares a criterion with a criterion or an alternative with an alternative, while the latter compares criteria with alternatives or vice versa.

A key observation is the degree of separation in the results of the three methodologies. Table 10 for the AHP results indicates a range between 0.12 and 0.03, Table 10 for the PROMETHEE results indicates a range between 450 and −906, while Table 11 for TOPSIS indicates a range between 1 and 0.01. Based on these results, PROMETHEE offers the widest range, which should be an important consideration when selecting the MCDM to use for an HAZOP with recommendations that have very similar residual risks.

3.3.2 | Validity of Results

The main criteria considered for validating the results are an inbuilt verification step for the MCDM methodologies. AHP has the CR, which is the inherent criteria/alternative weights verification step. This ensures the weights used for ranking the 20 recommendations are derived using a consistent determination of the comparison matrix.

PROMETHEE and TOPSIS do not have an inherent verification step in their process. They use the AHP weights for the evaluation matrix, which verifies the results to a certain extent. However, this does not validate the resulting CC_i (for TOPSIS) or net outranking (for PROMETHEE) results used for ranking the recommendations. Future work should involve determining whether other MCDM methodologies have inherent verification, considering there are 37 different MCDM methodologies.

3.3.3 | MCDM Selection Criteria for Use in Current and Future HAZOP Studies

The selection criteria have been split into two parts: one determines and ranks the criteria required to select the MCDM

TABLE 11 | TOPSIS determine relative closeness coefficient and recommendation ranking.

Recommendation	AHP beneficial criteria weight	S_i^+ (positive ideal solution)	S_i^- (negative ideal solution)	CC_i (relative closeness coefficient)	Rank
	1				
1	0.12	0.00	0.08	1.00	1
2	0.07	0.05	0.04	0.44	3
3	0.07	0.05	0.03	0.38	4
4	0.07	0.05	0.04	0.44	2
5	0.06	0.06	0.03	0.32	7
6	0.04	0.08	0.01	0.08	13
7	0.06	0.05	0.03	0.33	6
8	0.06	0.06	0.02	0.30	8
9	0.06	0.06	0.02	0.25	10
10	0.06	0.05	0.03	0.36	5
11	0.04	0.08	0.00	0.04	15
12	0.06	0.06	0.02	0.29	9
13	0.04	0.08	0.00	0.01	19
14	0.04	0.08	0.00	0.05	14
15	0.03	0.08	0.00	0.00	20
16	0.04	0.08	0.00	0.02	17
17	0.05	0.07	0.01	0.20	11
18	0.04	0.08	0.00	0.01	18
19	0.04	0.08	0.00	0.03	16
20	0.05	0.07	0.01	0.15	12
V+ (Ideal positive)	0.12				
V− (Ideal negative)	0.03				

methodology for this project, while the other part outlines how this selection process can be applied to the existing framework to identify necessary updates and guide its use for future work.

3.3.3.1 | MCDM Methodology Selection Criteria Ranking.

The criteria used for ranking include the outcome of each recommendation ranking, the effort required, the time taken to complete implementation and verification of the results.

Table 13 shows the result of ranking the aforementioned criteria. The scoring format used scores of 1, 3 and 5, where 1 is the score for the least performer and 5 is the score for the best performer. Ideally, all three MCDM methodologies should have a different score for each criteria.

The effort required was based on the number of formulas used, the complexity of these calculations and the number of tables created to complete these calculations and rank the recommendations. The effort scoring in terms of highest to lowest is PROMETHEE, TOPSIS and AHP. The time required is closely linked to the effort criteria. However, the main difference is the verification step required in the AHP to validate the results. The time scoring in terms of highest to lowest is PROMETHEE, AHP and TOPSIS. For verification scoring, TOPSIS and PROMETHEE were ranked the same score as they lack inherent results verification steps.

Following the scoring process and a review of the results, the AHP was selected as the best MCDM methodology for this case study.

3.3.3.2 | MCDM Methodology Selection Criteria Process.

Table 14 should be used to select the MCDM methodology for future HAZOP studies. The table shows how the number of recommendations greater than 20 and less than 10 can be used to select the right MCDM methodology to use for HAZOP studies. In addition, HAZOP studies that have more than 5 recommendations with the same residual risk, recommendations with low degree of separation and less than 10, and the number of recommendations with similar AHP criteria weight can be used to guide the selection of the appropriate MCDM methodology.

If an HAZOP study has less than 10 recommendations with low degree of separation or the AHP recommendation criteria weights are similar, PROMETHEE should be used as it offers a significant degree of separation in the final outcome. However, for HAZOP studies that have a significant number of recommendations, AHP

TABLE 12 | MCDM in HAZOP recommendation ranking outcomes.

Recommendations	Risk before	Rank before	Risk after	Rank after	AHP rank	PROMETHEE rank	TOPSIS rank
1	15	1	15	1	1	12	1
2	12	2	4	20	2	17	3
3	12	2	12	2	3	7	4
4	8	14	8	9	4	2	2
5	8	14	8	9	8	13	7
6	12	2	8	9	9	9	13
7	12	2	12	2	5	6	6
8	12	2	12	2	7	3	8
9	12	2	8	9	11	14	10
10	12	2	12	2	6	10	5
11	12	2	12	2	13	16	15
12	8	14	8	9	10	19	9
13	8	14	8	9	15	20	19
14	8	14	6	17	16	4	14
15	6	19	6	17	18	18	20
16	12	2	8	9	17	8	17
17	12	2	8	9	12	5	11
18	6	19	6	17	20	1	18
19	12	2	12	2	19	11	16
20	12	2	12	2	14	15	12

TABLE 13 | MCDM methodologies in HAZOP case study ranking outcome.

Criteria	AHP	PROMETHEE	TOPSIS
Outcome	3	1	5
Effort	5	1	3
Time	3	1	5
Verification	5	1	3
Total	16	4	16
Rank	**1**	**3**	**2**

TABLE 14 | MCDM methodology selection criteria for real life HAZOP studies and case studies.

Selection criteria	AHP	PROMETHEE	TOPSIS
Number of recommendations < 10			
Number of recommendations ≥ 20			
Number of recommendations with similar residual risk > 5			
Recommendations with low degree of separation and < 10			
Number of recommendations with similar AHP criteria weight			

or TOPSIS are preferred, as PROMETHEE requires the creation of a significantly large evaluation matrix, which is prone to error as the number of recommendations increases.

In summary, AHP or TOPSIS can be applied when the HAZOP has a significant number of recommendations. However, PROMETHEE can be considered when the post-recommendation (residual) risk values are closely similar, and a degree of separation of recommendation is required to complete the ranking. The purpose of using these three MCDM methodologies for this case study is twofold; first, to confirm MCDM methodologies can be successfully applied to HAZOP studies; and second, to develop a criterion for selecting the most suitable MCDM methodology for future HAZOP studies.

4 | Conclusions

The primary objective of conducting HAZOP studies is to address the recommendations generated from them. However, there is evidence that these recommendations remain unresolved years after the HAZOP studies have been completed. Ranking these recommendations should aid addressing them. After all, what is the purpose of conducting an HAZOP study if you do not intend to implement the recommendations. MCDM methodologies can successfully be applied to HAZOP studies to rank recommendations. A case study of MCDM application to an HAZOP study was conducted by applying three different types of MCDM methodologies, AHP, PROMETHEE and TOPSIS, to the HAZOP study of a high-hazard plant with five nodes.

The outcome of this case study was used to determine the best MCDM methodology for this HAZOP based on a select criteria and to create a framework for selecting the most suitable MCDM methodology for subsequent application to HAZOP studies. This framework uses the number of HAZOP recommendations, the degree of separation between the associated residual risk of recommendations and the number of recommendations with similar residual risk. These results achieve the project aim and objectives of studying the HAZOP study process and MCDM processes to confirm they can be applied to high-hazard industries, conducting a case study to demonstrate the successful application of the three main types of MCDM methodologies to an HAZOP study, and proposing an MCDM framework that considers the benefits and limitations of each type to inform application to future HAZOP studies.

Existing literature include applying a hybrid of MCDM methodologies to rank hazards and create MCDM-based risk matrices. This project case study aligns with existing literature by applying MCDM methodologies to HAZOP studies. However, the main difference is that this study addressed scenarios where recommendations from the HAZOP study have similar risk and there are limited resources to implement all recommendations. The following insights should be considered for future work: explore other types and hybrid methodologies for HAZOP studies, as this study is limited to 3 out of the 37 different MCDM methodologies; consider additional MCDM selection criteria including include the mix of participating experts, their relevant experience and their bias towards it; use MCDM types that have inherent results verification processes; use software tools for completing the MCDM quantitative assessments particularly for complex outranking MCDM methodologies; increase team involvement and incorporate an MCDM expert to support application of the MCDM methodologies.

Funding

No funding was received for this study.

Data Availability Statement

Data sharing is not applicable to this article, as no new data were created or analysed in this study.

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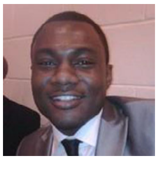
Biographies



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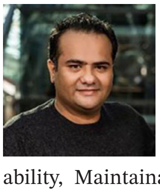

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